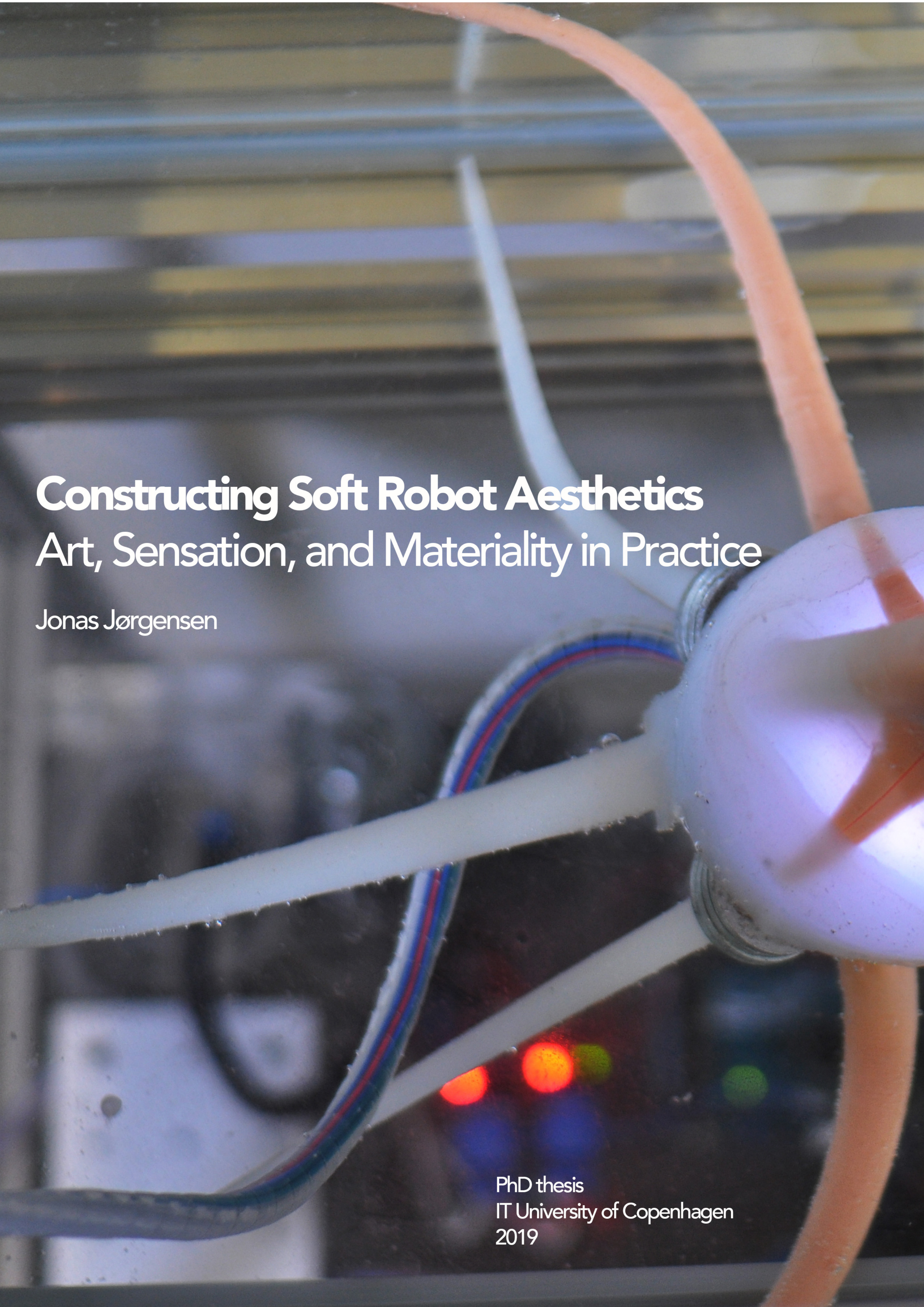

Constructing Soft Robot Aesthetics

Art, Sensation, and Materiality in Practice

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PhD thesis
IT University of Copenhagen
2019

Constructing Soft Robot Aesthetics: Art, Sensation, and Materiality in Practice

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PhD thesis
Submitted to the IT University of Copenhagen
May 16 2019

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Abstract

Over the past decade, robots have spread throughout society, entering the everyday lives of an increasing number of people. Concurrently with this development, a novel class of robots has seen the light of day. *Soft robotics* designates a new approach to designing robots, anchored in the simple idea of using pliable and elastic materials such as silicone rubbers rather than metal or plastic.

This thesis presents a study of soft robots that spans art and science. It explores alternative versions of what soft robotics might be or become if approached from the point of view of art and aesthetics. The overarching problem addressed is *how artistic and aesthetic practices might augment soft robotics and contribute to a more nuanced understanding of the potentials and consequences of rendering a robot soft*. The thesis combines analytical and practice-based research methods to address this problem, drawing on the fields and disciplines of artistic research, art history, human-robot interaction, and soft robotics.

The thesis consists of seven research publications bound together by an introduction.
The research presented examines what qualities and capacities of soft robots that emerge in contemporary projects within fields of aesthetic practice that incorporate soft robotics technology. It contributes both to rethinking and contextualizing soft robot aesthetics in relation to historical artworks and art practices and to constructing an aesthetic genealogy of soft robotic art that can help elucidate its aesthetics.

By means of an empirical human-robot interaction experiment, the thesis seeks to nuance statements and claims made about human perceptions of soft robots within technical literature and to gain insights into the spontaneous interaction behaviors elicited by soft robots. Through artistic practice, the thesis explores how soft robotics technology can function as an artistic medium. Furthermore, it shows how artistic and aesthetic practices can be productive of other types of knowledge about soft robots and, as a byproduct, generate outcomes that are of use to robotics research in a broader context.

A central insight that emerges from the thesis' transdisciplinary engagements with soft robotics is that in practice, the softness of a soft robot can come to matter in several ways. Different versions of softness in a robot are actualized within different practices with dissimilar consequences. Accordingly, the thesis argues that in order to fully unfold the technology's potential, a transdisciplinary perspective on softness is required.

Resumé

I løbet af det seneste årti har robotter spredt sig til alle samfundssfærer og er blevet en del af mange menneskers hverdagsliv. Sideløbende med denne udvikling er en helt ny type af robotter blevet udviklet. *Soft robotics* betegner en ny tilgang til at skabe robotter, der tager udgangspunkt i at bruge bøjelige og elastiske materialer såsom silikone i stedet for metal eller plastik.

Denne ph.d.-afhandling præsenterer et studie af bløde robotter, der går på tværs af kunst-, ingeniør- og naturvidenskab. Afhandlingen udforsker alternative bud på hvad bløde robotter er eller potentielt kan blive, når de tilgås med afsæt i kunst og æstetisk teori. Det overordnede problem afhandlingen adresserer er *hvordan kunstneriske og æstetiske praksisser kan udvide soft robotics og bidrage til en mere nuanceret forståelse af potentialet og konsekvenserne af at gøre robotter bløde.* For at tilgå dette problem benytter afhandlingen analytiske og praksis-baserede metoder og trækker på kunstnerisk forskning, kunsthistorie, menneske-robot interaktion (human-robot interaction), og soft robotics.

Afhandlingen består af syv publikationer der bindes sammen af en kappe. Forskningen der præsenteres undersøger hvilke kvaliteter og egenskaber ved bløde robotter, der kommer til syne i samtidige projekter med bløde robotter indenfor æstetiske praksisfelter. Den bidrager desuden til at gentænke og kontekstualisere bløde robotters æstetik i forhold til historiske kunstværker og kunstpraksisser og derved konstruere en æstetisk genealogi for blød robotkunst, der kan bidrage til at belyse dennes æstetik.

Ved hjælp af et empirisk menneske-robot interaktionseksperiment søger afhandlingen at nuancere udsagn og påstande om menneskers opfattelse af bløde robotter fremsat inden for den tekniske litteratur, og at få indblik i hvilken menneskelig interaktionsadfærd bløde robotter afføder. Gennem kunstnerisk praksis undersøges det desuden hvordan soft robotics kan fungere som et kunstnerisk medium og det illustreres hvordan kunstneriske og æstetiske praksisser er i stand til at producere andre slags viden om bløde robotter og sekundært generere resultater, der er brugbare for den bredere robotforskning.

Gennem afhandlingens transdisciplinære arbejde med bløde robotter fremskrives en forståelse af blødhed i en robot som en egenskab der kan få konkret betydning på mange forskellige måder. Forskellige versioner af blødhed aktualiseres inden for forskellige praksisser med uens konsekvenser. Som følge heraf argumenterer afhandlingen for at et transdisciplinært perspektiv på blødhed er nødvendigt for at udfolde bløde robotters fulde potentiale.

Acknowledgements

I would like to thank first my supervisors Laura Beloff and Gunhild Ravn Borggreen for their supervision and guidance. Laura – also for your truly inspiring generosity, boldness, and curiosity. Gunhild – for always meeting my work with both critical questions and encouraging enthusiasm, and for involving me in ROCA and early on for encouraging me to formulate the project proposal that gained me the position as a PhD fellow at ITU.

I also extend my thanks to all the members of the REAL (Robotics Evolution and Art Lab) and MAD research groups for making my time at the IT University of Copenhagen thoroughly enjoyable and interesting. Special thanks go to Andres Faina and Jørn Lambertsen for helping me solve numerous practical issues. Also to Frank Veenstra for our collaborative work, and Sebastian Risi for supervising this work. I would like to thank David Kadish, Rosemary Lee, and Hugo Mulder for being great office mates and fellow cross-disciplinary travelers in art/architecture and something else.

My thanks also go to my midway evaluation committee members Elizabeth Jochum and Jacob Wamberg for your comments and questions, which became important for the remaining work. Elizabeth also for our subsequent research collaboration. I also wish to thank the inspiring students that I have worked with on soft robotics projects – Mads Bering, Anne-Sofie Emilie Belling, and Sofie Glerup Larsen.

Finally, I thank my parents Johannes and Lotte and my brother Lasse. Last but not least, I am forever indebted to you Kirsten for your encouragement, help, and support. To Georg and Astrid, equally so, for bringing joy, love, and wonder.

Contents

1 Introduction

A boom in robotics research within the past decade has made robotics technology not only a growing industry, but a pervasive part of many people's everyday lives, as well as a technical issue with global political reach. Roomba vacuum cleaners are everyday features of private homes, drones are included in national legislation, humanoid robot tutors are teaching in primary schools, and health-care robots are used in nursing homes. As a part of this "robotic turn", the subject of robots has also been receiving increasing attention from researchers working in a number of fields other than the technical sciences. Concurrently with these developments, a novel class of robots have seen the light of day. *Soft robotics* designates a new approach to designing robots that is anchored in the simple idea of using pliable and elastic materials such as silicone rubbers, rather than metal or plastic, to build robots. The endeavor is often motivated by the observation, of roboticists, that nature shows by example how having a soft body makes it easier to accomplish many of the tasks that robots traditionally have had difficulty with, such as grasping and moving dynamically. Due to their pliability, soft robots are, however, also claimed to be inherently safer for humans to interact with. Hence, they are also imagined to be especially well-suited for applications that require close human-robot interaction. Albeit still a nascent research subject, soft robotics technology has already been successfully implemented in industrial settings, but a number of applications "in the wild" have also been proposed including uses in eldercare, prostheses, rescue operations, wearable technology, and collaborative robots (cobots). Research has already been conducted on developing an automated soft robotic shower facility for disabled and senior citizens (Papageorgiou et al. 2015) and the automation company Festo has successfully demonstrated three generations of cobots that incorporate soft robotics technology.

When I first encountered a soft robot in a YouTube video about four years ago, I remember being immediately struck, but not by its technical abilities. Instead it was the robot's quaint looks and movements that first captivated me. Its appearance seemed to radically break with everything one tends to associate with how a robot looks and behaves. It could bend, deform, and change shape. It had movements that were gradual and fluid rather than reminiscent of the stylized staccato of "the robot" dance style. It had a continuous surface and a coherent body that would yield and accommodate to objects upon contact, and it was considerably smaller than a human body. Albeit purely mechanical, it seemed to inhabit a strange borderland between machines and organisms, between the technological and the biological. Rather than announcing a new technical solution to the automation of labor, to me this robot announced a novel aesthetic.

Over the course of working on this thesis, I have had the chance to discuss soft robotics with a number of people through participating in public demonstrations and academic events. And the anecdote provided above hardly seems to apply only to my personal experiences. Yet within research discourses on soft robotics, the aesthetic qualities of soft robots have hitherto largely been ignored. Any consideration of the significance that aesthetic aspects might have for soft robotic design practices and interactions between humans and soft robots have been elided in favor of a focus on functionality and safety. "Conventional, rigid-bodied robots […] are unsafe for interaction with humans", soft roboticists Rus and Tolley write, for instance, and continue:

> Soft robots provide an opportunity to bridge the gap between machines and people. In contrast to hard-bodied robots, soft robots have bodies made out of intrinsically soft and/or extensible materials (for example, silicone rubbers) that can deform and absorb much of the energy arising from a collision. […] The advantages of using materials with compliance similar to that of soft biological materials include a considerable reduction in the harm that could be inadvertently caused by robotic systems […] increasing their potential for interaction with humans. (Rus and Tolley 2015, 467)

The few times when soft roboticists occasionally stray from the vocabulary of functionality and safety, one is instead presented with assertions that soft robots look, feel or move in a more "natural" way than rigid robots and for that reason will be more pleasant for humans to interact with (Zitzewitz et al. 2013; J. Rossiter and Hauser 2016; Laschi, Mazzolai, and Cianchetti 2016; Pfeifer, Lungarella, and Iida 2012). In accordance with the field's prevailing focus on technical issues, the methods used to develop and design soft robots have also been anchored mainly in engineering, and the research conducted has been driven by utilitarian interests and the aim of developing robots that are useful for practical tasks and efficient.

In contrast, this thesis studies soft robots with an explicit focus on aesthetics across the arts and sciences. It seeks to interrogate what the potential might be of recognizing, affirming, and emphasizing the aesthetic qualities and aspects of soft robotics technology and its associated practices rather than ignoring them. In extension hereof, the thesis enquires into the possibility of including aesthetic practices and art methodologies within the repertoire of soft robotics research methods or of them functioning as a supplement to these.

The thesis consists of seven research publications (hereafter “papers”) and an introduction (“kappe” in Danish) with eight chapters and appendices. The introduction introduces and contextualizes the overarching research problem that the papers address and presents and elaborates on theoretical and methodological considerations that have been developed in the work on the papers and the thesis’ practical component. It also serves to summarize, compare, and discuss the issues and conclusions presented in the individual papers and identifies questions for further research.

2 Main problem, research questions, and terminology

The overarching problem that the thesis addresses is *how artistic and aesthetic practices might augment soft robotics and contribute to a more nuanced understanding of the potentials and consequences of rendering a robot soft*. Departing from this conceptual and practical problem, the research conducted has been narrowed down via an emphasis on the following three research questions:

- RQ1: *What qualities and capacities do aesthetic and artistic explorations of soft robotics technology bring to light?*
- RQ2: *How can soft robotics be brought to function as an artistic medium?*
- RQ3: *What influence might the aesthetic qualities of soft robotics technology have on human interaction with soft robots?*

Considering that soft robotics is an emerging technology that is still being invented, the thesis combines theoretical and practice-based approaches to address these questions. It contributes to both conceptualizing and physically realizing a novel or reformed version of soft robotics as both a concrete set of technologies and an associated set of practices.

As is evident from the formulations of the project's research questions, the thesis is precariously situated between and seeks to navigate interests and agendas hailing from different academic fields and disciplines. RQ1 is predominantly posed from the point of view of robotics research, as it sets out to inquire further into and extend soft robotics, however, doing so by drawing on insights from other fields. RQ2 instead articulates an artistic and art historical interest in probing, exploring, inventing, analyzing, theorizing, and contextualizing soft robotics technology as a medium for artmaking. RQ3 is compatible with the interests of both robotics research and robotic art, yet comes closest to a question that might be formulated from within the interdisciplinary research field *human-robot interaction* (*HRI*).

Even if the thesis' research focus implies that existing soft robotics research practices are lacking in some respect, and that this aspect is worth recovering, I wish to point out at this early stage that the research presented here should not be seen as dismissive of engineering and natural science in general nor in relation to soft robots. Instead, it seeks to acknowledge the competences and accomplishments of both natural science and technology as well as art and aesthetics. Hence, the research interest is in how art and aesthetic practice might augment existing approaches to soft robotics, rather than simply supplanting them, and the work has been undertaken with the aim of creating an encounter across disciplines and not a critical dismissal.

2.1 Different usages of “aesthetic” and “aesthetics” within the thesis

As indicated by its title, a central concept of the thesis work is *aesthetics*. The word “aesthetic” is generally used with a variety of different meanings and can function as both an adjective and a noun. Used in everyday language as an adjective, it can mean that an object is beautiful or that it potentially offers an aesthetic experience, that can be rewarding in some way, if attended to in a specific manner (Fenner 2003). As a noun, the word “aesthetic” can instead refer to a specific taste or set of preferences.

Traditionally within robotics research and HRI, design aesthetics have been addressed through a functionalistic lens. Aesthetic considerations have been subordinated to usability issues and have revolved mainly around whether specific designs of a technology are considered aesthetically pleasing by users, which is believed to encourage its wider adoption. The thesis presents an argument for utilizing a more comprehensive notion of aesthetics and for assigning aesthetics a central role in the development, design, and deployment of soft robots. Overall, the thesis uses aesthetics as a concept to address the means (methods or ways of doing something) by which sensation and art can be involved with and relevant for soft robotics and the knowledge that results from such engagements. Within the thesis, the two words “aesthetic” and “aesthetics” are used with two main meanings: An “aesthetic” is used to refer to the specific “style” of soft robotics, and “aesthetics” is used as a catchall for philosophical theories dealing with art and sensuous knowledge.

Due to the terms’ centrality within the thesis discourse, I will provide brief descriptions of both of these meanings from the outset below.

2.1.1 Aesthetic as style

"Aesthetic" as a noun, refers to a specific "style", and relates to accounts of art history as a "history of styles".[1] Within such, style refers to a "distinctive manner which permits the grouping of works into related categories" (Fernie 1995).[2] When using the term aesthetic with this meaning, I am thus using it to describe what I take to be characteristic aspects of e.g. a specific soft robotic artwork or a set of principles underlying it (its aesthetic). Or to refer to characteristic aspects of soft robotics technology in general when this technology is utilized or viewed as an artistic medium (the aesthetic of soft robotics).

Addressing soft robotics as "an artistic medium", as I already have, exposes one perhaps to critiques levelled against formalist art history and modernist art theory. Here, the word *medium* was used to refer to the physical support of the artwork, e.g. pigments on canvas in the case of painting, and e.g. wood or marble in the case of sculpture. But the *medium specificity* of e.g. painting and sculpture also functioned as a guarantor of aesthetic autonomy and artistic quality and was held to dictate their inherent historical teleologies (Greenberg 1960). This claim was met with intense critique subsequent to Western art entering its *post-medium condition* in the late 1960s (Krauss 2000). However, the concept of medium utilized in this thesis aims to be non-essentializing and hence it diverges from the medium concept within modernist art theory. It acknowledges that different media can produce specific practices but also that media are produced through specific practices, and that this reciprocal process is open to historical contingencies and could be otherwise. That is, the experiences that soft robotics can give rise to obviously derive from the technology's physical properties and technical functionalities, but equally from contingent historical ways of engaging with or attending to it. And the aesthetic practices that are cultivated around the technology may in turn potentially produce novel kinds of sensations, and new ways of sensing that alter such wider practices. The aesthetic potential of soft robotics technology as an artistic medium is thus not claimed to be given solely by nor to be inherent in the technology itself or in how this physical substrate is apprehended by the human sensorium.[3] Instead, aesthetics of soft robotics are

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[1] It lies beyond this thesis to give an account of this tradition, but a good overview is provided in Laurie Schneider Adams' *The Methodologies of Art* (Adams 2009).

[2] It should be noted here that the wider art historical and aesthetic concept of style has been problematized on several occasions. As art historian James Elkins writes, "Each of the component terms of style has been disputed, and style itself has been rejected on various grounds; yet it remains inseparable from working concepts of art and its history" (Elkins 2003).

[3] I am using the term "apprehend" to refer to how the mind seizes or becomes aware of an object. This usage is in line with Immanuel Kant's theoretical description of how the imagination acts to synthesizes perceptions via a process of apprehension.

seen to always stand in relation to wider practices and a repertoire of meanings and values that readily attach themselves to it. The aesthetic style of soft robotics encompasses characteristic qualities of the technology that may be apprehended via the senses in an uncomplicated manner (e.g. specific shapes, movements, tactilities etc.) but also associated meanings, narratives, and capacities that are constructed in the practices that surround this medium (by soft roboticists, artists, and many others). A medium is thus not physical nor is it just phenomenological, cultural, or discursive; rather it is a central assumption of the thesis that the aesthetic style of soft robots is actualized and apprehended as both materiality and mediation. I will return to the theoretical background that underlies this perspective in Chapter 4, which presents the theoretical and conceptual framework of the thesis in more detail.

2.1.2 Aesthetics as theories of art and sensation

The second usage of "aesthetics" is as a catchall for theories of art and sensuous knowledge. In the context of the thesis used so, the term thus refers to theoretical accounts of soft robotic art or of how soft robots are grasped within practices that involve sensation. This usage is linked to the tradition of philosophical aesthetics, which I address in Chapter 4. However, before continuing, I will provide some brief clarifications on the theoretical perspective on aesthetic theory taken in this thesis.

Firstly, when talking about aesthetics as theories of art and sensation, this thesis does not focus on universalizing or naturalizing aesthetics nor aesthetic judgment. Consequently, the thesis does not endeavor to uncover or describe aesthetic qualities of soft robotics that all people can agree on, or that are universally present. Nor is its main interest how soft robotics might give rise to the traditional aesthetic experiences of beauty and the sublime. Instead, the thesis seeks to explore and provide situated accounts of how art practices and interpretations of art and artmaking can generate other kinds of knowledge about soft robotics, and to illustrate and propose ways in which sensuous knowledge and art methodologies might come to matter for engaging with soft robots.[4] From the historical tradition of philosophical aesthetics, the thesis adopts ideas about how art and sensation can produce knowledge. Among these are a view of art as driven by a non-purposeful and critical impulse and of aesthetic experience as potentially encompassing a non-conceptual, non-discursive

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[4] I use the term "situated" with reference to Donna Haraway's notion of *situated knowledges*. A situated account acknowledges the observer as situated by specific perspectives on the world. But also that knowledge production is tied to and bounded by social and historical contexts. It equally emphasizes the agency of objects within knowledge production and sees matter as a "witty agent", that continually manages to trick and surprise us (Haraway 1988).

kind of knowledge about the world. However, in relation to the latter, the thesis contends with modern critical aesthetic theories that aesthetic experiences should not be considered to be "pure" nor disinterested, but are influenced by or even predicated upon personal experience, practices, and culture (as I also alluded to in the previous section).[5] Briefly, within the practice and thinking developed in the thesis, an aesthetic approach to soft robotics comes to designate an ambition of cultivating a sensibility towards the ways in which soft robotics technology provides affordances for human sensuous apprehension and meaning-making in dialogue with an understanding of its physical characteristics and wider material capacities. Hence, the thesis' title, "Constructing Soft Robot Aesthetics", is also a play on these two meanings of aesthetic and aesthetics; it refers to both the physical making of soft robots with novel designs as well as to the crafting of analyses of soft robotic art and sensuous engagements with soft robots.

The two meanings of "aesthetic" as style and "aesthetics" as theories about art and sensation described above are used in the thesis as they are practical for mapping recurrent features of soft robots as aesthetic objects as well as for describing specific practices that can supplement the methods of soft robotics. Yet I acknowledge that the two concepts are not separate – in practice they are often connected. That is, an aesthetic (a style) can contain, be generative of, or work-through an aesthetics (a theory of sensuous knowledge or a theory of art) and vice versa. Historical examples of this are legion and include the pre-war avant-garde movements' tandem theoretical and artistic productions (e.g. Surrealism and Dada) as well as philosophers' engagements with specific artists (e.g. Gilles Deleuze's work on Francis Bacon or Maurice Merleau-Ponty's on Cézanne). Moreover, within a given historical context, an aesthetic (a style) implies certain values and priorities that are bound to specific ways of living and relating.

2.1.3 The difference between "aesthetic" and "artistic"

Despite drawing on aesthetic theory to support the claim that both art and practices of sensation can be productive of knowledge, I do not wish to conflate these two areas of activities. Art is clearly about more than sensation, as is obvious from e.g. the fact that it can also be conceptual, and likewise does sensation not in itself constitute any artform. Yet art always involves sensation to some degree, even conceptual artworks, for instance, are always physically instantiated. An aesthetic attitude or aesthetic principles can, however, be applied to many other things than

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[5] This notion is present in e.g. Walter Benjamin's "The Work of Art in the Age of Mechanical Reproduction" [1939] essay (Benjamin 2008).

artworks – from natural phenomena, social interactions, to management styles. And the traditional aesthetic experiences of beauty and the sublime are equally afforded by other phenomena than art. Hence, the two fields of art and sensation overlap but are not identical. I seek to acknowledge these differences by using “aesthetic” mainly as an adjective to refer to practices where sensation is involved, and ways of comprehending that are anchored in the senses (e.g. embodied knowledge, tacit knowledge etc.). I reserve the term “artistic” for the procedures, methods, and interests that have manifested themselves within historical and contemporary artmaking practices. In accordance with how the composite term is commonly used I, however, refer to the activities of practitioners within the fields of art, design, and architecture as “aesthetic practice”.

3 Research status

In this chapter, I seek to situate the thesis research within a larger context and to explicate the state-of-the-art research on which it builds. The thesis engages with and extends two primary strands of existing work – academic research on soft robotics and work by artists, designers, and architects that involves soft robots. The chapter reviews seminal work from each of these two strands. It serves to contextualize the thesis papers, but also updates the thesis contribution as a whole by addressing more recent work that was not addressed in the thesis papers.

In section 3.1 the current state-of-the-art technical research on soft robotics is reviewed. I use the term "technical" here to refer to research that is oriented towards engineering disciplines and aimed at developing technical solutions that have practical applications.[6] As will become clear, this category encompasses the bulk of the existing research on soft robotics. This part of the review thus also functions as an introduction to the existing interests and dominant approaches to soft robotics that the thesis seeks to augment. Furthermore, the review serves to clarify what contemporary soft robotics technology encompasses and describes in more detail the technologies that the practice-based work of this thesis builds upon. The primary focus will be elastomer-based soft robotics, as this is the most widely adopted technology to date, and also the technology that has served as the basis for the practical component of this thesis. Hence, a number of specialized technical subfields within soft robotics research have been omitted.

Section 3.2 maps and reviews work from within art, design, and architecture and research projects within these fields that involve soft robotics. These three fields have recently begun to appropriate soft robotics technology, and each contains examples of engagements with the technology that have different aspirations than technical research. Even if the thesis papers primarily engage with soft robotics in relation to art, contemporary examples of soft robotics within design and architecture have been included in the section, as artistic work with soft robots is still rather limited, and because work within these two additional fields has added significantly to exploring the aesthetic aspects of soft robotics technology.

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[6] Some of the more interdisciplinary soft robotics research projects have also aimed at generating basic understanding of bodily mechanisms in certain animals, such as the functioning of an octopus arm. These projects proceed by way of a synthetic approach wherein the biological mechanism is sought to be replicated with technology, and through such reverse engineering it is hoped that one can arrive at a better understanding of how the mechanism works in the animal. Yet these projects still tend to justify themselves by the prospect of using the studied mechanism in robots for specific practical applications.

An engagement with the larger cultural prehistory of the notion of a soft robot would undoubtedly be relevant to a full consideration of the aesthetics of soft robots in order to also address the cultural imaginaries they activate. Yet, it is beyond the scope of this thesis to conduct such work. However, I have chosen to start each of the two sections 3.1 and 3.2 with some short considerations on how soft robotics might be contextualized historically within both technical research and Western art history.

3.1 Technical soft robotics research

3.1.1 Defining and historizing soft robotics

Soft robotics is usually defined as a field of research that aspires to replace some or all of the rigid parts conventionally used in robotics with soft parts. The measure of softness used is Young's modulus, defined as the relation between stress and strain for a linear material. Soft roboticists Daniela Rus and Michael Tolley thus define soft robots as "systems that are capable of autonomous behavior, and that are primarily composed of materials with [Young's] moduli in the range of that of soft biological materials" (Rus and Tolley 2015). This definition notwithstanding, a lot of the current research on soft robots does not deal with such complete systems, but instead merely building blocks and technologies that might become parts of such e.g. soft actuators and sensors and methods for fabricating these.

The field of soft robotics understands itself as more interdisciplinary than traditional robotics research, as it endeavors to combine insights and approaches from engineering, computer science, biology, and material science (Trimmer et al. 2015). Moreover, soft robotics research is characterized by its interest in bio-inspired design strategies – actuation and control solutions, for instance, have been developed that are based on soft-bodied animals or soft parts of animals including caterpillars, cephalopods, and elephant's trunks. These approaches are frequently coupled with an interest in *morphological computation* – the notion that a robot's body and its mechanical properties can perform part of the computation that usually occurs in silico as part of the control loop of a robot (Laschi and Cianchetti 2014). Among the technical benefits of soft robotics, when compared to traditional robots, soft roboticists frequently mention: Firm grasping, polymorphism and bodily adaptation to confined spaces, energy efficiency through reuse of potential energy stored in the elastic materials, but also their ability to interact safely with objects and bodies through passive compliance (Luo et al. 2017; Abidi and Cianchetti 2017; Wang, Nurzaman, and Iida 2017; Santina et al. 2017). As mentioned, the latter is often used as a selling point for the technology in relation to practical tasks that require human-robot interaction.

In recent years, soft robotics has become one of the fastest-growing topics within robotics research (Bao et al. 2018). The prehistory of today's research on soft robotics beyond the past decade is still an understudied subject. However, a still unacknowledged predecessor can be found in European automata from the eighteenth century. Historian Jessica Riskin has suggested that a fraction of these devices, which she refers to as "eighteenth century wetware", can be considered precursors of *artificial life* (*ALife*) research (Riskin 2003). But they equally anticipate today's interest in soft materials within robotics research. As Riskin mentions, soft and pliable materials namely figured prominently in such automata. They derived from a materialist, mechanist understanding wherein animals where seen as machines, and in turn machines where starting to be seen as similar to animals, Riskin argues (Riskin 2003, 99–100). Consequently, these creations "called attention to certain differences in texture, substance, and mode of action between animal and artificial machinery" yet "simultaneously worked to undermine these differences" (Riskin 2003, 100). Whereas mechanical animals of previous and subsequent historical periods merely sought to represent the likeness and characteristic movements of certain animals, automata from the 1730s to the 1790s aimed at *simulation* and the imitation of physiological processes (Riskin 2003, 100). This involved the epistemological practice of "using machinery to approximate nature, then experimenting on the model and drawing conclusions about its natural prototype" (Riskin 2003, 98). A dialectic between the conception of life and the conception of the machine, which Riskin describes as a driver of innovations in automata designs, thus prompted a preference for soft materials to emerge. "These machines", Riskin writes, "all reflected the assumption that an artificial model of a living creature should be soft, flexible, sometimes also wet and messy, and in these ways should resemble its organic subject." (Riskin 2003, 112). Hence, anatomical models, artificial limbs, as well as the so-called "talking heads" and automata of the period, all incorporated soft materials such as silk, linen, leather, cork, and parchment (Riskin 2003, 103–14).

In a recent review article, roboticist Liyu Wang and co-authors trace the contemporary technical research in soft material robots back to the late 1970s, when the first work on robot grippers incorporating granular materials was published (Wang, Nurzaman, and Iida 2017, 5). From here, the historical trajectory of soft robotics jumps to the mid-1980s and the first robot designs with continuously deforming bodies made from elastomers actuated with pneumatics. In the early

1990s, these beginnings were supplemented with tri-cellular elastomer units from the Suzumori lab at Okoyama University, from which different manipulators and walkers could be assembled. To this was added the first use of electrorheological fluids and electroactive polymers gels in soft robots from the late-1980s and mid-1990s respectively. Finally, the theoretical work of Rolf Pfeiffer on the influence of material properties on the function, behavior, and control of robots served as an important element of soft robotics research of the past decade, Wang and colleagues argue (Wang, Nurzaman, and Iida 2017, 6–7).

A recently published comprehensive bibliometric analysis of publications related to soft robotics in the period from 1985 to 2017 draws a different historical map of soft robotics as a research field (Bao et al. 2018). Although mentioning historical work that includes the McKibben artificial air muscles developed in the 1950s, the authors state that articles concerning soft robots were first published in 1990. They further note that the term “soft robotics” was initially used to describe a rigid robot with compliant joints and only subsequently became a term used to distinguish robots made of soft, compliant, and deformable materials from traditional robots (Bao et al. 2018, 230). From 2008 onwards, “soft robotics” has been widely adopted as a keyword in scientific articles, and in the period following 2012, the number of soft robotics publications released each year has increased (Bao et al. 2018, 230). The analysis by Bao and colleagues shows that the most frequently used keywords in soft robotics research have been “actuator, fabrication, control, material, sensing, simulation, bionics, stiffness, modeling, power, motion, and application” (Bao et al. 2018, 229). Quite significantly, the authors further remark that all published review articles on soft robotics to date have been conceived from a technical standpoint and focused on summarizing technical accomplishments as well as defining open technical problems that project novel routes for further research (Bao et al. 2018, 235). To this one might add, that review articles are not the only articles to have taken an exclusively technical perspective on soft robotics. To date there have been no full-length papers or articles published on silicone-based soft robotics, within *human-robot interaction* (*HRI*) and *social robotics*, the subfields of robotics research that have traditionally dealt with issues related to robot design aesthetics.

Taking the keywords identified by Bao and colleagues as my starting point, I will in the following subsections briefly describe the state-of-the-art solutions that have been developed within soft robotics and the technical issues they have addressed. This review serves mainly to contextualize the technical solutions developed in the thesis.

3.1.2 Actuation, power, stiffness

Soft robots can be actuated by electromechanical motors, just as most traditional robots are, e.g. by using embedded pull-strings or tendons. But the shift to soft materials also makes it possible to utilize other means of actuation in novel ways. Fluidic actuation (pressurized gasses and liquids) has previously been used to power rigid robots with e.g. *pneumatic artificial muscles* (*PAMs*), but in soft robotics, these sources of actuation are used extensively to create movement by means of deformation and expansion. Early work utilized bellows actuators (Wilson 1984) but a seminal research contribution was the *pneumatic networks* (*pneu-nets*) actuators (Ilievski et al. 2011; Shepherd et al. 2011). These consist of small channels and compartments embedded in elastomeric structures that can be inflated to facilitate a bending motion. The bending occurs because of an asymmetric strain resulting from the deposition of a more rigid material on one side of the actuator (e.g. a stiffer rubber, fabric, paper, or plastic film) (see Fig. 1).

The original pneu-nets actuator has been further refined to provide faster movement (Mosadegh et al. 2014). Other types of fluidic soft actuators include fiber- and mesh/fabric-reinforced elastomeric bladder actuators (Galloway et al. 2013; Cianchetti et al. 2013; Connolly et al. 2015; Cappello et al. 2018). The latter was utilized for “the blue robot” in Paper 6. A benefit of these, compared to pneu-nets actuators, is that a wider range of motions such as bending, twisting, coiling, axial extension, radial expansion etc. can be programmed materially into the actuator. But also that they can withstand higher actuation pressures and hence supply more force (Rus and Tolley 2015). Foam-based actuators (Murray et al. 2015), origami-inspired actuators (Li et al. 2017), and vacuum-powered actuators are also related types (Yang et al. 2016; Robertson and Paik 2017).

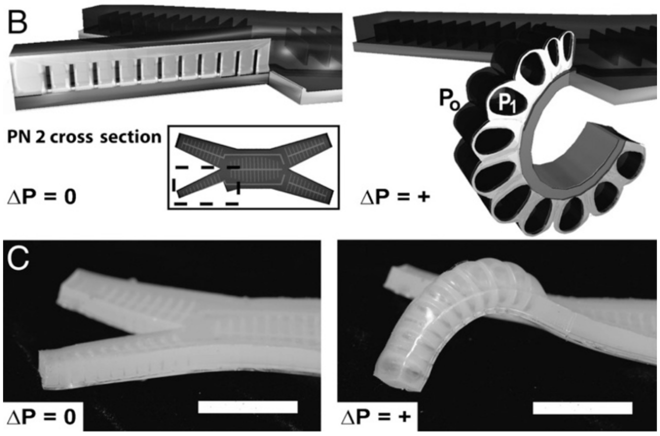

Fig. 1. Illustration from Shepherd et al. (2011) showing the principle of the first pneu-nets type soft actuator, and its implementation in one of the legs of their multi-gait robot.

A number of more unconventional means of actuation have also been explored for soft robotics, such as electrically powered *shape-memory alloys* (*SMAs*) (Lin, Leisk, and Trimmer 2011; Laschi et al. 2012; Seok et al. 2013), *dielectric elastomer actuators* (*DEAs*) (Gu et al. 2017), *electroactive polymers* (*EAPs*) (Bahramzadeh and Shahinpoor 2013), thermally expanding ethanol-silicone composites (Miriyev, Stack, and Lipson 2017a), and soft electrohydraulic transducers (*Peano-HASEL* actuators) (Kellaris et al. 2018). But also controlled gas explosions (Shepherd et al. 2013; Stergiopulos et al. 2014; Bartlett et al. 2015; Loepfe et al. 2015) and chemical reactions that create a pressure differential (Wehner et al. 2016). Moreover, biohybrid soft robots have been constructed that are driven by tissue-engineered rat heart cells that respond to light stimulation (Park et al. 2016) or that incorporate *microbial fuel cells* (*MFCs*), which produce an electrical current by feeding on biomatter (Philamore et al. 2016).

The subject of actuation also brings the challenge of stiffening. Stiffness is needed to transmit force and to maintain a position or supply a force over a longer period without excessive energy expenditure. Whereas early soft robotics tended to focus on completely soft morphologies, more recently examples of soft-hard hybrids have appeared that combine the best of rigid and soft robotics by e.g. endowing soft robots with a hard skeleton or having soft and hard robots collaborate to solve tasks (Stokes et al. 2013; Ramezani, Chung, and Hutchinson 2017). A standard technique that has been developed for dynamic stiffening in silicone-based soft robotics is to encase a granular material (often ground coffee) in a compartment and extract the air by applying a vacuum. Other solutions based on wax melting by heating it have also been suggested (Laschi, Mazzolai, and Cianchetti 2016).

3.1.3 Materials, fabrication, bionics

Different types of silicones (Ecoflex, Dragon Skin, Sylgard 184 (PDMS), Elastosil M4601) have been the most common materials used to construct soft robots. Other materials used include hydrogels, fabric, latex, and gelatin (Laschi, Mazzolai, and Cianchetti 2016). Silicone parts are usually cast manually in a mold, a method that is inspired by the techniques of *soft lithography* developed within chemistry research (Xia and Whitesides 1998; Ilievski et al. 2011). Commercially available silicones often have two liquid components. These are mixed and the silicone is then degassed in a vacuum chamber to remove air bubbles before it is poured into a mold. The molds are usually 3D printed, sometimes with wax inserts that are subsequently melted and removed. However, as a part of the thesis work, I have developed an alternative method in which layers of laser-cut acrylic plates are glued together to form molds. This approach is documented in a tutorial that was published as a part of the *Soft Robotics Toolkit* (see Appendix 10.4).

Recently, a number of projects have sought to directly 3D print soft robotic components, either by means of commercially available flexible filaments for use in standard FDM 3D printers, on multi-material 3D printers, or with custom-built systems. The latter have included modified 3D printing platforms that work by either depositing liquid silicone in layers that are heat-cured, or by injecting copolymer gels into a liquid silicone matrix to create hollow channels and compartments (Yirmibesoglu et al. 2018; Bartlett et al. 2015; Yap, Ng, and Yeow 2016; Jonathan Rossiter, Walters, and Stoimenov 2009; Bartlett et al. 2015; Schaffner et al. 2018; Wehner et al. 2016). Integrating the design and manufacture more closely to achieve a higher degree of automation in the process has also been proposed (Wehner et al. 2016; Paik 2018).

As mentioned earlier, designs for soft robots and soft robotic components have often been bio-inspired. This is also the case for two of the robots I have constructed described in Papers 3, 4, and 5. Papers 1 and 4 also address bio-inspiration and its limitations as a design method vis-a-vis the approach to soft robotics developed in the thesis practice and papers.

3.1.4 Sensing

A central technical challenge that accompanies the shift to soft materials, is how to implement electronic sensors, which are usually hard components that are connected to the control system with wires. If the morphology stretches, this solution is not viable, as the wires can detach or create a tear. Hence, a great deal of research has centered on developing new types of soft and stretchable sensors, that can be integrated into soft morphologies. Conductive fabric, liquid conductors, electroactive polymers, and conductive silicones are some of the materials that have been used (Lee et al. 2017). Optical, chemical, and biological soft sensors have also been proposed (Rus and Tolley 2015). As the soft robots constructed in this thesis use regular hard electronic sensors, and simply bypass the issue by positioning them in places where the robots do not stretch, I have chosen not to review this subfield of research in detail. However, it is worth mentioning that one of the novel aspects of soft robotics is that a number of developed components are multifunctional and can function as both sensors and actuators. Hence, actuation and sensing capabilities can be integrated into the same soft component.

3.1.5 Control, simulation, modeling, motion

Soft robots require new control strategies as their compliant bodies possess infinite degrees of freedom. Hence, calculating the values of actuation parameters that result in a specific body configuration cannot be accomplished simply by solving a set of reverse kinematics equations, as is the case for rigid robots with finite degrees of freedom. Moreover, the mechanics of elastic materials are computationally heavy to simulate accurately in software physics engines, that might potentially aid in the design of specific robot functionalities. Despite these challenges, a range of complex motions have been realized in soft robots – from diligent manipulation to locomotion by means of walking, jumping, crawling, peristaltic movement / undulation, rolling, swimming, and flying (Laschi, Mazzolai, and Cianchetti 2016; Ramezani, Chung, and Hutchinson 2017). The design of these has often relied on other approaches, rooted in empirical experimentation, intuition, and trial and error. This aspect of soft robotics design methodology is addressed in more detail in Papers 1, 5, and 7. Paper 1 articulates this issue as an indication that aesthetic approaches are also of relevance to soft robotics research. Paper 5, the most technically oriented paper included in the thesis, instead proposes a design method to navigate the issue. This is achieved by combining the manual design of the robot’s morphology with an algorithmically aided design of its movement. Paper 7 addresses the issue in relation to an examination of the epistemologies and modes of knowledge production within technical soft robotics research and soft robotic art, respectively.

3.1.6 Application

As evinced by Bao and colleagues’ bibliographic study, most academic publications on soft robotics research explicitly address potential applications of the technology. Since the field’s inception, the list of proposed applications has steadily grown and now includes: surgery, rehabilitation, assistive technologies, explorations and rescue operations (in unstructured environments), environmental monitoring, human-machine interfaces, wearable input devices, prostheses, orthoses, exosuits, and cobots (Laschi, Mazzolai, and Cianchetti 2016; Rus and Tolley 2015; Lee et al. 2017). However, at present soft robotics has only seen limited commercial exploitation in products by a few companies. Soft Robotics Inc. produces custom-made pneumatically-actuated rubber grippers for high-speed pick-and-place tasks. Pneubotics are developing robotic arms and other projects based on inflatable fabric structures. Empire Robotics Inc. produces soft rubber end-effectors resembling tennis balls that can grasp objects by means of granular jamming.

3.2 Soft robotics in aesthetic practices and research

Before the research field of soft robotics was established, notions and fantasies about soft artificial life forms clearly existed within different pockets of Western culture. These, arguably, constitute a preface for contemporary aesthetic engagements with the technology. I have already mentioned the tradition of European automata but within science fiction, androids with soft tissue sustained by chemico-biological fluids are also legion as witnessed by series and films such as *Star Trek, Blade Runner*, and *Westworld*. Such entities can also be traced back to Karel Čapek's *R.U.R.* (1920/2006) play, where the word 'robot' first appears. Here, the soft materials and techniques used to produce autonomous machines in the image of the human worker are elaborately described in technical detail. Rossum, the scientist who discovered the basic principles underlying their manufacture, we are told, had made attempts to synthesize the protoplasm of natural living tissue, but eventually discovered "a material that behaved just the same […] despite being, chemically, quite different." (Čapek 2006, 6). An interest in forms of soft artificial life that are distinctly non-human in terms of both morphology and ethology equally pervades science fiction. In David Cronenberg's movie *eXistenZ* (1999), for instance, one encounters soft organic-looking virtual reality consoles, known as "game pods". These entities are described as being similar to animals and said to be grown from amphibian eggs stuffed with synthetic DNA.

These few select examples, to which several others could be added, illustrate how the quality of softness has been central in cultural representations of and imaginations about robots and artificial life. At present, past visions of cultural practitioners thus seem to have converged with the interests of technologists in soft robotics. Yet, technical soft robotics research has also already begun to affect culture. The Disney movie *Big Hero 6* (2014), for instance, which featured a fluffy inflatable robot protagonist, was inspired by soft robotics research conducted at Carnegie Mellon University (Hauser 2015). The commercial *RealDoll* love dolls (which are also manufactured from Ecoflex silicone) have also recently been equipped with actuation, sensors, and AI software (Crist 2018).

3.2.1 Art historical precursors of soft robotic art

As noted in Paper 1 and Paper 7, a few soft robotic artworks exist that predate soft robotics as a research field. But other Western visual arts traditions also share traits with soft robots. As argued in Paper 2, the tradition of *soft sculpture* can be considered an antecedent. By way of their organic appearance and simplified bio-inspired designs, soft robots also extend the formal language of one of the two main traditions within modern abstract art that formalist art historian Alfred Barr described as *biomorphic* – works that tend to feature curvilinear, bulbous or rounded shapes derived from nature. In addition, the capacity for transformation inherent in soft robotics makes the technology resonate with Surrealist interests, but also the theme of metamorphosis within romanticist art.

One of the first motorized sculptures, Naum Gabo's *Kinetic Construction (Standing Wave)* (1919-1920), also has links to soft robotics, as it uses the elasticity of a material for its aesthetic effect. The piece consists of a steel rod protruding from a casing that houses an electric motor. Vibrations from the motor cause the flexible rod to resonate, which creates the image of standing waves that propagate on the rod.[7]

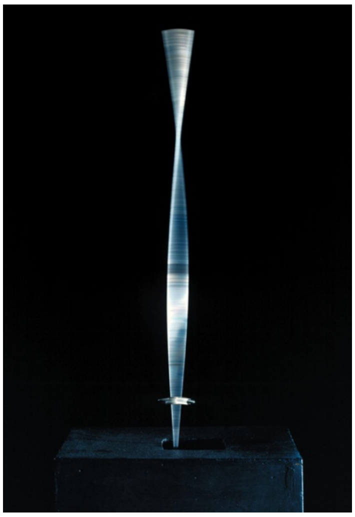

Fig. 2. *Kinetic Construction (Standing Wave)* (1919-1920) (replica 1985). Image from https://www.tate.org.uk/art/artworks/gabo-kinetic-construction-standing-wave-t00827

Given that most silicone-based soft robotic artworks are actuated with pneumatics, *inflatables* within 1960s and 1970s media art can also be considered art historical predecessors of contemporary soft robotic artworks.[8] One example of such an early work is found in Andy Warhol's *Silver Clouds* (1966) conceived through a collaboration with engineer and co-founder of *E.A.T.* (*Experiments in Art and Technology*) Billy Klüver.[9]

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[7] A similar technique was used by Tsai Wen-Ying in his kinetic and stroboscopic works from the 1960s that were featured in the seminal cybernetic art exhibition *Cybernetic Serendipity* in 1968.

[8] I use the term "media art" in a broad sense to refer to artworks that depend on a technological component to function.

[9] E.A.T. was a groundbreaking non-profit organization launched officially in 1967 for the purpose of developing collaborations between artists and engineers.

Fig. 3. Andy Warhol, *Silver Clouds* (1966). Images from: https://publicdelivery.org/andy-warhol-silver-clouds/#Warhols_balloon_rooms

The piece consists of a number of metallic foil pillows that hover in mid-air in the gallery. Each pillow is filled with a precisely calibrated mixture of atmospheric air and helium that prevents the pillows from falling to the floor or from rising to the ceiling. This happens as the mixture gives the pillow the same overall density as atmospheric air (DiClemente 2014). Through its interest in leveraging the physical properties of the materials of the composite system of gas and balloon to attain a specific function (floating), *Silver Clouds* touches upon a central ambition of contemporary soft robotics research, albeit working with static forces rather than dynamic response.

Another artist from the period working with inflatables was Jeffrey Shaw, who during the late 1960s and the 1970s produced a number of works such as *MovieMovie* (1967), *Octopus* (1968), *Pneutube* (1968), *Supertube* (1969), *Airground Mattress* (1970), and *Waterquake* (1970) alone and as a member of the *Eventstructure Research Group*.

Fig. 4. Jeffrey Shaw, Theo Botschuijver, and Sean Wellesley-Miller. Left: *Pneutube* (1968). Middle: *Supertube* (1968). Right: *Airground Mattress* (1970).

These inflatables were often constructed from either thin polyethylene tubes or PVC compartments and designed to an architectural scale. Moreover, often intended to be ephemeral, they were staged as choreographic elements in performative events, and were hence dubbed *eventstructures*. In relation to soft robotic artworks, it is worth noting, that the movement by means of gradual inflation and their metamorphosis were often conceived as integral parts of the performative events for which they were designed. Moreover, the events often staged the inflatables to engage with the specific social settings in which they took place, and, like other works at the time, made use of audience participation and intermedia aesthetics (film and light shows were projected onto some of the structures or shown inside them, and smoke was used for inflation). Hence, the works resulting from the practice have been categorized variously as early interactive art, performances, environments, expanded cinema, and architecture. Within experimental architecture of the period inflatables were also in vogue and used for structures and furniture by groups such as Haus-Rucker-Co, Ant-Farm, and many others, who associated the affordable and readily available technology with progressive politics.

Within the media art tradition of robotic art proper, which is also rooted in the late 1960s (Kac 1997; Penny 2013), there are also a number of examples of prior works that probe an aesthetic that bears similarities to soft robotics. Moving from the static force inflatables of Warhol and Shaw's kinetic works, a next step might be the dynamic robotic inflatables of Chico MacMurtrie, founder of *Amorphic Robot Works* (*ARW*). ARW's oeuvre spans both robotic sculptures and large-scale public robotic installations. The works were initially constructed from refurbished metallic parts but have, within the past fifteen years, branched out to also include inflatables constructed from high-tensile fabrics with embedded sensors (Amorphic Robot Works n.d.).

In MacMurtrie's take on his practice, his inflatable robots "offer an alternative vision of robotic sentience — one in which the machine appears vulnerable and ephemeral" (Amorphic Robot Works n.d.). As he puts it, "The soft machines strive to achieve simple gestures or actions, as if searching for basic dignity or a sign of their existence." (Amorphic Robot Works n.d.). Some of ARW's works also extend these interests into more explicitly political gestures, notably the still ongoing series of *Border Crossers*, which when inflated, reach from one side of a wall to the other.

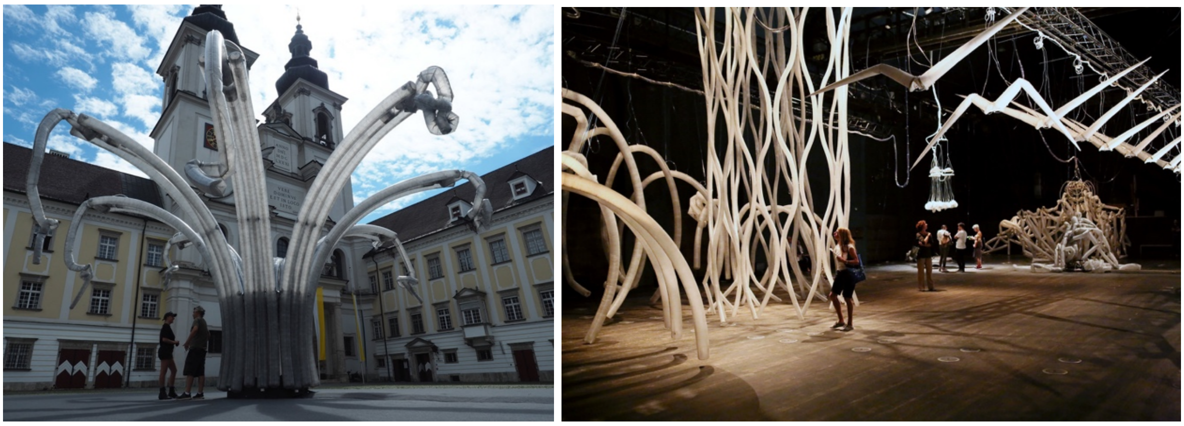

Fig. 5. Left: Chico MacMurtrie/ARW, *Pneuma Fountain* (2017). Right: Chico MacMurtrie/ARW, *Pneuma World* exhibition (2016). Images from: http://amorphicrobotworks.org/pneuma-fountain/ and http://amorphicrobotworks.org/pneuma-world/

Theo Jansen's series of *Strandbeests*, initiated around 1990, is also related to soft robotics. The mechanical creatures are constructed from standard plastic electricity tubes that endow the morphologies with an inherent flexibility and elasticity by which they become able to convert wind energy into movement. Likewise, Louis-Philippe Demers' *The Blind Robot* (2012) uses compliant articulated finger joints to facilitate the robot's gentle touching of audience members' faces and upper bodies.

In addition to the proto-soft robotic artworks described above, sculptures by a number of contemporary fine artists also link to soft robot aesthetics. For instance, Hannah Levy's casts of food stuffs, objects, and plant parts, often in the colors of skin or vegetation, which use the same soft and highly elastic silicone that is most often used for soft robotics. Patricia Piccinini's hyper-realist silicone sculptures also imagine other possible types of living beings by combining and reassembling organic and technological parts into novel configurations. Pakui Hardware (Neringa Cerniauskaite and Ugnius Gelguda) likewise create installations inhabited by techno-organic sculptural objects that incorporate silicone parts alongside materials such as fur and glass and colored liquids.[10]

3.2.2 Review criteria and structure

During the years spent working on this thesis, the number of artworks utilizing soft robotics technology has grown. As I mention in Paper 1, some works have been the outcome of collaborations between soft roboticists and artists, whereas others have been undertaken solely by

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[10] See http://www.hannahslevy.com/ , https://www.patriciapiccinini.net/ , and http://www.pakuihardware.org

artists. The latter has been made possible by the increased availability of 3D printing, and relatively cheap rubber materials, combined with the dissemination of basic soft robotics fabrication techniques on websites such as *Soft Robotics Toolkit*, *Instructables*, *Make magazine*, and *Adafruit*.

In the included papers, I discuss contemporary soft robotic artworks by Jonathan Pêpe, Ece Polen Budak, Paula Gaetano-Adi, Ingrid Bachmann, and Stine Deja and Marie Munk. Hence, in this section I will present some remaining seminal soft robotic artworks that are not addressed in the papers as well as projects from within design and architecture that engage with the aesthetic aspects of soft robotics technology. In the final subsection, I will address some shared characteristics and dominant interests of these works, and provide some reflections on the methods by which soft robotics are approached within architecture, design, and art. The review includes both artworks, design objects, and architectural prototypes that are presented as research contributions by its authors, but also works that are not articulated as such. This reflects the inclusive concept of research utilized in the thesis, wherein non-conceptual and non-discursive productions are seen as equal to academic texts as valid research outcomes (presented in Chapter 4). Even if soft robotics remains a niche subject and technology within fields of aesthetic practice, the review does not seek to include all existing projects. Projects have been included or excluded based on a judgement of whether they add significantly to advancing previous aesthetic engagements with soft robotics. Moreover, only projects that use rubber materials and feature actuation have been included – i.e. non-actuated rubber sculptures, actuated works with other synthetic soft materials (plastics, glass fiber, fabric etc.), soft organic materials (dead animals, fur, meat, tissue cultures etc.), or inflatables (foils, balloons etc.) are not addressed in this part of the review. Neither is the wider historical and contemporary tradition of robotic art in general.[11]

As will become evident, many of the included projects are cross-disciplinary in character, in the sense that they encroach on the territory and subject matter of other fields (e.g. architects working with wearable technology). For this reason, I have chosen not to organize the review based on the three fields from which the projects are drawn. Instead, the projects are presented under three headings based on the kind of soft robot they present:

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[11] Robotic art is a growing field about which there already exists plenty of literature (Herath, Kroos, and Stelarc 2016; Kac 1997; S. Wilson 2003; Whitelaw 2006; Penny 2013; Shanken 2014; Demers 2014). I reference some of this literature in the thesis papers. As the overarching problem of the thesis is formulated explicitly with a focus on softness, a thorough engagement with historical artworks based on traditional robotics technology and the writings about them was deemed to lie beyond the thesis' scope. I leave it for further work to reflect more in-depth on soft robotic art as an extension of this tradition.

1. Architectural models and building elements
2. Wearables/prostheses
3. Autonomous robots

The three categories were constructed from surveying the existing works. They are useful as organizing categories as they imply different networks of relations and ways in which a soft robot might act. Moreover, the categories imply different scales on which the robot will function – e.g. the scale of the human body, the interior of a building, the outdoors, or the city. Hence, presenting the works under these headings facilitates uncovering commonalities between them to a higher degree than would be achieved by categorization based on disciplinary fields.

3.2.3 Architectural models and building elements

Of art, design, and architecture, the latter was the first to take an interest in contemporary soft robotics technology. Within architectural history, the "soft" in soft robotics semantically invokes the vision of "Soft Architecture Machines" propelled by Nicolas Negroponte in his book with this title from 1975 (Negroponte 1976). Yet Negroponte's vision of softness was not related to physical softness, instead the term "soft" was intended to promote an understanding of architecture as a set of spatial technologies that are responsive to human activities. Within architecture, soft robotics can thus instead be seen to more directly extend the tradition of architectural experiments with biomorphic shapes from the 1960s and 1970s that included using the pneumatic systems and structures and different kinds of large-scale inflatables (Rossi, Nagy, and Schlueter 2014). Their use also connects to a more general interest in biomimetics within architectural design historically (Gruber 2011). The German architect Frei Otto (1925-2015) is an apt example of this interest. Widely known for his light-weight structures, Otto also developed the concept of the *pneu*, a system composed of a non-extensible membrane that encapsulates a medium (such as atmospheric air), as a central principle of light-weight constructions (Velikov et al. 2014). Pneus are still used in experimental architecture projects along with tendon-driven compliant thin plastics, fabrics, and braided filament structures, they are a material for actuated soft adaptive architectural structures (Velikov et al. 2014; Beesley 2009; Ramsgaard Thomsen 2011; Vestartas et al. 2018).

As early as in 2010, silicone-based soft robotics technology was already being used within architectural research for similar purposes in the project *ShapeShift* (2010). *ShapeShift*, its authors state, aimed to explore electro-active polymers embedded in a silicone-substrate at an architectural scale and their aesthetic qualities (Kretzer and Rossi 2012). For this purpose, a series of coupled identical geometric elements made out of an EAP composite was used to generate dynamic forms. The work initiated in *ShapeShift* subsequently inspired a workshop on "Soft Robotics for Architects" conducted at the Department of Architecture at ETH Zürich, where participants collaborated to produce a prototype for a pneumatically actuated building façade (Rossi, Nagy, and Schlueter 2014). A modular design based on simple geometric shapes (triangular and hexagonal forms) was also used for this project – pneu-nets actuators were cast into flat modules that were assembled into a plane. Upon actuation, they could facilitate the opening of different areas of the flat structure.[12]

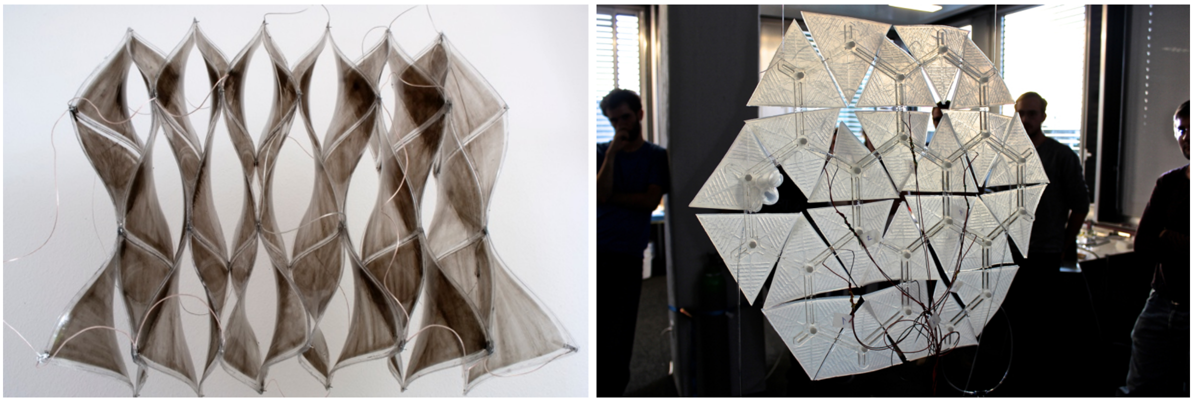

Fig. 6. Left: *ShapeShift*. Right: The façade prototype from the "Soft Robotics for Architects" workshop (Rossi, Nagy, and Schlueter 2014). Images from: http://materiability.com/portfolio/shapeshift/#&gid=2&pid=1 and https://srfa2013.wordpress.com/2013/10/28/levitation/

The central idea of *ShapeShift* and the façade project of using a number of modular soft robotic components together to assemble larger structures or systems has since become a recurrent feature of architectural soft robotics projects (Decker 2015; Fougere, Goold, and Velikov 2015; Kim et al. 2015). The idea of soft robotic parts functioning to open up the building to the outside has equally been reiterated in different variations. Within the project *Pneuma-Technics* (Fougere, Goold, and Velikov 2015), the ability of a building to dynamically control the light and air intake is thus articulated via a metaphorical elision of buildings and biological organisms – as the authors put it, they aim to develop "a breathing architecture that is sensitive to its changing environment" (Fougere, Goold, and Velikov 2015, 274). In other projects, smaller soft robotic components are instead proposed to augment buildings with novel practical solutions: pneumatically actuated

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[12] Similar dynamic facades already exist in buildings. A famous example is Jean Nouvel's design for the Institut du Monde Arabe (1987), where the apertures of modules can be changed to control the intake of sun.

silicone tiles to change the acoustic properties of a room (Decker 2015) and a multifunctional dielectric elastomer silicone module that could be used for display purposes, audio playback, or as a touch sensor (Decker 2017).

Despite the fact that silicone-based soft robotics designs do not easily translate to an architectural scale, it has also been suggested that soft robotic structures may find immediate application as walls, ceilings, and floors, and it has been proposed that they could constitute autonomous living units and larger environments (Kim et al. 2015).[13]

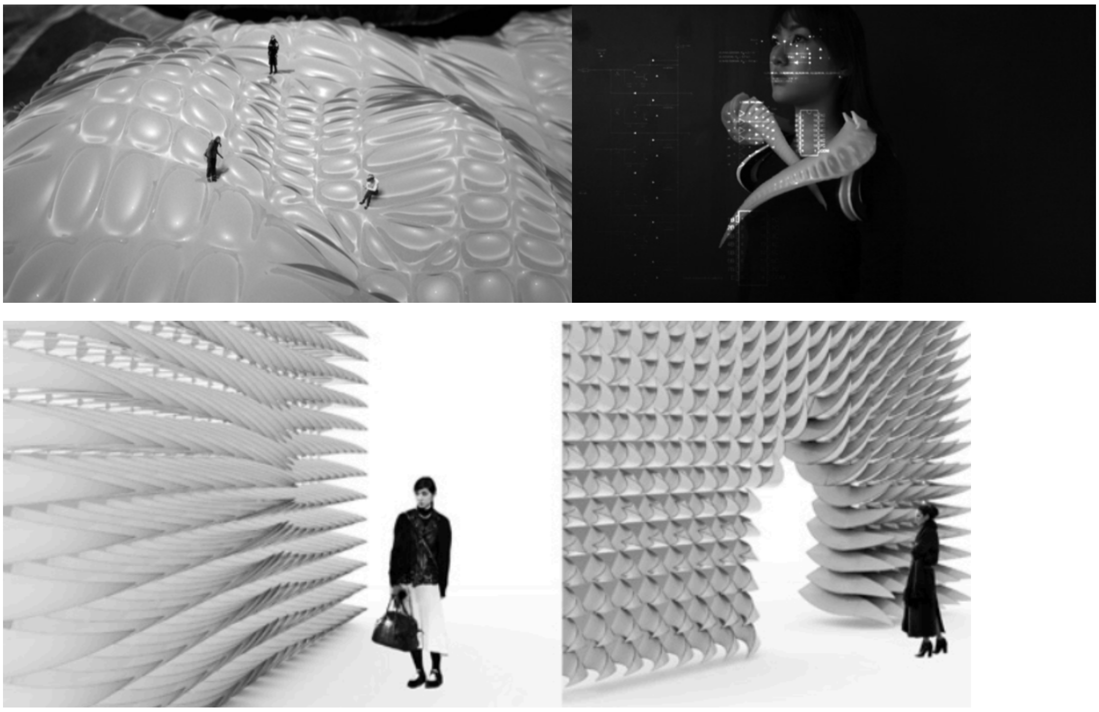

Fig. 7. Illustrations of some of the soft systems proposed by Kim and colleagues (2015). Top left: Soft environment. Top right: Soft wearable. Bottom: Adaptive soft wall.

The issue of how to defeat gravity when using soft robotics for architectural purposes has been creatively circumvented by MIT Media Lab architecture researcher Carson Smuts and colleagues, who have suggested using soft robotics in a context that calls for an altogether different kind of architecture, namely outer space. As the researchers note, this environment (much like the underwater environment) is ideally suited for soft structures, as:

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[13] As Ruairi Glynn, director of the Interactive Architecture Lab at the Bartlett School of Architecture (UCL), pointed out to me, elastic silicone is not feasible to use for actual buildings, both because it is too heavy to sustain its own weight and because it is too expensive (Ruairi Glynn in conversation November 2016). Within biology this characteristic of soft matter is also known to set an upper limit on the size of completely soft-bodied organisms that can live on land.

> Structurally, zero gravity means that we do not have to contend with architecture's greatest arch-nemesis, gravity. This opens up a new world of possibilities where we can deploy structures that no longer have to counteract/resist gravitational force. (Smuts 2018)

In space, the function of an architectural surface is also not fixed but can change dynamically. As Smuts and colleagues note, “in zero gravity there is no such thing as a floor. […] this surface now lies somewhere in between—a surface in flux with temporal possibilities”. The prototype they constructed in order to broach this issue (or opportunity) is called *SpatialFlux*. It was conceived as “A seamless pneumatic surface that morphs to embrace the human body in zero gravity” (Smuts 2018) and has been tested on an hour-long zero-gravity flight (yet is still pending academic publication). Although a highly evocative and quite spectacular project, the solution it proposes is functionally perhaps not that well considered. The pneu-nets technology and the silicone used delivers very little force and as no stiffening is implemented, the robot’s embrace is unable to really hold a person very firmly in place.

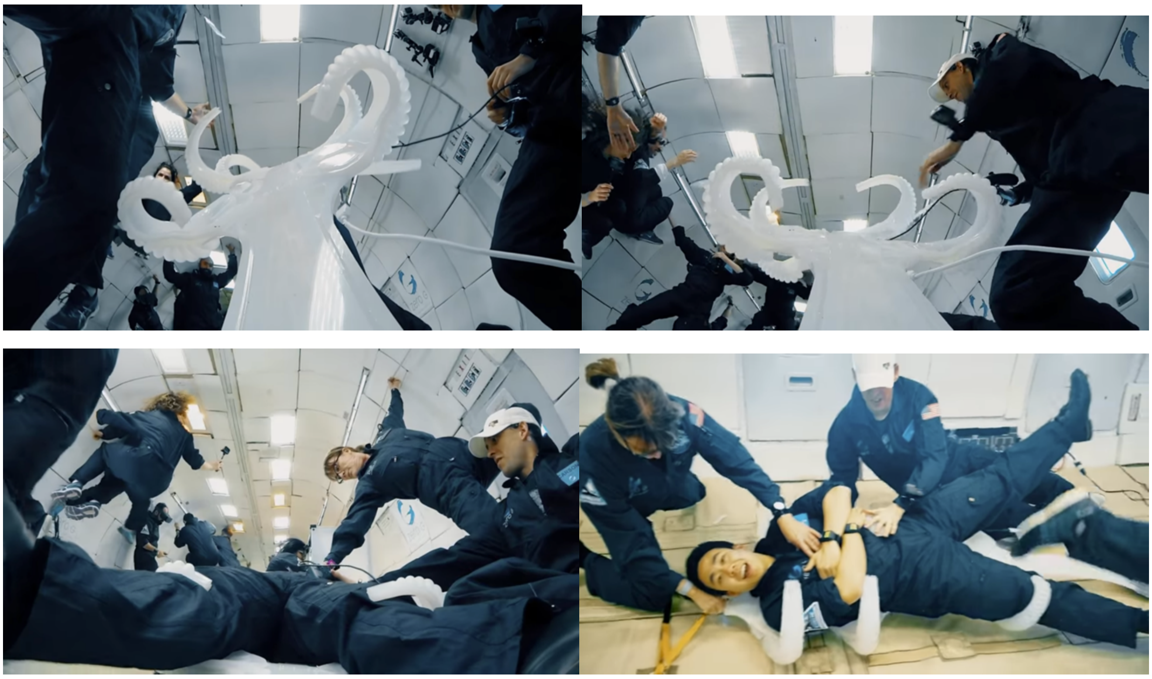

Fig. 8. *SpatialFlux*. Still images from video at: https://www.media.mit.edu/projects/spatial-flux/overview/

Soft robotic actuators have also been used for building models of a more speculative character, where practical realization seems a less relevant concern. *Furl* (2014) by Francois Mangion and Bijing (Becky) Zhang is a model of a kinetic pavilion that responds to readings of a user's brainwaves by means of *electroencephalography* (*EEG*). It features a series of individually actuated pneu-nets that are installed as a dynamic roof-like structure.

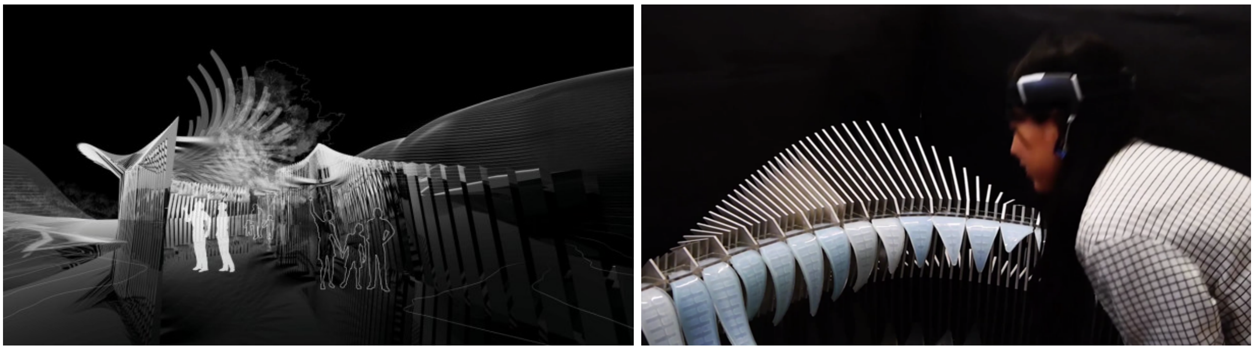

Fig. 9. Francois Mangion and Bijing (Becky) Zhang, *Furl* (2014). Left: Concept drawing. Right: The soft robotic model of the pavilion. Still images from video.

Mangion and Zhang describe how the implementation of EEG is intended to suggest how the environment might begin to respond to human thoughts (thus extending Negroponte's vision), and how *Furl* proposes "a new platform for a kinetic responsive architecture which can let space interact with users [sic] needs and adapt itself to environmental conditions" (Mangion and Zhang 2014). *Furl* is one of a series of student projects from the Interactive Architecture Lab at the Bartlett School of Architecture (UCL) that has pioneered speculative and aesthetic work with soft robotics.

To date, the most sustained engagement with the aesthetic potential of silicone-based soft robotics and its possible implementation in the built environment is found in Michael Wihart's PhD dissertation "The Architecture of Soft Machines" (2015), submitted to the Bartlett School of Architecture. In the thesis, Wihart develops the concept of "soft architectural machines" via readings of William S. Burroughs' *The Soft Machine* (1961) and George Teyssot's essay 'Hybrid Architecture: An Environment for the Prosthetic Body' (2005) combined with reflections on architectural installations by Daniel Liebeskind and Philip Beesley and his own practice-based work. Within the latter, silicone-based soft robotics figures as one of the physical mediums used for a series of prototypes dubbed "pneumorphs". Surveying work on inflatable architecture from the 1960s and 1970s, Wihart also points out how prototypes by architects such as Frei, but also Simon Conolly and the duo Mark Fisher and Sean R. Wellesley-Miller, anticipate contemporary soft robotic actuators, yet they were executed in non-expandable thin materials rather than elastomers and constructed on an architectural scale (Wihart 2015, 325–29).

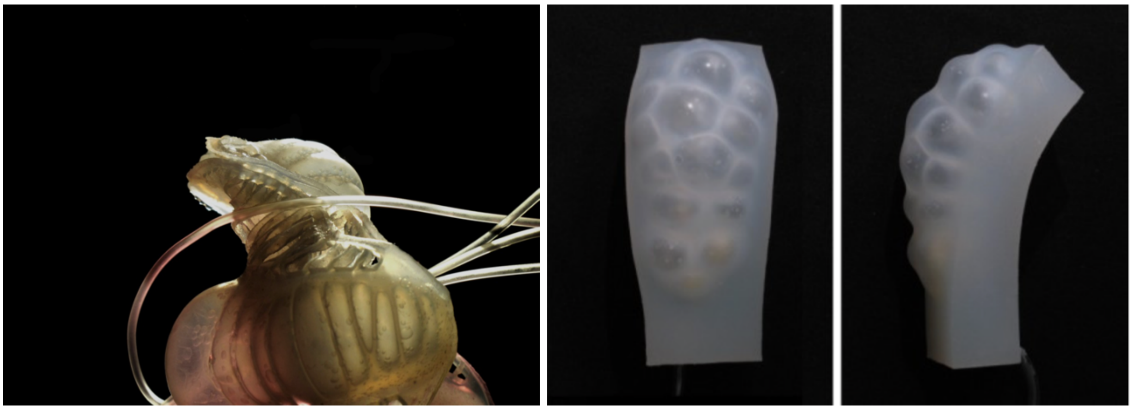

Fig. 10. Two of Michael Wihart's "pneumorph" prototypes. Left: *Nemone Stuelp!* (2013). Center and right: *Spawn pneumorph Sp.A13* (undated). Images from Wihart (2015).

Wihart's thesis proposes that the concept of the soft machine "may engender new forms of subjectivity, experience and enquiry and become an integral participant in architectural design spaces encouraging inclusive and co-constituting modalities of thought." (Wihart 2015, 385). He further points out that integrating softness via the machine in architecture leads to a questioning of "some of architecture's most fundamental paradigms of permanence and immutability." (Wihart 2015, 387). This brings about the need for what Wihart refers to as a 'soft tectonics', i.e. a novel conception of architecture become soft and pliable (Wihart 2015, 344). Drawing on his prototyping practice, Wihart contributes to the development of the latter by proposing a set of "morphodynamic primitives" that can be accomplished with pneumatically actuated silicone structures – "epithelial envelopes", "stuelps", "edges", "apertures", and "folds" (Wihart 2015, 344). Of these, "stuelps" is especially noteworthy, as it is both a novel technical and aesthetic technique of soft robotics. By "stuelping" Wihart refers to a soft structure that can turn its inside out when actuated (see Fig. 11) – something that if implemented in an actual building, might question the traditional static separation between interior space and the outdoors.

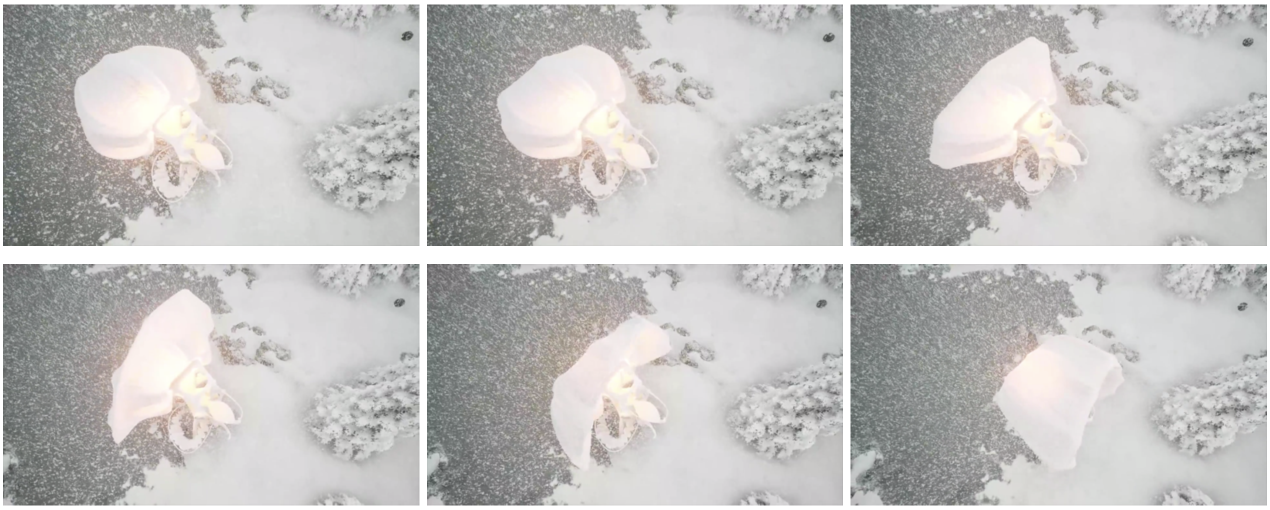

Fig. 11. Images from Wihart's VR simulation *Oasis 8* (2013 – ongoing) that features a "stuelping" building in a snow storm seen from above. Still images from video at: http://www.wihart.net/portfolio/oasis-8-vr/

In its transdisciplinary approach, which integrates cultural theory, speculative philosophy, architectural history, physical prototyping, material explorations, studio practice, and a number of other elements, Wihart's work is perhaps the previous work that in spirit comes closest to the research of this thesis. Wihart's unique work broke new ground by conjoining soft robotics with architecture and considering the "space-making" possibilities of soft robotic components as models for architectural constructions (Wihart 2015, 330). But also by reflecting on and physically querying the specific forms and transformational topologies afforded by soft silicone and pneumatic inflation. The latter is richly documented in the thesis, which features carefully staged and cropped Baroque-like close-up photographs of Wihart's prototypes against a black background.

3.2.4 Wearables and prostheses

Some of the architectural projects discussed above, including *Furl* and *SpatialFlux*, can be seen to imagine architectural soft robotic parts that are directly interfaced with the human body and mind. Within a number of projects, this impulse is pushed further and soft robotics technology is used to construct wearable devices and prostheses.[14]

The project *Sarotis* (2016) by Maria Paneta and Ava Aghakouchak departs from an interrogation of alternative ways of seeing and interacting with the world, afforded by 3D camera technology. Paneta and Aghakouchak constructed a soft robotic wearable neck piece intended to

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[14] I use the word "prosthesis" here in its meaning of an addition, application, or attachment. Hence, the category also includes e.g. orthoses.

amplify people’s awareness of space by translating spatial information, captured by the camera, into haptic stimulation (Paneta and Aghakouchak 2016). But they also suggest it might function to augment virtual reality (VR) headsets with haptic feedback. They illustrated the latter in a speculative short film based in the notion that soft prostheses will usher in a cyborgian dissolution of the distinction between human and technology (Paneta and Aghakouchak 2016).

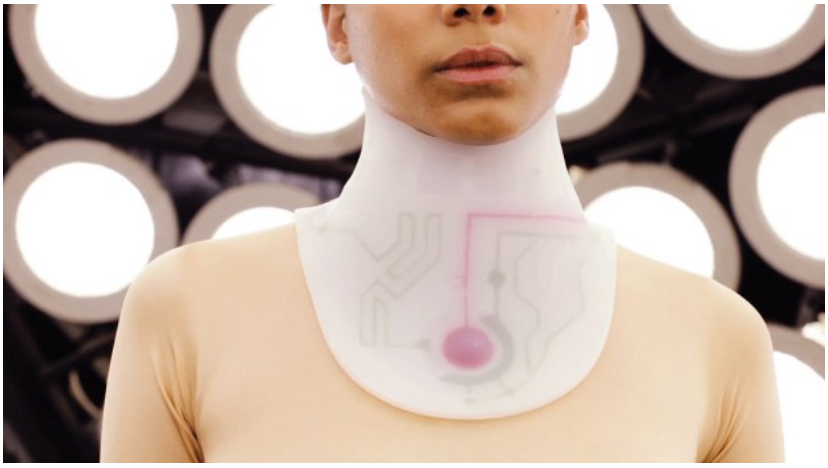

Fig. 12. Maria Paneta and Ava Aghakouchak, *Sarotis* (2016). Still from short film at: https://vimeo.com/184714613

The film features a version of the prototype cast in translucent silicone, which has embedded microfluidic channels through which liquids of different colors are pumped as a kind of machinic signaling (Paneta and Aghakouchak 2016).[15]

Another work, also from the Interactive Architecture Lab, and based on a similar technology, is the *Aposema* (2017) mask by Adi Meyer, Silvia Rueda, and Sirou Peng. The speculative prototype was conceptualized as a responsive facial prosthesis that, coupled with an augmented reality (AR) display, may serve as a communicative aid in a near future where the ability to empathize with fellow humans is imagined to have been impaired from excessive social media use (Meyer, Rueda, and Peng 2017).

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[15] This use of networks of microfluidic channels and colored fluids to dynamically change the appearance of the surface of a soft robotic structure was first developed at the Whitesides lab at Harvard (Morin et al. 2012). The research was funded by DARPA (the Defense Advanced Research Projects Agency) and a proposed application for the technique was for camouflage.

Fig. 13. Adi Meyer, Silvia Rueda, and Sirou Peng, *Aposema* (2017).

Soft robotic wearables have also been developed within various sub-fields of design research. Caroline Yan Zheng was originally trained in fashion design, but is currently pursuing research on the potential of soft robotics technology to "foster emotionally rich sensory experience" (Zheng 2014). She has utilized soft robotic actuators in her studio practice in interactive wearables and jewelry, and also conducted public workshops on "sentimental soft robotics" (Zheng 2017). Drawing on experience design and co-design methods, Yan Cheng has also explored the possibility of using simple soft robotic actuators to generate affective and pleasant touch (Zheng 2018).

Fig. 14. Caroline Yan Zheng, *Wear the heart on the sleeves* (2017). Prototype of interactive soft robotic necklace that responds to a heartbeat sensor.

Media artist Paul Carlo Esposito's piece *Life Alert* (2018) presents another example of soft robotics used for a decidedly non-utilitarian augmentation of the human body. The work sees the artist enveloped by a suspended tubular silicone structure that incorporates pneumatically actuated soft tentacles similar in shape to a bitter melon or cucumber. For the performance, a co-performer sprays liquid onto the robotic costume, which audience members are also allowed to touch.

Fig. 15. Paul Carlo Esposito, *Life Alert* (2018). Images from: http://paulespo.com/lifealert

By comparison, Avner Peled focuses on including soft robotics as a prosthetic medium of telepresence in his political art practice. In an unpublished paper, the potential of telepresence via a soft robotic avatar is aligned with the observation that “Research shows that assuming a different embodiment may decrease racial bias, both among the controller and the interlocutor” (Peled, n.d.). In collaboration with researchers from the Suzumori lab, Peled has created a soft telepresence robot that resembles an Axolotl lizard. The robot features an embedded camera and pneumatic actuation of the neck, arms, and the face, with the latter housing five separate actuators.

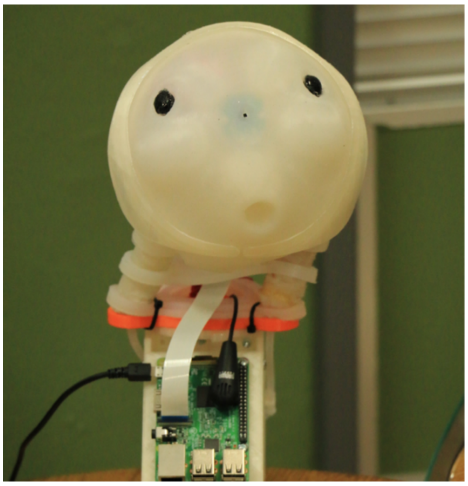

Fig. 16. A prototype for the soft telepresence avatar robot’s neck and head by Avner Peled.

3.2.5 Autonomous robots

In the preceding two subsections, I have presented projects wherein the aesthetic of soft robotics technology is addressed by imagining soft robotic parts as either elements of the built environment or devices that attach to the human body. In this section, I will consider work in which soft robots are not inscribed within these two relational complexes but are instead imagined to lead a more independent existence on their own. I refer to these robots as "autonomous robots", even if the robots in several of the projects described above in technical terms might be considered equally autonomous. The prototypes and robots I have constructed myself all fall within this category.

With a background in industrial design, but currently working across the fields of interaction design and media art, Harvey Bewley has constructed a number of soft artefacts or "performing objects" as he refers to them. Contextualized within interaction design research discourse as attempts to broaden the design space for physically embodied computational artefacts and as a means to achieve "a more connected and bodily engagement with computational devices" (Bewley and Vallgårda 2017, 234), Bewley's early prototypes were made from different soft materials such as plastic foil, Lycra, and latex rubber that were actuated with pull-strings or pneumatics. In a position paper, co-authored with interaction designer Anna Vallgårda, these objects are enlisted in a proposal "to shift focus to their [soft robots'] aesthetic and performative qualities" (Bewley and Vallgårda 2017, 234). Hence, interpretations are presented of the material and temporal forms that these objects manifest that attempt to take into consideration the cultural associations they evoke (Bewley and Vallgårda 2017, 234). Bewley's early latex prototypes were characterized by their skin-like appearance combined with contrastingly sturdy brass fittings, through which pressurized air is supplied. Moreover, some integrated LED lights and utilized an extra internal bladder to achieve a dynamic wrinkling of the surface.

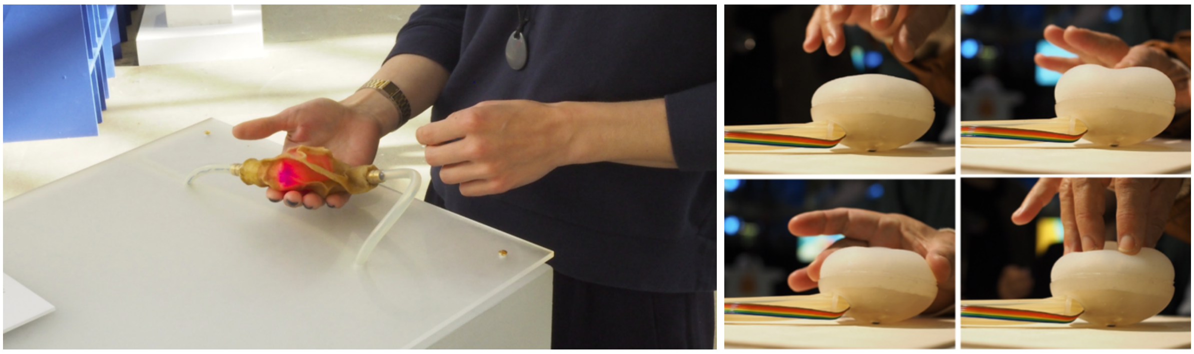

Fig. 17. Left: One of Harvey Bewley's wrinkling latex prototypes from the exhibition *Elastic Interactions of the Third Machine Age* (2015). Right: *Blo-nut* (2018). Images from: http://www.harveybewley.com/ and Bewley & Boer (2018).

Bewley recently developed the donut-shaped three-chambered pneumatically-actuated silicone prototype *Blo-nut* and a larger latex morphology dubbed *Lat-Sac*. Referring to communication scholar Eleanor Sandry's work on non-anthropomorphic and non-zoomorphic social robots, Bewley presents these prototypes as explorations of a novel type of social robot and an attempt at "embracing novel and provoking 'otherness'" (Bewley and Boer 2018, 1069). Together with colleagues from the IT University of Copenhagen, Bewley developed a Max/MSP-based graphical user interface that allows for easy prototyping of expressive inflation patterns on the donut-shaped morphology. With this system, interaction designer Laurens Boer and Bewley together conducted a study on its expressive and interactive potentials, drawing on established interaction design methods including expert trials, design fiction, and user studies (Boer and Bewley 2018). As this device and Bewley's other prototypes do not feature sensors the study was conducted by means of wizard-of-Oz puppeteering.

Boer and Bewley reach two interesting conclusions from their expert trials: firstly, even with the simple morphology of *Blo-nut* and their simple pneumatic actuation system, three invited movement experts "were able to mobilize their creativity in the shaping of the expressions". Secondly, that the "setup had a certain openness that invited a plurality of associations" (Boer and Bewley 2018, 671). Boer and Bewley drew attention to how the experts tended to conceive of the expressivity of *Blo-nut* as multi-sensory, in the sense that the movements, the haptic qualities and the sounds of the pneumatic system all contributed to the overall impression (Boer and Bewley 2018, 672). Although *Blo-nu*t and *Lat-sac* were presented as potential near-future artificial pets within the design fiction framing the user study, Boer and Bewley mention that *Blo-nut* was also described by some participants as a gadget, consumer product, hospital equipment, and a laboratory prototype, due to its hard shell, geometric appearance and associations with a respirator. Moreover, they find the "breathing" effectuated by the pneumatic actuation to be central to impressions of the two robots as being alive (Boer and Bewley 2018, 674).

Bewley's prototypes have pioneered explorations of the visual, kinetic, and haptic aesthetics of latex-based soft morphologies and novel expressive techniques such as the wrinkling described above, as well as initial research on soft robotic kinetic expressivity. His collaborations with interaction designers bear witness to the potential of integrating creative non-utilitarian approaches to soft robotics into established academic fields and research discourses.

Like Bewley's performing objects, industrial designer Nicole Hone's *Hydrophytes* (2018) also explore expressive soft robotic movement. Yet their aesthetic diverges drastically from

Bewley's wrinkling latex – the series consists of small intricate morphologies that are staged to look pretty with colored lighting. The morphologies were created by so-called 4D multi-material printing using manufacturer Stratasys' PolyJet technology and are presented as a series of artificial aquatic plants (Hone 2018). The diminutive creatures are each imagined to serve different roles within an aquatic ecosystem. They do not feature sensors nor actuation, but can be actuated by hand with a pump to facilitate movement of their "limbs".

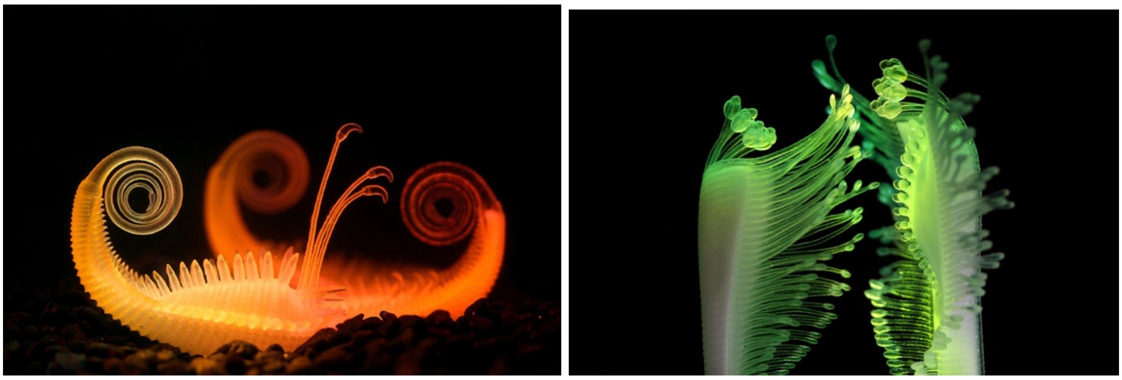

Fig. 18. Nicole Hone, *Hydrophytes* (2018). Images from: https://www.nicolehone.com/#/hydrophytes/

Unlike Bewley's and Hone's soft morphologies, *Cypher* (2018), a recent project from the architectural studio Ozel Office led by Güvenç Özel, presents a complete soft robotic system that also has sensing implemented. The piece is described by the office as an interactive *mixed reality* robotic sculpture. It consists of a black soft robotic entity constructed from silicone mounted atop an aluminum frame. Onto this structure a helmet with a VR headset is tethered. The infrared sensors on the surface of the morphology can initiate pneumatic actuation of the bulging compartments that surround them, and a lidar detects people in its vicinity. In the mise-en-scène displayed on the VR helmet, the user appears to have entered a scaled-up version of the inside of the soft robotic entity (see Fig. 19 bottom left image). By using hand gestures, the user can alter the shape of the VR structure, and these changes are simultaneously mapped onto the physical entity. A machine learning algorithm has been implemented to eventually allow the system to better predict and respond to user gestures (Ozel Office 2018). In the video presenting the work, it is staged in interactions with drag performance group *Barbie's Addiction*, who are clad in black latex suits echoing the dark and glossy surface of the sculpture.

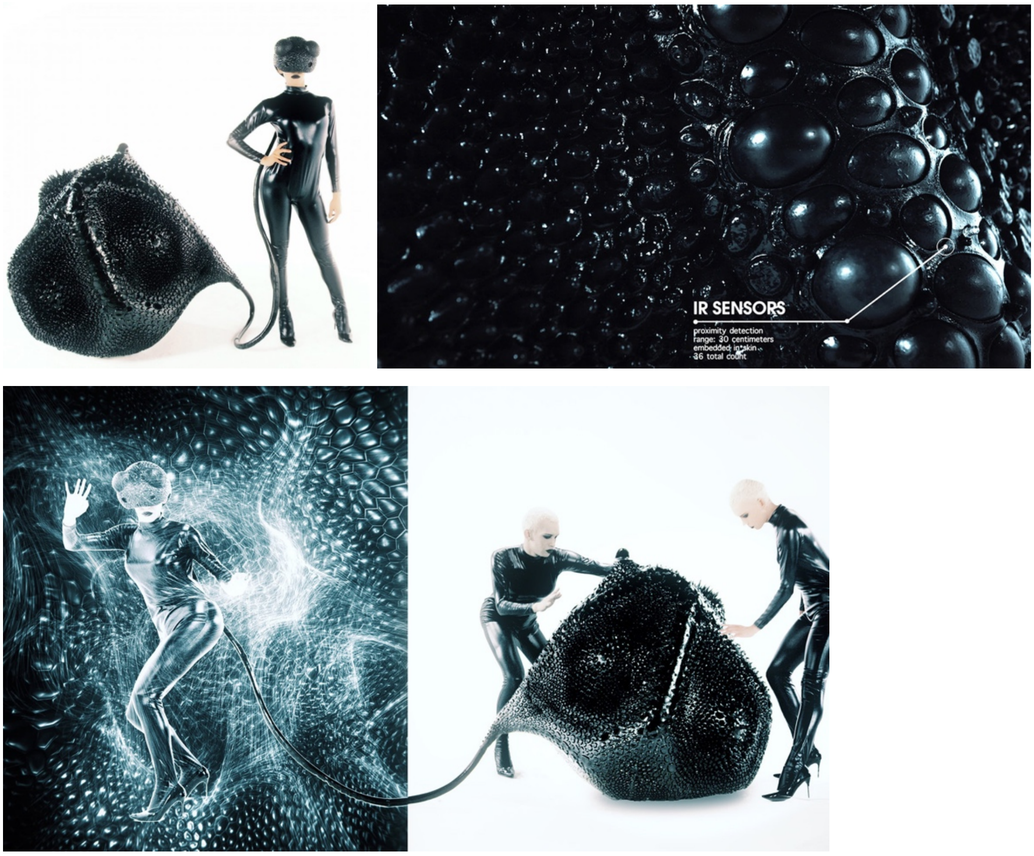

Fig. 19. Ozel Office, *Cypher* (2018). Images from: https://www.dezeen.com/2018/08/14/shape-shifting-cypher-sculpture-ozel-office-controlled-motion-sensors-virtual-reality/ and http://www.ozeloffice.com/index/#/cypher/

3.2.6 Summary: Soft robotics in art, design, and architecture

Most projects within architecture, design, and art that incorporate soft robotics, do so by appropriating already existing technical solutions and principles, notably the pneu-nets type actuator. Yet some use even simpler designs where compartments devoid of inner subdivisions and bifurcations are inflated to expand and create bulbous movement. In a few works, new types of structural designs are instead presented (e.g. Wihart's pneumorphs and stuelps and Bewley's wrinkling structures). Whereas soft robotic actuators are mainly imagined to be used for robotic manipulation and robotic locomotion within the technical literature, these functionalities are all but lacking within aesthetic practice projects. This is one way in which it becomes evident that architecture, design, and art reorient soft robotics towards other ends. A number of additional characteristic features stand out that equally illustrate how soft robotics technology and its aims are modified in aesthetic practices.

Many of the projects work with alternative appearances for soft robots. Within technical research, soft robots tend to be composed of simple geometrical shapes, and their appearance has only been an explicit concern in relation to practical tasks where it is pivotal – in soft robotic camouflage technology (Morin et al. 2012; Pikul et al. 2017) and stretchable electroluminescent pixel displays (Larson et al. 2016). Some architectural projects extend the formal vocabulary of technical soft robotics research in their modular approaches, wherein arrays of geometrically shaped components are integrated into serial structures. But others, such as the *Aposema* mask, Wihart's pneumorphs, and *Cypher*, instead possess multiple irregularly sized compartments positioned in organically organized patterns reminiscent of biological structures. Wihart's pneumorph prototypes also explore the shapes and topological transformations elastic silicone affords when inflated. In addition, the elaborate and detailed structures present in e.g. the works of Hone are decorative and fulfill no practical function. Some projects (e.g. Esposito's prosthesis and Bewley's latex morphologies) also evoke the messy, dirty, worn, or unappealing appearances that elastomers can attain, which tend to be suppressed within the visuality of technical research. And some incorporate light sources to diffusely illuminate and stage the semi-translucent silicone material in specific moods.

In addition, the projects explore ways that soft robots might move, not to fulfil a practical mechanical function, but in order to become expressive, appear animated, or communicate an affective state or an intent. In Paper 1 I note how "breathing" is used in many projects for these purposes. In most projects, movement is programmed rather crudely by simple switching on a pump at a constant rate and subsequently releasing air with a valve. In Hone's work, more varied and organic movement can be seen, but it is executed by means of a single hand pump in the video documentation and not by means of robotics technology proper (such as pneumatics controlled by a microcontroller) (Hone 2018). Hone's work thus uses manual actuation and echoes the proposition I presented in Paper 3 of leveraging the interactions between soft materials and water to design biomorphic movement. By contrast, Bewley and Boer's work explores more elaborate programmed inflation patterns.

As I discuss in Paper 1, the experience of physically touching a soft material is thematized by several artworks featuring soft robots. This interest is also present in the wearable projects where soft robotic components attach themselves to the human body, here it is even explicitly extended into speculations on what form a merger between human bodies and soft robotics might take. Soft robotics technology becomes an affordance of augmented sensation and is interfaced with psychometric signals, such as the heart rate (Yan Cheng's *Wear the heart on the sleeves*) and brain waves (*Furl*), or it is integrated with immersive VR displays (*Sarotis*, *Cypher*).

An awareness of context is another pronounced element in aesthetic practice projects and their modes of presentation. The specific associations evoked by certain soft materials were remarked on by Vallgårda and Bewley, and the openness of simple soft robotics prototypes to elicit different types of associations was also noted by Boer and Bewley. In accordance with the latter, soft robotic parts are often recontextualized and staged by different means to support certain narratives. The meaning-making potentials of soft robotics are orchestrated in documentation photos and videos that feature heavy cropping, black and white backgrounds, spectacular settings (a zero-gravity environment, sci-fi-esque architecture, scenic nature), and juxtapositions with other objects. Several of the projects present soft robots as elements of imagined future scenarios, sometimes in the vein of *critical design*, providing commentary on contemporary technological culture (e.g. *Sarotis*, *Aposema*, *Blo-nut*). In relation to context awareness, it is also worth noting that Peled also does not simply intend to construct a general-purpose soft telepresence robot, but instead imagines it as an aid in overcoming social and political issues that form part of his own biography.

Finally, transformation, on both a physical as well as a semantic level, can be added to the already mentioned themes. That is, buildings are imagined to change shape, human bodies are augmented or rehabilitated, and the physical world morphs into virtual reality and vice versa in *Cypher*, a work that is additionally presented alongside drag performers with transformed gender identities. In the same manner, a notion that traverses several works is permeability, understood here as referring to bodies and structures that are penetrable and allow matter or material entities to pass through. Air or liquids visibly enter and flow through the soft robotic morphologies, but buildings are also imagined to open up towards their environments and to incorporate them (letting sun, air, or inhabitants in). The soft robotic wearables are equally imagined as integrated with the signals and material flows of the human body.

As regards methods, aesthetic practice involving soft robotics that is contextualized as research has tended to proceed by way of studio practice, collaborative workshops, interaction design experiments, and speculative design practice. Of the three fields of architecture, design, and art, the first has produced the most academic publications involving soft robotics, yet the majority of these are short conference papers. Currently, only very few more substantial and sustained research contributions exist that deal with and address the aesthetic aspects of soft robotics. Wihart’s thesis is the only large work, and here, soft robotics figures only as one of more technologies around which his concept of the soft machine is developed. Even if most of the works presented in this review have been produced within research institutions or under formal higher education programs, not all have reached academic publication. Moreover, those that have were not published in robotics research publications.[16] Instead they were published in an art-science journal and conference proceedings on architecture, interaction design, movement computing, and subfields within HCI (human-computer interaction). Furthermore, the projects have not been mentioned in robotics publications, nor have the academic papers been cited in such.[17] This publishing and citation pattern illustrates how the insights and approaches represented by the projects have so far led an existence remote from the discourses on soft robotics within robotics research.

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[16] The only exception to this is the short article on the "Soft Robotics for Architects" workshop that was published in the *Soft Robotics* journal (Rossi, Nagy, and Schlueter 2014). This short article is, however, written from a predominantly technical and practical perspective.7/9/19 8:32:00 PM

[17] This was verified by checking each of the publications quoted in section 3.2 in Google Scholar for listed citations and by searching for the project names in Google Scholar.

4 Theoretical and conceptual background

The concept of aesthetics used in this thesis is rooted in the historical tradition of philosophical aesthetics. However, within the thesis, aesthetics as a concept is updated and operationalized as an epistemological model by drawing on contemporary theoretical discourse on *artistic research* that emphasizes the epistemological knowledge producing aspect of art practices. It is further modified by notions hailing from *new materialism*, in order to temper its traditional psychological and anthropocentric bias.

I chose to frame the thesis work with this wide and composite notion of aesthetics rather than a single contemporary theory of aesthetics for two main reasons. Firstly, it would allow me to incorporate different theoretical sources eclectically within the different papers that best fit with their specific research questions and interests. Secondly, the decision reflects the centrality of practice within the project. From the outset, practice has been conceived as a main driver of the thesis' knowledge production, which is reflected in the fact that 5 of the 7 included papers address robots that I have designed and built myself. Hence, I was reluctant to delimit the contingent outcomes of practice by constraining or articulating them within a narrowly defined theoretical framework from the outset.

In the following, I will provide some background for the specific concept of aesthetics that is developed and articulated within the thesis papers and practice. I will introduce central ideas and assumptions of the three theoretical strands; philosophical aesthetics, artistic research, and new materialism, which contributed to the concept's construction. In the final section of the chapter, I will discuss how the theoretical positions of the three strands can be seen to modulate each other, and describe how their differences are negotiated within the thesis research.

The chapter was written after the completion of the thesis papers and the practice work. But in the research process, the three theoretical strands remained steady references for the thinking and doing developed and have contributed central ideas and assumptions underlying the methodologies and arguments presented in the thesis papers.

Drawing on my recollection of the research process and the synthesis of the three strands presented in this chapter, I will end the chapter by formulating a set of instructions which have served as orientation points for the research practice, i.e. as basic references and coordinates from which the thesis' perspective was constructed.

4.1 Philosophical aesthetics

The word “aesthetics”, derived from the Greek word class *aisthesis* which refers to sense-making or sense-perception, was coined by Alexander Gottlieb Baumgarten in a philosophical context in 1735. For Baumgarten, aesthetics initially referred to a systematic attempt at constructing a metaphysics and psychology of art (Fenner 2003). However, for Baumgarten, aesthetics is not merely linked to art, he also used the term more broadly to refer to “the science of sensuous cognition” (Guyer 2016). In Baumgarten’s theorizing, aesthetics was thus connected with epistemology (theories of knowledge), as aisthesis also was originally for the pre-Socratic Greeks, who regarded physical sensory perception as trusted knowledge (Kane 2007). Central to this was Baumgarten’s concept of *analogon rationis*, used to describe how the human mind possesses an ability analogous to reason that allows it to obtain a valid, yet purely sensory, knowledge about the world. As Baumgarten put it,

> I cognize the interconnection of some things distinctly, and of others indistinctly, consequently I have the faculty for both. Consequently, I have an understanding, for insight into the connections of things, that is, *reason* (*ratio*); and a faculty for indistinct insight into the connections of things (Baumgarten 2005, 146)

Baumgarten understood the latter of these faculties to consist of seven “lower faculties of cognition”, that together “comprise *that which is similar to reason* (*analogon rationis*), or the sum of all the cognitive faculties that represent the connections among things indistinctly” (Baumgarten 2005, 146). And according to Baumgarten, the kind of knowledge thus obtained through the senses was not inferior, but rather parallel to that acquired by reason.

Moreover, Baumgarten posited that the acquisition of sensuous knowledge could itself be a source of pleasure by way of sensible representations of perfection, which is how he described beauty (Guyer 2016). In Baumgarten’s magnum opus *Aesthetica* (1750), the term aesthetics thus acquired a number of synonyms in order to cover all the different areas encompassed by the science of sensuous cognition:

> Aesthetics (the theory of the liberal arts, the logic of the lower capacities of cognition, the art of thinking beautifully, the art of the *analogon rationis*) is the science of sensible cognition. (Baumgarten quoted in (Guyer 2016))

Alongside Baumgarten, Immanuel Kant is the philosopher who is most decidedly associated with philosophical aesthetics. In *Critique of Judgment* (1790) Kant, develops central notions that have been central points of address for aesthetic theory up until today. These include the concept of aesthetic judgements as rooted in *taste*, and not reason, and the associated idea of aesthetic *immediacy* (though that dates back to earlier rationalist aesthetics (Shelley 2017). But also the notion that the pleasure involved in judgements of taste is *disinterested*, i.e. not focused on personal desires nor purposeful practical aspects, such as what an object might do or help one accomplish. Like Baumgarten, Kant also claimed aesthetic experiences to have a non-conceptual content. The aesthetic idea, Kant thus described as a

> presentation of the imagination which prompts much thought, but to which no determinate thought whatsoever, i.e. no [determinate] *concept*, can be adequate, so that no language can express it completely and allow us to grasp it. (Kant 1987, 314)

Hence, within Kant's schema, aesthetic judgements are characterized by a "purposiveness without purpose", in that they take the form of a cognitive judgement, yet without subsuming the aesthetic object under a concept.

Baumgarten and Kant's accounts of aesthetics have been widely criticized, especially in the second half of the 20th century when it became obvious to a generation of younger artists and art historians that a modernist formalist account of art, sustained by Kantian aesthetics, was no longer tenable. A number of artistic practices had emerged within the neo-avantgardes that were motivated by decidedly different interests, and in retrospect, it also became clear that art historical modernism was untenable as the modernist medium specific teleology of art had disregarded historical avant-garde art traditions, which had unfolded in parallel with modernist painting and sculpture (Wood et al. 1993). The notion that art and aesthetic experiences can embody a non-conceptual knowledge or understanding, however, still figures centrally within contemporary discourses on artistic research.

Yet here, a different and more inclusive account of these types of knowledges is given that can also accommodate a view of knowledge production as historically and culturally embedded.

4.2 Artistic research

Henk Borgdorff, professor of Theory of Research in the Arts at Leiden University, has been a prominent voice in the theorization of artistic research as a specific form of knowledge production that has unfolded over the course of the past two decades. Borgdorff's formulation of artistic research has been useful for the thesis project as it provides overarching methodological guidelines on how to undertake practice-based research in the arts. It also contributes a perspective on what the components of this type of research are and what kind of knowledges and outcomes it can be expected to yield.[18]

Artistic research is broadly described by Borgdorff as "*research in and through art practice*" that "seeks to convey and communicate content that is enclosed in aesthetic experiences, enacted in creative practices and embodied in artistic products." (Borgdorff 2010, 44–45).[19] However, importantly, in Borgdorff's description, artistic research is seen to diverge from "art practice in itself" (Borgdorff 2010, 44–45). Albeit anchored in artistic practice, artistic research namely also encompasses

> the articulation of the unreflective, non-conceptual content enclosed in aesthetic experiences, enacted in creative practices and embodied in artistic products. (Borgdorff 2010, 47)

Its point of departure is thus an ambition to contribute towards thinking and understanding and not just to the development of an individual artistic practice (Borgdorff 2010, 44–45). It is linked to and

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[18] Several other definitions of artistic research and theorizations of its potentials exist (Hannula, Suoranta, and Vadén 2014; Mersch 2015; Biggs and Karlsson 2010; Cazeaux 2017). I have chosen to draw on Borgdorff's description as it provides an account of artistic research as a distinct methodology, yet sees it as compatible with methods from other disciplines (Borgdorff 2010, 46). This is not the case in e.g. Dieter Mersch's theorization, where art and aesthetic research is posited to be irreconcilable with science and philosophy (Mersch 2015, 10).

[19] As is evident from this formulation, Borgdorff's theorization of artistic research aims to be inclusive of most existing kinds of artistic practice and synthesizes a wide range of different theoretical traditions, from idealist aesthetics, phenomenology, critical theory, and philosophy of science to cognitive science and STS (Borgdorff 2013, 2010). Borgdorff is formally trained in music, sociology, and philosophy.

engages with one or more research communities, areas, or issues and hence by definition entails more than just the production of artworks (Borgdorff 2010, 54)

Given it proceeds by way of practice, artistic research demands other kinds of dissemination than traditional research, which can be adequately communicated in the form of a written text. As Borgdorff puts it, alluding to the non-conceptual character of aesthetic experience:

> the experiences and insights that artistic research delivers are embodied in the resulting art practices and products. In part, these material outcomes are non-conceptual and non-discursive, and their persuasive quality lies in the performative power through which they broaden our aesthetic experience, invite us to fundamentally unfinished thinking, and prompt us towards a critical perspective on what there is. (Borgdorff 2010, 47)

Alongside academia, contemporary art practices thus constitute the context within which the outcomes of artistic research are to be evaluated (Borgdorff 2010, 46).

Borgdorff differentiates artistic research from other types of research that take art as their subject by drawing on Christopher Frayling's influential article "Research in Art and Design" (1993). From Frayling, he adopts the tripartite division of "research *on* the arts, research *for* the arts and research *in* the arts" (Borgdorff 2010, 46). "Research *on* the arts" is characterized by an "interpretative perspective" and aligns with humanities and social science research on art practices. "Research *for* the arts", instead refers to an instrumental perspective characteristic of applied technical research that aims at developing tools and material knowledge of use for artistic practices. "Research *in* the arts", artistic research proper, instead takes artistic practice as "its methodological vehicle" and "unfolds in and through the acts of creating and performing."(Borgdorff 2010, 46).

Albeit explicitly seeking to align artistic research with existing definitions of academic research found in the official charters of research funding bodies, Borgdorff equally stresses that methodologically artistic research differs from more traditional types of research. Hence, the traditional methodological and organizational requirements stipulated for something to count as research are not all directly applicable to artistic research but must be adjusted to fit with the specificity of art methodologies. As Borgdorff notes, the requirement that a research study sets out with well-defined questions, topics, and problems, for instance, appears to be at odds with the experimental character of art (Borgdorff 2010, 56). Artistic work is often undertaken on the basis of intuition, guesses, and hunches and is characterized by being open to serendipitous discoveries made along the way. Moreover, within artistic practices, the exploration and navigating of unknown territories is facilitated by tacit understandings, accumulated experience, and artistic sensitivities rather than by pursuing answers to explicitly stated research questions via formalized methods. Hence, artistic research is discovery-led and not hypothesis-led (Borgdorff 2010, 56).

Regarding the type of knowledge that artistic research can produce, it does not take the traditional epistemological form of "propositional knowledge", as already mentioned, nor is it adequately subsumed under alternative views of knowledge as "skill" or "acquaintance" (Borgdorff 2010, 55). In contrast with a view of knowledge as truth, in the sense of "justified true belief", the kinds of knowledge produced in artistic research, Borgdorff proposes, may instead broadly be described by two perspectives as related to either a kind of "world disclosure" or "world constitution" (Borgdorff 2010, 61). The first of these perspectives on what artistic research has to offer, "world disclosure", is hermeneutic and holds that artworks and artistic research can offer new views, experiences, and insights that can alter "our relationship with the world and with ourselves". The second, artistic research as "world constitution", is constructivist and stronger in the sense that it posits that artworks and artistic actions constitute or aid in producing the reality (or alternative realities) of certain objects, events, and phenomena (Borgdorff 2010, 60).

4.3 New materialism

In addition to aesthetic theory and theorizations of artistic research another recent theoretical strand has been influential to the thinking and doing developed in this thesis. The heterogenous field of theory referred to as *new materialism* was initiated roughly at the start of the millennium. Encompassing a number of different disciplines and fields that include feminist theory, philosophy, science studies, and cultural studies, new materialism is anchored in, inter alia, Deleuzo-Guattarian and Simondonian thought and the *feminist techno-science* tradition. Prominent new materialist thinkers include Manuel DeLanda, Rosi Braidotti, Jane Bennett, Donna Haraway, Karen Barad, and Elizabeth Grosz.[20] As noted in Paper 1, new materialism can historically in part be seen as a

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[20] In the thesis papers, I reference works by Gilbert Simondon, Félix Guattari, Rosi Braidotti, and Donna Haraway but also a number of scholars who are not regarded as new materialist theorists per se, yet work with similar themes and theoretical traditions, notably Katherine Hayles and Mark B.N. Hansen. In addition, I draw on STS and ANT scholars, including Andrew Pickering, John Law, Marianne Lien, and Annemarie Mol, whose work in some respects also aligns with new materialist interests.

reaction against the dominant focus on representation, language, discourse, and ideology within the humanities and social sciences following the *linguistic turn* in the 1970s. Against this previous theoretical paradigm's emphasis on sociocultural mediation, new materialist thinking seeks to reorient theorizing towards the primacy of matter, which it argues has hitherto been a neglected aspect within humanistic and social theory. Hence, rather than doing away with representations and the social altogether, new materialism endeavors to remedy a theoretical blind-spot by emphasizing the entanglement of material and discursive practices (Sencindiver 2017). Partially overlapping with *posthumanist theory*, new materialist theorizing in general partakes in a rethinking of the dualisms of Western thought (nature/culture, matter/mind, human/nonhuman etc.). It pays special attention to matter precisely because it has been neglected by dualist thought (Dolphijn and Tuin 2013). A central interest is thus materiality and processes of "materialization" and their dynamics, which are approached by way of a *flat ontology* that seeks to place humans, nonhuman organisms, inorganic objects, technologies, and processes on an equal footing (Sencindiver 2017).

Against accounts of matter as uniform, fixed, inert substance, new materialism takes a dynamic view of matter as active, processual, and agential, and as co-productive of social worlds, human life and experience (Coole and Frost 2010). As a consequence, new materialism considers both postmodernist social constructivism and positivist scientific materialism to be untenable, and instead favors accounts of "the co-constitutive 'intra-actions' between meaning and matter" (Sencindiver 2017).

A focus on matter and materials and the dynamic processes they afford is inherent in the notion of soft robotics, and an interest in materialization and material transformation equally exists as an undercurrent within the research field (see Paper 1). New materialist concepts and themes thus parallel already existing focal points within soft robotics research. Hence, the theoretical formation, is well-positioned to extend the initiated inquiry into the materialities of soft robots beyond natural science epistemologies.

4.4 Operationalizing aesthetics with new materialism as a practice-based methodology

In the preceding sections I have introduced three theoretical strands that constitute the theoretical foundation of the thesis' research practice and methodology. As it stands, despite sharing an interest in how to conceptualize material entities, the three strands, are characterized by different interests and can be seen to diverge with respect to some of their central theoretical claims. Hence, in this section, I will seek to explain both the role each plays as an element of the thesis, and the specific aspects from each that figure into the concept of aesthetics utilized.

Firstly, within the thesis, the tradition of philosophical aesthetics and theoretical accounts of artistic research are used to support the propositions that:

- Sensuous modes of engaging with and apprehending soft matter and soft robotics exist that can be considered knowledge producing
- Art practices that make use of these and other art methodologies are potentially capable of producing a non-conceptual type of knowledge about soft robots

In Chapter 2, I have already addressed how the concept of aesthetics used eschews universal claims and the interest in beauty and the sublime found in many aesthetic theories in favor of situated accounts of how art and practices of sensation can engage with soft robotics. Quite importantly, inspired by new materialism, the thesis additionally seeks to relativize Borgdorff's distinction between "research *on* the arts, research *for* the arts and research *in* the arts". Against the view that these three approaches are disparate, a core assumption of this thesis has instead been that the "interpretative perspective" of the humanities and the social sciences, and the "instrumental perspective" of applied technical research, as well as the research that unfolds in and through the creation of artworks, can fruitfully be brought to intersect within a research practice and that drawing on these different perspectives can aid in producing a more nuanced and encompassing account and vision of soft robotics. The thesis is therefore interested in the contrasts, similarities, syntheses, transitions, and frictions that result from operating with them in parallel and switching between them. Hence, it should be stressed that the practice the thesis develops is not simply aimed at creating stunning artworks with soft robotics technology. The creation of artworks is but one of the methods utilized in an effort to facilitate mutual exchanges between soft robotics, art, and aesthetics.

The thesis also modifies Borgdorff's conceptualization of artistic research in another sense. In Borgdorff's account, the artistic production of knowledge is located within the artistic practice itself, i.e. it takes place in the production of artworks. In accordance with this, artworks are described by Borgdorff as vessels that contain "findings". The reception situation (when spectators are confronted with the artwork), is not included within the actual epistemological production, but is instead described as an instance of dissemination of the artistic research. The thesis takes a different position. It seeks to acknowledge and maintain the specificity of a non-conceptual knowledge produced by means of art methodologies. Yet it simultaneously attempts to illustrate and describe how experiences and interpretations of artworks and artistic processes can generate insights that have epistemological and instrumental value. By doing so, it also sees artworks and artistic practices that are not conceptualized as artistic research as potentially contributing to this production of knowledge.

A central hurdle to overcome in synthesizing aesthetic theory, artistic research, and new materialism into a theoretical foundation for a research methodology is how to think the concept of the aesthetic. Traditionally, it has been anchored in psychological and metaphysical considerations on specific types of human experience (aesthetic experiences). But new materialism tends to disregard and work against both anthropocentric and idealist thinking. New materialism has, however, already been influential on contemporary fine arts and media arts practice, and the operationalization and translation of its theoretical propositions into practice that has occurred here provides some methodological guidance on how to navigate this issue.

In relation to art, new materialist theories have been used to foreground the agency of matter within artistic practice and to re-envision artmaking in new terms wherein matter also has agency and artmaking is no longer simply considered the human creation of things.[21] In their anthology *Carnal Knowledge: Towards a 'New Materialism' through the Arts (2012)*, artists and theorists Barbara Bolt and Estelle Barrett exemplify this with reference to Heidegger's example of the silversmith who creates a chalice, which is featured in his "The Question Concerning Technology" essay. The silversmith, they argue, cannot be considered the sole author of this object, but is merely "co-responsible" for creating it, as he is "indebted to other [nonhuman] co-collaborators for the emergence of the 'thing' as a silver chalice" (Barrett and Bolt 2013, 6). Extending this view, they argue that seen through a new materialist lens, artmaking may be recast as "a co-collaboration, not a form-matter synthesis", wherein "matter as much as the human has responsibility for the emergence of art." (Barrett and Bolt 2013, 6).[22] Moreover, against a post-Kantian view of aesthetic experience as anchored in the human subject, Barret and Bolt assert that:

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[21] I am using the term "agency" here to refer to something that non-human things hold that allows them to affect other entities. This understanding of agency resonates with some but not all new materialist uses of the concept.

[22] This interpretation of Heidegger's example of the silversmith and reasoning also resonates with Deleuze and Guattari's definition of the artisan "as one who is determined in such a way as to follow a flow of matter" (Deleuze and Guattari 1987, 409).

> A [new] materialist aesthetic doesn't place the aesthetic experience in the human subject. Rather the 'I' as an articulation of a material-semiotic actor, situates the aesthetic as a relationship 'between' – between the human and non-human, the material and immaterial, the social and physical. (Barrett and Bolt 2013, 6)

This assessment, they argue, aligns with Julia Kristeva's description of aesthetic experiences as involving an intertwining of the physical, the psychic, and the social, and with Karen Barad's notion of *intra-action*. It complicates both the Kantian notion of the disinterested viewer as well as views of art experiences as merely culturally coded (Barrett and Bolt 2013, 6).

Rick Dolphijn and Iris van der Tuin have also articulated aspects of a new materialist perspective on art. However, theirs is more aimed at the analysis of finished artworks than at conceptualizing artistic practice. They posit that with respect to artworks, a new materialist perspective is interested in "how the form of content (the material condition of the artwork) and the form of expression (the sensations as they come about) are being produced in one another" (Dolphijn and Tuin 2013, 91). As they note, it thus diverges from most post-Kantian studies of art, which tend to treat the material and discursive dimensions separately, notably those influenced by the linguistic turn and theories such as deconstruction that seek to address the artwork's "messages" (Dolphijn and Tuin 2013, 91). Instead, alongside Bolt and Barrett, Dolphijn and van der Tuin contend that the new materialist ambition is to consider matter and meaning as entangled and mutually constitutive. To do so, they posit, entails "rewriting events that are usually of interest to natural scientists" (Dolphijn and Tuin 2013, 91), which may be accomplished by studying metamorphoses and dynamic changes without excluding specific aspects of them in advance, or as they put it, by "being open to the process in its full manifestation" (Dolphijn and Tuin 2013, 91).

From the aesthetic theory, artistic research methodology, and new materialist thinking presented in this chapter, a set of practical instructions for thinking and doing can be derived. As already mentioned, these have served as guidelines for the thesis' research practice, and they condense central aspects of both its methodology and research themes. The instructions take the form of ambitions to focus on:

- The epistemological potentials of sensation and art
- Matter and materiality

- Analyzing the discursive/cultural and material together (meaning and matter) and working across subject matter from natural science, art, and the humanities
- The performative capacities of soft robots – processes, actions, and temporal aspects
- Seeing soft robots as agents and softness as a feature that enables different things and can be assembled differently within different contexts and practices
- Articulating relationships – what soft robot aesthetics do, and how
- Making interventions and developing practices, seeing the analyst as a participant (in different practices, communities, fields, and disciplines)

5 Methodology

The following chapter presents the thesis' research process and its overarching research design. The methods applied are specified and brief descriptions of their roles and character within the project, as well as their epistemological foundations are given. As a cross-disciplinary practice-based project spanning the fields of artistic research, art history, robotics, and HRI, no set package of established methods immediately presented itself to the project. Hence, it is necessary to discuss the different options available and the ones chosen.

The thesis' approach is related to and inspired by recent methodological formations that combine a cultural and aesthetic research interest with technical knowledge to interrogate specific technologies through close readings and by "looking under the hood" into their technical modes of functioning. These include *media ecology*, *software studies*, *platform studies*, and *media archeology*.

5.1 Research process

When I was hired as a PhD fellow at the IT University of Copenhagen, my thesis project proposal was predominantly an art historical study of critical robotic art practices with a minor practical component that was not yet fully developed. After delving into the existing literature on robotic art, I redefined my project around soft robotics, as this subject would better allow me to integrate practice and theory and to draw on my background in electrical engineering and physics.[23] This decision was also motivated by the fact that my main supervisor pursued predominantly practice-based research and that I had joined the interdisciplinary REAL (Robotics, Evolution and Art Lab) research group, alongside highly skilled colleagues with backgrounds in computer science and engineering on whom I could rely for technical assistance, if necessary.

From the outset, it was the ambition to work in a way that would leave room for both natural science and art, and to develop a way of working wherein concepts, approaches, and interests from each of these disciplinary fields could cross-fertilize. As I aimed to integrate material practice with theory and explore the aesthetics of soft robots by constructing such robots, artistic research

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[23] I completed the first year of an electrical engineering BSc program and then switched to studying physics and art history concurrently, completing a BSc in physics and a BA and MA in art history.

presented itself as a methodology from the beginning. It would potentially allow me to develop new types of soft robots, and in this way contribute to inventing aesthetics of soft robotics in and through practice. Yet, it was also my assertion that in order to do so, I needed to engage with and learn from the few existing examples of soft robots within art. But also that there might be prior art historical traditions that could aid in describing, analyzing, and understanding soft robot aesthetics. Hence, art critical and art historical approaches were also needed. In addition, it was my working hypothesis that the insights and results gained by artistic and art historical methods might have consequences for robotics research. More specifically, I speculated that the encounter between soft robots and humans staged within soft robotic artworks might shed light on what kinds of interactions soft robots intuitively encourage, and might suggest what kinds of responses their aesthetics can elicit. To substantiate and explore this notion further, in a way that would be recognized by the robotics research community, I would need to conduct an empirical human-robot interaction experiment.

5.2 Research design

Overall, the thesis' research approach has been exploratory. The project started out from the overarching research problem presented in Chapters 1 and 2, and the initial ideas described in the previous section. The specific research questions in each publication were developed as the thesis work progressed. This approach, in combination with the decision to write an article-based thesis with papers written for different academic outlets with different audiences, has produced a thesis consisting of different case studies. The included papers thus each contribute to answering one or more of the research questions but by means of different approaches and methods. This organization of the research was motivated by the assumption that the aesthetic aspects of soft robotics might have different significance and different effects within different contexts. Hence studying specific examples, and comparing and contrasting soft robots within technical research and art practices was deemed necessary in order to address the main problem of the thesis ("*how artistic and aesthetic practices might augment soft robotics and contribute to a more nuanced understanding of the potentials and consequences of rendering a robot soft*").

5.3 Methods

To address the three main research questions of the project, methods from different disciplines were required. RQ1 ("*What qualities and capacities of soft robotics do aesthetic and artistic explorations of the technology bring to light?*") required art historical and art critical analysis and interpretation. RQ2 ("*How can soft robotics be brought to function as an artistic medium?*") was predominantly engaged through my own artistic research and prototyping practice. RQ3 ("*What influence might the aesthetic qualities of soft robotics technology have on human interaction with soft robots?*") was addressed mainly by drawing on methods from HRI research, yet this research also incorporated ideas generated in the analytical and practice-based work that preceded it. In the final paper, Paper 7, analytical approaches from *actor-network theory* served as a methodological inspiration and provided a model for comparing soft robots within art and technical research on a more level ground (than the concept of aesthetics which privileges art).

The choice to draw on the epistemological model of artistic research, rather than other formulations of practice-based research, such as *design research* (Bayazit 2004) or *research through design* (Gaver 2012), was motivated by the fact that the project originated from an interest in art and aesthetics. While aesthetic considerations have been important for design, philosophical aesthetics has tended so see art as the privileged sphere of aesthetics. In addition, contemporary definitions of artistic research stress a dynamic interrelation between analytical and theoretical considerations and artistic practice (Borgdorff 2013; Hannula, Suoranta, and Vadén 2014). Moreover, the specific model of artistic research utilized articulates artistic research as an open methodological framework that can be interfaced with approaches and methods from other fields.

Despite circumnavigating the problem of defining what art and artmaking is, distinct features of artistic practice as a method are implicit in discourses on artistic research when artistic research is contrasted with the research practices of other fields and disciplines. Artistic research is taken to be characterized by building on accumulated tacit knowledge and experience and a sensitivity attained through working artistically for an extended period, to be exploratory and based on hunches and intuition, and to incorporate serendipitous discoveries.[24] Accounts of the knowledge produced through artistic research tend to describe this knowledge as hermeneutic, critical, or

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[24] Prior to and concurrently with the thesis work I have undertaken artistic practice alone and in collaborations and produced new media artworks that have been exhibited at art institutions including Chronus Art Center (Shanghai, China), Science Gallery Dublin, Forum Box (Helsinki, Finland), Kunsthal Grenland (Porsgrunn, Norway), and Nikolaj Kunsthal (Copenhagen, Denmark).

constructivist in character (Borgdorff 2013; Hannula, Suoranta, and Vadén 2014; Borgdorff 2010). However, due to art's preoccupation with perception and sensation, this knowledge has also been argued to potentially be compatible with recent cognitive science perspectives on embodiment and embodied knowledge (Borgdorff 2010). In addition to my own practice work and prototyping, input to the research has also been gained during three hands-on workshops that I conducted at the *Pixelache Festival* in 2016, the Robot Art Forum at the *ICRA 2018* conference, and at Aalborg University (descriptions of the workshops are included in Appendix 10.3). Informal conversations with visitors at a number of public demonstration events where I exhibited prototypes also filtered into my thinking.[25]

Besides artistic research, the thesis papers also draw on art history, which, as a discipline, comprises numerous methods. Anchored in the humanities, art history has traditionally derived its epistemology from hermeneutics.[26] In accordance with this, art historians have often taken an idiographic approach to knowledge, aimed at specifying and understanding unique, contingent, historical phenomena and cultural artifacts via interpretation. Yet, art historical research also aligns with the nomothetic tendency towards generalizing (characteristic of the natural sciences) in order to uncover general patterns or laws – e.g. in its efforts to understand the historical evolution of art or specific categories or groups of works. The thesis papers draw on a number of traditional art historical methods, including: *ekphrasis* (aesthetic description of artworks), formal analysis, comparative analysis, and contextual analysis. The tradition of poststructuralist-inspired philosophical art history, and its interest in how concepts drawn from other disciplines might be adopted to describe characteristic operations contained in certain artworks, has also served as inspiration for the mode of analysis undertaken in Paper 2.

The main object of this thesis' inquiry is not how "users" experience soft robots, but rather the potential of art and aesthetic practices to add to soft robotics and elucidate it as a phenomenon. Yet one could argue that by demonstrating that soft robots' aesthetic appearances influence how people interact with them, aesthetic practices automatically attain relevance for applied soft robotics research. This argument forms part of the reasoning underlying the decision to include a more traditional empirical study based on the collection of qualitative and quantitative data from an

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[25] These include: The annual *Kulturnatten* (*Culture Night*) held at ITU in 2017 and 2018, *Vartov's videnskab* (a science talk series in Copenhagen), and the *HRI'18* conference in Chicago.

[26] However, within the study of media art there is a tradition for art historical accounts written by practitioners focused on the interests of their practice. Recently, efforts have also been made to transfer approaches to art history that are not oriented towards traditional hermeneutic interpretation from e.g. affect theory, new materialism, material semiotics, and ANT.

interaction experiment in the thesis. As already mentioned, this experiment draws on established methods from HRI research. HRI emerged as a field of research in the 1990s and comprises researchers from different disciplines including robotics, psychology, artificial intelligence, and cognitive science (Dautenhahn 2013). Despite HRI being a multidisciplinary field, the majority of HRI researchers come from an engineering background (Irfan et al. 2018). HRI research is described as "dedicated to understanding, designing, and evaluating robotic systems for use by or with humans" in order to "understand and shape the interactions between one or more humans and one or more robots" (Goodrich and Schultz 2007). Although calls to pay more attention to the context of interaction and to focus on longitudinal studies (e.g. by adopting ethnographic methods) have recently emerged (Dautenhahn 2018; Kiesler and Goodrich 2018), field publications often take the form of user studies based on interaction experiments modelled on experimental psychology experiments. Hence, methodologies rooted in positivism are often used, and the research tends to value controlled experiments, quantitative measurements, reproducibility, and generalizability and to be aimed at uncovering causal relations. Paper 6 on the interaction experiment draws on existing approaches within HRI research but integrates statistical analysis of data with qualitative analysis of written text and qualitative analysis of video recordings of human-robot interaction. Moreover, the experiment sought to present the robots in a way that is more open-ended and less utilitarian in scope than usual HRI experiments.

Besides artistic research, art history, and HRI, the thesis also draws on established design, fabrication, and control methods from technical soft robotics research. In Paper 5, evolutionary robotics methods are also used.

6 Summary of papers

List of included thesis publications:

PART I: *RESITUATING SOFT ROBOTICS*

1. J. Jørgensen. "Prolegomena for a Transdisciplinary Investigation into the Materialities of Soft Systems." (2017) In ISEA 2017 Manizales: Bio-Creation and Peace: Proceedings of the 23rd International Symposium on Electronic Art. University of Caldas, 2017. 7 pages. Conference paper [published]

2. J. Jørgensen. "From Soft Sculpture to Soft Robotics: Retracing Entropic Aesthetics of the Life-like" in: *Changing Interfaces* (ed. Hava Aldouby). Leuven University Press (forthcoming). 19 pages. Invited book chapter [under review]

PART II: *SOFT MOVEMENT AND COMPUTATIONAL AESTHETICS*

3. J. Jørgensen. "Leveraging Morphological Computation for Expressive Movement Generation in a Soft Robotic Artwork." (2017) In *Proceedings of the 4th International Conference on Movement Computing, 20:1–20:4. MOCO '17*. New York, NY, USA: ACM, 2017. doi:10.1145/3077981.3078029. 4 pages. Conference paper [published]

4. J. Jørgensen. "Tales of C: Cephalopodic Aesthetics and Computational Media". 15 pages. [pending submission for publication]

5. F. Veenstra, J. Jørgensen, and S. Risi. "Evolution of Fin Undulation on a Physical Knifefish-inspired Soft Robot". In *Proceedings of the Genetic and Evolutionary Computation Conference 2018 (GECCO '18)*. ACM, New York, NY, USA. 8 pages. Conference paper [published]

PART III: *SOFT INTERACTIONS AND INTRA-ACTIONS*

6. J. Jørgensen, K. B. Bojesen, and E. Jochum. "Is a soft robot more 'natural'? Challenging the perception of soft robotics and perceived naturalness in human-robot interaction". 28 pages. Journal article [submitted for publication in *International Journal of Social Robotics*]

7. J. Jørgensen. "Enacting the Soft Automaton: Empirical Ontologies and two Soft Robots from Media Art and Technical Research." In *EVA Copenhagen 2018 – Politics of the Machines – Art and After*, Aalborg University, Copenhagen, Denmark, 15 – 17 May 2018. Electronic Workshops in Computing (eWiC), BCS (British Computer Society): The Chartered Institute for IT, UK. 9 pages. Conference paper [published]

The thesis paper collection consists of seven publications. The decision to include seven publications reflects that four of the papers are conference papers and hence shorter than journal articles. Moreover, Papers 3 and 4 are about the same project, but present different aspects of it, and Papers 5 and 6 were written with co-authors.

The order in which the papers are presented largely follows the chronology of when work on the different papers commenced, with the exception of Paper 2, which has been moved up to become the second paper of the collection. To provide an overview of the work, the papers have been organized under three headings that recapitulate shared themes.[27] The first two papers, under "*RESITUATING SOFT ROBOTICS*", both contribute to articulating the conceptual and historical contexts of the thesis research. The three papers collected under "*SOFT MOVEMENT AND COMPUTATIONAL AESTHETICS"* address the artwork *Tales of C*, which was produced as a part of the thesis and an evolutionary robotics experiment with a soft swimming robot. The first paper in "*SOFT INTERACTIONS AND INTRA-ACTIONS*" presents the results of the human-robot interaction experiment and the second paper provides a comparative analysis of two soft robots from media art and technical research and the sets of practices that envelop them.

Below, the individual publications are summarized, and their main findings situated within the thesis as a whole. In addition, the connections between the different papers are addressed in terms of how they have influenced each other within the research process. The papers have been written for different audiences within different disciplines and fields. The summaries thus also seek to briefly explicate their context of publication and also provide a short commentary on the writing style of the papers where this is deemed relevant.

6.1 Paper 1 – "Prolegomena for a Transdisciplinary Investigation into the Materialities of Soft Systems"

The first paper was published in the proceedings of the *International Symposium of Electronic Art* (*ISEA*) *2017*. Its main endeavor is to lay the ground for a transdisciplinary perspective on soft robotics, and to articulate some of the immediate potentials held by such a perspective.[28]

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[27] The themes under which the papers are placed should, however, not be seen to be their explicit main focus nor do they fully encompass what is addressed in the individual papers. The themes have been constructed in hindsight after all papers were written, and hence did not precede the texts.

[28] I take transdisciplinarity to mean linking practices and discourses from different disciplines. A transdisciplinary research practice differs from an interdisciplinary research practice by not leaving the disciplines it involves intact but transforming their methods or basic concepts in the research. However, numerous other definitions of transdisciplinarity exist (Osborne 2015).

The paper starts with a short introduction to the field of soft robotics. It then introduces the main question of how one might approach soft robotics in a way that accommodates both natural science and art, and how to create a productive interplay between their different approaches to soft matter. The paper suggests that the concept of *materiality*, as defined by N. Katherine Hayles, might serve as a conceptual means for this work and proceeds to explore how the materiality of soft robots is constituted within examples of soft robotic artworks and technical soft robotics research projects. It is argued that within the reception situation of the soft robotic artworks, a soft materiality that is primarily accessible via direct bodily and corporeal engagement is prevalent. And that it is through invoking the sensation of touch and the use of a "breathing" motion that these soft robots come to appear similar to natural organisms (i.e. appear animated or "life-like"). Within a number of technical robotics research projects, it is instead a processual and dynamic chemico-biological materiality that is enacted. Moreover, the method descriptions in some technical publications evince an interplay between material experimentation, conceptual thinking, and social interests that the paper suggests can be described by Andrew Pickering's notion of *the mangle of practice*.

The analyses presented highlight how soft matter and soft materiality attains an active role within both artworks and robotics research, but in different ways. That is, the two sets of practices both position soft matter not as inert or fixed, but as capable of transformation or of acting upon and affecting other entities, as well as contributing to the generation of its own forms.

The paper ends by introducing a selection of the first prototypes that I constructed as a part of the exploratory prototyping research and hints at how they extend and complicate the main question of the paper.

The paper contains a number of ideas that were taken up and treated in more detail in the subsequent papers. These include:

1. Physical softness might be actualized differently and have different consequences for a robot within robotics research and robotic art (addressed in Paper 7)
2. Analysis of the art historical tradition of *soft sculpture* might add to understanding the aesthetics of soft robots and soft robotic art (treated in Paper 2)
3. Water affords specific kinds of soft robotic movement (discussed in Papers 3 and 4), and an evolutionary algorithm could be used to evolve the swimming behavior of a soft robot (Paper 5)

4. Soft robots encourage other types of physical human-robot interaction than rigid robots (Paper 6)

In the paper "ecology" is mentioned as a possible concept for considering soft robotics more broadly. However, the theoretical tradition of writings on ecology was deemed too vast to include in the thesis and the ecological perspective was abandoned in the subsequent papers as an explicit part of the theoretical framing.

6.2 Paper 2 – "From Soft Sculpture to Soft Robotics: Retracing Entropic Aesthetics of the Life-like"

Paper 2 is a chapter I contributed to the anthology *Changing Interfaces* about 21st century media art edited by Hava Aldouby that will be published by Leuven University Press. The chapter is an extended and reworked version of a paper I presented at the *MediaArtHistories* conference in 2017.

The paper extends the project of rethinking and recontextualizing soft robotics in relation to artworks and art practices initiated in Paper 1 but takes a more art historical approach. It thus partakes in constructing an aesthetic genealogy of soft robotic art, in order to articulate novel aspects of its aesthetics. The analysis undertaken is anchored in philosophical art criticism and art history as it enlists art historical sources and art historical accounts together with concepts drawn from other fields in an argument that reorients the traditional understanding of the aesthetic interests of postminimalist soft sculpture.

The paper departs from the observation that works of *soft sculpture* produced in the late-1960s, by a heterogenous group of artists, are frequently described as being similar to living organisms and bodies, despite the fact that these works are mostly non-figurative and non-moving. This becomes the point of departure for an examination of the contiguity between perceptions of softness and experiences of something as endowed with the qualities of life or a living organism. In other words, in what sense softness might be generative of the impression of something as being "life-like".

Drawing on the critical reception of postminimalist soft sculptures, the paper draws attention to two different ways in which soft sculptures come to appear life-like. The first relates to a reflexivity between kinesthetic experiences of the viewer's own body and soft matter. The second is anchored in the "entropic aesthetics" to which the title of the paper refers. This aesthetics is present in interpretations of postminimalist soft sculpture that read these works as analogies of the physical relationship between a biological organism and its environment. It is argued that within such readings, life is portrayed as processual, and the organism's physical entwinement with the surroundings is stressed. Hence, this description parallels the physical description of how living organisms sustain themselves by continually exporting entropy to their surroundings.

Building on this analysis, the paper goes on to consider two contemporary soft robotic artworks – *BRALL* by Ece Polen Budak and collaborators and *Synthetic Seduction* by Marie Munk and Stine Deja. Drawing on the meaning of entropy as sameness, the paper reads these artworks, where soft life-like robotic entities merge with architecture and the domestic environment, as extending the entropic aesthetic of postminimalist soft sculpture. The works are contextualized in relation to the proliferation of *ubiquitous computing* within the past two decades – a historical development that the paper argues has endowed the human habitat with life-like qualities. *BRALL* and *Synthetic Seduction* are understood to reflect and engage with this condition. The paper ends by posing the question of what soft sculpture and soft robotics might add to soft robotics, and calling for artists to partake in constructing distinct soft robot aesthetics.

6.3 Paper 3 – "Leveraging morphological computation for expressive movement generation in a soft robotic artwork"

This short paper (4 pages) was published in the proceedings of the interdisciplinary *Movement Computing* (*MOCO*) *2017* conference. It is the first of two papers dealing with the artwork *Tales of C* and was written when the artwork was still in its early phase of development. Based on the prototyping experience that served as input for Paper 1, I decided to start work on this artwork that would feature a more complete robotic system.[29] This would provide an opportunity to explore the control aspect of soft robotics in more depth, i.e. the kinds of movements and ways of programming that a silicone body dictates.

The paper describes the technical aspects of the artwork and presents the design, fabrication, and movement programming of the cephalopod-inspired soft robot featured in the work. It describes how the robot's design was conceived from the arm prototype and the tentacle prototypes (the

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[29] While conducting the thesis research, I was involved in the creation of two other artworks: *The Condition* (2015-16) and *Beyond Digital Towards Biological* (2017). A paper was published on the first of these, but I chose not to include it in the thesis as the work did not involve soft robotics. No academic publications were written about the second work, which did include soft robotics. The two works are documented and described in Appendices 10.1 and 10.2.

Phytomatonic series) presented in Paper 1, and how the concept for the movement programming emerged through experimenting with the robot.

Stylistically, the paper is written in a predominantly descriptive language characteristic of technical research publications. Yet it breaks with this genre by proposing an aesthetic interpretation and versioning of the *morphological computation* concept. That is, the main conceptual proposition and contribution of the paper is that besides aiding in practical tasks, the pliability inherent in soft robotics can also make it easier to design and program expressive robotic movement.[30]

6.4 Paper 4 – "Tales of C: Cephalopodic Aesthetics and Computational Media"

Paper 4 is the second publication on *Tales of C*. It seeks to articulate and perform the thinking developed through the work.[31] It presents central ideas formed in the process of constructing the artwork and contextualizes it in relation to sources that inspired it. Stylistically, the text approaches these tasks in a non-linear fashion as it blends theoretical observations and contextual information with descriptions of the installation and its prototyping. The paper is not driven by a single argument but moves through juxtaposition. It is organized in short thematic sections with headings that are either words starting with a "C" or remarks that audience members made about the artwork when it was exhibited (captured in a video recording). The latter are used for the parts of the text that contain descriptions of the installation. In places, the text evokes scholarly writing within the humanities, but this discursive style is broken up by more associative jumps of an idiosyncratic character that have influenced the work but are not necessarily justified, logical, or rigorous. The more experimental writing style of the paper was chosen to take seriously the non-conceptual character of aesthetic and artistic thinking and practice. It provides a way of writing that is performative as well as representational, wherein discontinuities, ambiguities, and indeterminacy in thought and experience need not be fixed or resolved. The compartmentalized overall structure of the text also echoes the breaks and jumps of the narration featured in the installation.

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[30] Unlike most HRI research on expressive movement (e.g. (Hoffman and Ju 2014)), this thesis takes a non-representational view of expression as something that precedes signification. Hence, the experimentation with the cephalopod robot was also not aimed at generating movement with specific legible meanings. The presented interpretations of the movements came afterwards. This view of expression is inspired by Deleuzian thought (see e.g. (Massumi 2002)).

[31] The paper has not yet been submitted for publication, as it has taken a long time to find a format that would be adequate to the kind of knowledge produced in the project.

The paper starts with considerations triggered by the event of witnessing the behavior of the arm prototype from Paper 1. This arm prototype served as the initial main inspiration for the design of the cephalopod morphology. In the context of the paper, however, the observed physical coupling between the arm and the water also comes to serve as a metaphor for the entanglement of organism and environment, object and subject, the concrete and the abstract, which are recurrent themes of the text. The text additionally touches on the following themes:

- The overlap between descriptions of cephalopods' ethology and ontology and accounts of 21st century computational media (both are seen as transgressive, fluid, and bordering on the imperceptible)
- The notion of intelligence as interlinked with body morphology (found within the contemporary robotics research paradigm of *embodied intelligence* and prefigured by the ancient Greek notion of *mêtis*)
- The tension between logical reasoning and symbolic representation and informal, messy, embodied, or fluid forms of cognizing
- How specific ways of attending always imply a loss of other contexts

The title of the artwork, *Tales of C*, refers to "tales of the sea". These often revolve around the otherness of monstrous sea creatures that sailors have encountered on their journeys. In the text, "C" thus becomes a shorthand for cephalopod but also attains other meanings that can include computation, cunning, calculation, capitalism, Chthulucene, co-evolution, compliance, and control.

6.5 Paper 5 – "Evolution of Fin Undulation on a Physical Knifefish-inspired Soft Robot"

Paper 5 was published in the proceedings of *The Genetic and Evolutionary Computation Conference (GECCO) 2018* conference. It was written in collaboration with Frank Veenstra, a fellow PhD student at ITU with a background in biology and bionics, working on evolutionary robotics. Associate professor Sebastian Risi, a computer scientist with expertise in evolutionary algorithms, supervised the project.

Frank had helped me conduct a workshop on soft robotics at the Pixelache Festival and had seen the soft robotic prototypes I had produced. He suggested using the biological species of knifefish as an inspiration for a soft swimming robot. I designed and built the robot by drawing on techniques and solutions from earlier prototypes and the robot featured in *Tales of C*. Like the latter, the knifefish-inspired robot features servo motors (with attached bamboo sticks) that are cast into silicone as its means of actuation.[32]

The paper addresses the problem of how to design a controller for a soft morphology (a controller is here understood to be the software program that controls the robot's movements). Designing a controller is challenging for soft morphologies, as movement equations cannot be derived from geometrical considerations like they can for rigid robots. As a workaround for this problem, the paper proposes to use an evolutionary algorithm to evolve the controller directly in the physical hardware (the actual robot) instead. Thereby, one is able to reap the benefits of having both an elaborate robot design and an automated discovery of its most optimal behavior. In a series of evolutionary experiments, this strategy was used to optimize the swimming speed of the knifefish-inspired robot. This approach enabled us to discover controllers that could outperform the best controller we could program manually on the robot.

I have chosen to include the paper in the thesis as it illustrates how practical solutions, insights, and experience gained from aesthetic and experimental prototyping of soft robotics can also contribute to solving a research problem that is articulated as decidedly technical in scope. But also because it extends the underlying approach of several of the thesis' other papers in a technical setting. That is, its methodology is based on intervening in a complex system rather than analyzing the system's individual constituent parts. Moreover, its central concern is with what is referred to as the *reality gap* within robotics research – the observed difficulty in transferring behaviors found in computer simulations to the physical hardware and the physical world without major inconsistencies. Hence, the paper also extends the thesis theme of non-representational performative ways of producing knowledge and the limits of conceptual and quantitative representations of the world.

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[32] The division of the remaining research work was as follows: I conceived the idea of encoding the swimming movement as a Fourier series and wrote the initial control program that translates the genome (a string of bytes) into the phenotype (fin movement). Together, Frank and I designed and constructed the evaluation setup. Frank implemented the evolutionary algorithm and conducted the evolutionary experiments. Frank redesigned the robot, and we built the new version together. We both wrote the paper together with Sebastian – Frank performed most of the data analysis and I wrote most of the background on knifefish robots and the use of evolutionary algorithms with soft robots, the sections on the robot's design, and the sections on comparing the robot behaviors with the actual knifefish.

6.6 Paper 6 – "Is a soft robot more 'natural'? Challenging the perception of soft robotics and perceived naturalness in human-robot interaction"

This article was written together with associate professor at Aalborg University Elizabeth Jochum, a human-robot interaction researcher with a background in theatre studies. Kirsten Borup Bojesen, Dr. Med. and PhD in medicine, helped with the statistical analysis of quantitative data.[33] The article has been submitted for publication in *International Journal of Social Robotics*.

The paper is an attempt to formulate and address the problem of the thesis in a way that will be considered relevant within the field of HRI research – the branch of robotics research where issues related to design and *human factors* are usually addressed. Overall, the paper seeks to engage with and to nuance statements and claims made about human perceptions of soft robots within technical soft robotics literature. In the paper, aesthetics thus refers to the appearance (visual, kinetic, and haptic) of a specific robot and how it is perceived by users. In relation to the thesis' main problem, the paper contributes predominantly towards answering RQ3 ("What influence might the aesthetic qualities of soft robotics technology have on human interaction with soft robots?"), yet its practical exploration also potentially contributes towards answering RQ2 ("How can soft robotics be brought to function as an artistic medium?").

The two main aims of the paper are:

1. To question the claim that soft robots are perceived as more "natural" and more appealing than conventional robots (within soft robotics research discourses)
2. To gain insights into people's perceptions of soft robots and the spontaneous interaction behaviors elicited by soft robots.

In relation to the second aim, the research further seeks to investigate whether soft robots are perceived differently than rigid robots and whether they elicit other types of interactions.

The article interprets empirical data from a case study interaction experiment. In the experiment, participants were asked to interact with one out of three robots – two soft robots (referred to as the "red robot" and the "blue robot") with different designs and a comparable rigid

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[33] The division of the research work was as follows: I designed and built the three robots, designed the interaction experiment, organized and conducted the experiments, analyzed the qualitative questionnaire data, transcribed and analyzed the video data, wrote the first draft of the paper, and recorded and edited the videos that accompany the article. Kirsten did the statistical analysis of data. Elizabeth contributed advice on how to conduct the interaction experiment and took part in revising and editing the paper.

robot. The interactions were video recorded and participants were also asked to fill out a questionnaire afterwards.

Based on statistical and qualitative analysis of data obtained from the questionnaires, the article problematizes the assumption that soft robots are more “natural”, and argues that the term “natural” is problematic and inadequate to describe human interaction with and perceptions of soft robots. In the article’s analysis of the video recordings of human-robot interaction, a number of examples of different ways that people interacted with the three robots are presented. Differences in interaction behaviors and participant discourse are identified between the three robots, which indicate that touch and perceived safety are potential aspects that might differentiate the interaction with soft robots from the interaction with the traditional robot.

From a humanities perspective, the argument presented against using the word “natural” to describe soft robots may appear redundant. That is, this word has already been pointed out to be problematic for a number of different reasons, notably within poststructuralism (e.g. Roland Barthes, Michel Foucault), deconstruction (Jacques Derrida), various strands of identity politics, and more recently in e.g. the writings of Timothy Morton. Yet, the strategy of conducting an empirical study, rather than rehearsing a theoretical argument, was adopted in order to enter into a dialogue with researchers from the field of HRI (many of whom will not be familiar with the theoretical formations mentioned above) by means of their own approaches and with methods that they consider legitimate. The choice to include statistics as a tool for analysis should also be seen in this light.[34]

However, the paper also attempts to push at the conventions of HRI research. In relation to this and the main problem of the thesis, it is important to point out how the experiment design draws on aesthetic practice by addressing robots beyond any specific use. That is, participants were asked to interact with and explore the robots rather than to complete a task with them. Moreover, qualitative analysis of video recordings of the embodied interactions figures as a key method in the research. The experimental approach also has an interventionist character – three robots without any predefined function are set up inside a university library, creating a somewhat open situation with an outcome that cannot be predicted in advance.[35] Hence, the way soft robotics technology is

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[34] It is still difficult to have studies published in HRI journals that do not include inference from quantitative data (Kerstin Dautenhahn, keynote address at *HRI’18 conference*).

[35] I submitted a video that presents the interaction experiment for the HRI’18 conference. The comments I received from a reviewer explicitly remarked critically on the open-endedness of the experiment (despite the video’s explicit reporting of the results): “A better motivation should be provided what is the aim of the research or what is the research question.” (anonymous reviewer in conference email to author December 22, 2017).

addressed and how the human-robot interaction is staged also shares an interest in emergence with new materialism. The paper thus performs (and implicitly proposes) a methodology that reverses the general approach of robotics: Rather than starting out with a predefined function of the robot in mind and then developing the robot, the paper starts with the robot and then investigates what interactions and imagined functions it suggests to potential users.[36]

The designs of the two soft robots used in the experiment also build on previous practice-based work. The "red robot" incorporates a tentacle I had originally constructed as a means of learning the "lost-wax casting" technique, which has a pinkish hue. I had noticed that people were very ambivalent about it when I presented it to them, and tended to think it was somewhat off-putting. The tentacle for the "blue robot" was cast in the mold I had used for the *Phytomatonic* series, but was wrapped with braided fishing line, which gives it a different behavior and appearance when inflated (the fabrication is described in Appendix 10.5). When working on the *Phytomatonic* series, I had experimented with orienting the tentacles in different ways (standing upright, lying down), and had observed that it provided very different impressions of the morphologies (see videos accompanying Paper 1). For the interaction experiment, I chose to have the tentacles hanging down from a metallic frame.

6.7 Paper 7 – "Enacting the Soft Automaton: Empirical Ontologies of Two Soft Robots from Technical Research and Media Art"

The final paper was published in the proceedings of the *EVA Copenhagen 2018 – Politics of the Machines – Art and After* conference.

The paper revisits two soft robots that were included as examples in Paper 1 to analyze these in more depth – Paula Gaetano Adi's *Alexitimia* and the Harvard Octobot. The theoretical frame of reference consists of writings by authors from the *actor-network theory* (*ANT*) tradition, including John Law, Marianne Lien, and Annemarie Mol. This tradition provides inspiration for a change in vocabulary away from the concept of *materiality* utilized in Paper 1 towards *ontology*, or more precisely *empirical ontologies*. Using the concept of ontology, understood here as "how things exist", and taking an ontological constructivist stance, it becomes possible to provide an account of

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[36] A related way of working is found in research by Petra Gemeinboeck and Rob Saunders that investigates how to harness the movement expertise of dancers to generate robotic movement for different morphologies (Gemeinboeck and Saunders 2017).

softness in a robot that acknowledges how softness can have different manifestations and afford different things within different practices.

Departing from a juxtaposition of two videos that present each of the two robots, the paper explores the practices and relations through which the robots come into being. It does this with a focus on how knowledge about the robots is produced and how their softness is actualized and what it enables. Attention is drawn to a number of dissimilarities: the different modes of presentation in the two videos, the different scales of the two robots, that one fabrication procedure is based on crafts and the other on mass production as models. But also that within both practices, soft matter seems to resist or escape representational capture (by language and mathematics). In the technical research this is seen as something that must be overcome, whereas in the artwork it is instead acknowledged as a creative resource.

Autonomy as a concept, the paper argues, is also constructed differently within the two sets of practices – the Octobot emphasizes autonomy as disconnection and as technical functionality separate from humans, whereas *Alexitimia* enacts a version of autonomy that is only actualizable in close contact with a human. The paper further argues that *Alexitimia*'s respecification of autonomy can be seen to align with posthumanist refutations of the humanist view of man as separate from and set above the world, providing an important counterpoint to an emerging more moralizing discourse on soft robot ethics.

7 Discussion and conclusions

Rather than drawing on a single established methodology, this thesis has combined and extended interests, concepts, and methods from art history, aesthetics, artistic research, HRI, ANT, soft robotics, and evolutionary robotics. It has used different theoretical frameworks and approaches, side by side and interchangeably, to address and construct different versions of and perspectives on soft robot aesthetics. This means that as a whole, the thesis is not easily placed within one discipline or a single field of research. Given that each thesis component contributes to describing, understanding, and constructing the same subject matter and phenomenon, the research conducted, however, lays a foundation for gaining a rich and multifaceted transdisciplinary perspective on soft robot aesthetics. Yet the question remains as to whether the thesis' partial results are cumulative and can be added up or not, in other words – should one seek to synthesize and integrate them or are they incommensurable and should instead be contrasted?

In the following, I will discuss the contribution of the thesis as a whole and how this contribution is articulated within and between the seven thesis papers. The discussion will address the question of how the insights presented in the thesis papers align with each other and what answers they offer in response to the thesis' research problem, as well as issues and potentials pertaining to the methodology developed in the thesis. To open up the discussion, I will start by considering what responses the constituent parts of the thesis provide to the overarching problem and subsequently address the three main research questions.

7.1 The overarching problem in light of the thesis research

This thesis has addressed the problem of "*how artistic and aesthetic practices might augment soft robotics and contribute to a more nuanced understanding of the potentials and consequences of rendering a robot soft*". To "augment" means to make something greater by adding to it or to increase something. In line with this, my approach to answering the question contained in the research problem has been to work through case studies and projects, components that in turn each add to the thesis by addressing the problem from different angles. These have been descriptive and analytical but also inventive and constructive in character. The research has involved, among other things, analyzing examples of soft robots within art and technical research (and their associated practices), creating prototypes and artworks, and conducting an HRI experiment. Given this broad range of approaches, perspectives on the proposed augmentation are instantiated in several ways: This augmentation is in part actualized and presented in the novel physical soft robotic systems and prototypes that have been developed and the aesthetic experiences and processes they may give rise to. However, the knowledge about soft robotics as a phenomenon presented in the thesis papers also contributes to deeper insight. And the thesis has also enacted and proposed novel approaches to working with soft robots that are anchored in art and aesthetics. I will seek to take these different forms of contributions into account when addressing the three research questions in more detail below.

7.2 Soft robot aesthetics within aesthetic practices

7.2.1 RQ1: *What qualities and capacities do aesthetic and artistic explorations of soft robotics technology bring to light?*

A quality is a distinctive attribute or characteristic possessed by someone or something (Oxford Dictionaries). A capacity, in contrast, is something that an object possesses that is only manifested in the object's interactions with other entities (DeLanda 2013). In Section 3.2, I have mapped works with soft robotics within art, design, and architecture and presented some recurrent themes and interests of these. However, this section should not be taken as an attempt to compile a complete list of characteristic aspects of soft robotics as an aesthetic medium nor a schematic model of a general theory of soft robot aesthetics. However, the summarizing account given in Section 3.2 may, serve to take stock of what the central interests of aesthetic projects involving soft robotics have been and what capabilities of soft robots it has emphasized.

Aesthetic projects have stressed the capacity of soft robots to appear similar to natural organisms and explored the consequences of this ambiguity. This ability has been enhanced by eschewing repetitive geometric designs in favor of more organically composed morphologies where repeating elements vary in size. The qualitative similarities with humans and animals have also been emphasized by implementing "breathing" (see Paper 1). In line with this, it has been explored how soft robots are able to move in specific ways and by doing so can come to appear animated or life-like, or to be associated with specific affective states, intents, or communications. A number of artworks thematize that soft robots can trigger a desire to touch and that doing so might provide a range of different experiences. All of the qualities and capacities highlighted here have not yet been addressed within soft robotics research, even if the perceived similarity of robots to humans or animals and robotic movement as well as tactile interaction are existing areas of inquiry within HRI research.

7.2.2 A central theme: Softness as a precondition for merging

Art, design, and architecture projects with soft robotics also exhibit a pervasive intuition about an issue that has also previously gone unacknowledged, but is relevant to consider for the potential future human uses of soft robots. In Section 3.2.6, I notice how a number of projects envision soft robots as prostheses, but also that some go further than that and articulate or depict soft robots as having been integrated into a feedback loop with the human body. Within the latter, it is thus less a case of a human using the soft robot as a tool, than of the human and the soft robot merging into a novel cyborg entity. And the notion of *softness as a precondition for merging*, which surfaces here, can in fact be seen to comprise a central motif and shared principle of aesthetic soft robotics projects in several other ways.

Merging and intertwining is implied in the aesthetic of permeability contained in several projects (see Section 3.2.6). But, interestingly, it also recurs within the analysis of soft sculpture and soft robotics presented in Paper 2. Here, I argue that postminimalist soft sculpture is described as life-like in part because it evokes the living organism's connectedness with its physical surroundings. And I notice that in the two analyzed robotic artworks, soft robots have been integrated into the domestic settings. Papers 3 and 4 (on *Tales of C*) equally emphasize how the physical properties of soft silicone and water appear to intertwine in the movement that the soft robotic arm prototype manifests. The notion of softness as a precondition for merging is equally reiterated when practitioners talk about their projects As I mention in Paper 1, Jonathan Pêpe describes the soft robotic parts of his *Exo-biote* (2015) as artificial organs that can be integrated into human bodies for enhancement purposes. And the viewer is virtually transferred from the outside to the inside of *Cypher*. Chico MacMurtrie also states that the trajectory of his "soft machines" "points toward increasingly close connections between the inflatable body, the human body, and the environment." (MacMurtrie 2016, 359). By the same token, Michael Wihart's understanding of the "soft machine" stresses that softness provides a basis for considering "how architecture can be conceived to allow humans to engage more seamlessly with their immediate surroundings." (Wihart 2015, 387). He also remarks that "the soft machine as a medium […] may engender new forms of subjectivity, experience and enquiry […] encouraging […] co-constituting modalities of thought."

(Wihart 2015, 385). And in line with new materialist thinking (and the argument presented in Paper 2), the materiality of soft robots and soft matter are thus taken to actively shape the actions and thinking of humans that interact with them. This is also the case in the article on soft robot ethics by Thomas Arnold and Matthias Scheutz (addressed in Paper 7), which even espouses a need for soft robot designs to "deflect users from personally and socially destructive behavior the soft bodies and surfaces could normally entice." (Arnold and Scheutz 2017, 81).

In relation to future applications of soft robotics, the perception of softness as enabling a tighter coupling or more thorough intertwinement between humans and robotics technology, widely thematized in aesthetic projects, raises the issue of whether soft robots at present might on some level be harder to differentiate from other entities, including organic bodies. And if so, is this to be seen as a benefit or a disadvantage? Could human interactions with them potentially lead to experiences of merging with a soft artificial other, with a resulting feeling of loss of self, agency, or control as a consequence? Or does this aspect conversely make soft robotics a more adequate prosthetic technology? Or, alternatively, might it present an opportunity to cultivate more posthuman non-dualist ways of envisioning human interactions with technology and human agency in general (as argued in Paper 7)?

7.2.3 RQ2: *How can soft robotics be brought to function as an artistic medium?*

The qualities and capacities of soft robots, described in the previous two sections, can all become ingredients in reconfiguring soft robotics to function as an aesthetic medium. Yet the thesis has sought mainly to answer the second research question posed about how soft robotics can become an artistic medium through its practical component. Below, I will summarize some of the strategies and interests that have emerged in this work. However, the insights and singular experiences it has delivered should also, in part, be seen to be contained in the prototypes and artworks themselves in a manner that precludes complete articulation in a text (Borgdorff 2013).

The early prototypes sought to explore soft robotic materialization processes – how soft robots come into being. They focused on uncovering the silicone material's capacities in experiments with making molds for it out of soil, combining it with salt, hydrogel, conductive powders etc. But they also tried to incorporate an awareness of the wider material ecologies in which the materials are enrolled – soil, for instance, was equally used in order to reference that silicone is produced from raw materials found in the ground (sand and hydrocarbons) and to suggest degradation and deterioration and thus subvert the clean product-like aesthetic of the new prevalent in the visuality of robotics research. In my experimentation with the prototypes, they were placed in environments and situations where softness suggested a possibility for new types of relations with other elements – drawing on e.g. interactions with soil, plants, or liquids.

In *Tales of C*, I investigated further how water affords a specific aesthetic of soft robotic movement, and how this movement could become expressive. Additionally, the work endeavored to recognize and reactivate alternative genealogies of the notion of a cephalopod robot that are absent in technical research – e.g. cultural understandings of cephalopods in myths, literature, philosophy, and contemporary news stories. It also sought to articulate the cephalopodic and soft robots in relation to computational media and artificial intelligence. Hence, the work was based on investigating both the physical characteristics of soft robotics technology and ways of programming expressive soft robotic movement, as well as the meaning-making potentials that arise when this technology is coupled with different contexts.

While not an artwork as such, the robots produced for the HRI experiment were attempts to create a minimal design for a soft robot that could be interpreted as autonomous and interactive with a non-humanoid and non-zoomorphic design. The robots utilized preprogrammed movement and a simple touch gesture for this purpose. The two different soft robot designs also explored different visual appearances for soft robots by means of color and shape – one design was purposively aimed at emphasizing the organic association, the other design instead an artificial rubber look. In Paper 6 it is argued that both robots triggered behaviors and discourse that positions them as social actors.

In *Beyond Digital Towards Biological* (see Appendix 10.2) soft robots were incorporated in a room-sized installation alongside other artificial life technologies. The robots were equipped with light sensors and programmed to respond with preprogrammed movements to facilitate a notion of animation and of an exchange with the central hanging robot featured in the installation. In the installation, the soft robots were juxtaposed with this more machine-like robot and minuscule moving liquid protocells in a petri dish, which served to emphasize their distinctive qualitative life-likeness on the scale of humans and animals. The green actuators in the pile of sand were additionally intended to evoke uncanniness by having shared qualities with both animals and plants.

7.3 Methodological and practical issues and benefits

A benefit of combining and applying different approaches to the same subject is that it potentially allows for a transfer of ideas, methods, and solutions between disciplinary fields that are normally separate. The research conducted in this thesis only allows me to speak on this potential benefit from my own specific inquiry into soft robot aesthetics. Hence, in the following subsections I will seek to exemplify how such transfers have occurred within the research process and discuss the possible limitations they might face based on how the thesis' research program has unfolded, taking into account the ideas and insights it has generated.

7.3.1 Practical solutions and tacit knowledge and skill transfer

As I have already noted in the paper summaries, robot morphologies and technical solutions developed have been transferred from prototypes and artworks to the interaction experiment and the swimming robot developed for the evolutionary robotics experiment. Moreover, the thesis research has also generated tools and methods for soft robotic actuator fabrication that have been published on the *Soft Robotics Toolkit* website (see Appendix 10.4). This illustrates how experimental and artistic practices, as a byproduct, can generate practical skills, knowledge, and technical solutions of use for robotics research more broadly. This, I argue, can be taken as an indication that the border separating aesthetic and technical interests is permeable, at the very least in a practical pragmatic sense in regard to soft robotics.

Aesthetic practice is often taken to involve intuitive ways of working that have been argued to be based on a tacit, informal, or embodied knowledge of materials and media gained through active experimentation (Borgdorff 2013; Schön and DeSanctis 1986). Artistic sensibilities have also been argued to be of relevance to robotics specifically by bringing to the subject a deep and subtle understanding of embodiment, materiality, and physical space (Penny 2013, 148). Yet, aesthetic approaches are perhaps even more relevant for soft robotics than other areas of robotics, as soft robots' modes of functioning are intimately tied to and derived from their materiality and the physical properties of soft elastic materials. Moreover, as I argue in Paper 1, there is precedence for more intuitive and experimental ways of approaching soft matter having aided in the discovery of seminal soft robotics technologies, including the pneu-nets actuator. As noted in Paper 2, there are also artistic traditions that have been involved in an investigation of the form generating capacities of soft matter. An aesthetic way of approaching soft matter via sensuous knowledge and intuition gains further relevance as a means of discovering new designs, as it can be considered a supplement to computer simulation techniques, which have proven difficult to apply to soft morphologies (see Paper 5).

Moreover, it is possible that aesthetic attitudes can help to discover functionalities in soft robots that are similar to those found in natural organisms. That is, a soft robot that is assessed or judged aesthetically to be similar to one or more specific natural organisms, might also possess some of the functionalities these organisms have. This notion would align with the belief in a fundamental relationship between scientific and aesthetic observation found within biological science in Romanticism, but also the argument put forth recently that artificial intelligence and artificial life research have a special relationship to art, as both can derive from "subjective resonance with nature" (Stanley 2018). Such a perspective, however, complicates a view of aesthetic judgements as guided by "purposiveness without purpose" as aesthetic practice then becomes engaged in uncovering purposeful functionalities.

In relation to the above, Paper 5 serves as an interesting example. On the one hand, the paper espouses a hierarchy that might seem at odds with any attempts to rehabilitate a role for sensuous knowledge and experimentation in soft robotics research. That is, it posits that evolutionary algorithms are superior to human observation, intuition, and trial-and-error in relation to programing an efficient swimming behavior of a knifefish-inspired soft swimming robot. Yet, the method it presents, however, relied on a soft robot that I designed by observing this biological model and by drawing on my experience of working in the medium of soft robotics. And this robot proved to be fully functional for swimming and able to swim in a way that could be shown to be quantitatively similar to the biological model.

Albeit merely more anecdotal evidence to support the perspective that aesthetic engagements with soft robotics can also lead to technical insights, it is worth mentioning here that when I conducted the workshop on soft robotics for students attending the Art&Technology program at Aalborg University, I was impressed to discover that on the second day some of the talented students were starting to discover soft robotic mechanisms that, unbeknownst to them, had been published in major scientific journals.[37] An apt example of aesthetic practice uncovering novel functionalities is also found in Michael Wihart's stuelping mechanism.

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[37] These included the 3D texture morphing technique (Pikul et al. 2017). When asked if they had seen this idea somewhere before, the students said they had not.

For aesthetic practice to fulfil a role in inventing new mechanisms that can be used more broadly it is, however, necessary for the designs to be developed with a sufficient level of technical sophistication. And that they are presented in a manner that makes them reproducible. Collaboration with technical researchers can be beneficial in attaining this.

7.3.2 Soft robot aesthetics beyond the white cube

Another way in which the thesis hypothesized that aesthetic engagements with soft robotics might become immediately relevant for robotics research is in relation to human-robot interaction. As mentioned, many of the proposed applications for soft robots entail interactions and physical contact with humans. Hence, aesthetic practices involving soft robotics might serve as a kind of basic research that explores different designs of soft morphologies and modes of interacting with soft robots, and their experiential aspects and associated meanings.

In accordance with this, the human-robot interaction experiment that I conducted was indeed influenced by the artistic work and the art historical research that preceded it. Prior to the experiment, I had constructed different tentacle designs, and I was interested in whether and how they would be perceived differently. Moreover, I had noticed the use of simulated breathing in several artworks as a simple technique to make soft robots appear animated. But also how touch was a prominent interaction modality in these works. I chose to incorporate both of the latter aspects in the design of the interaction experiment, which illustrates how ideas, interests, and knowledge produced within one discipline can be transferred and attain relevance for another. Interestingly, in fact, touch was a parameter with respect to which the interactions with the soft robots and the rigid robot diverged.

A comparison between the human-robot interactions in soft robotic artworks and in the HRI experiment also points to incongruencies between the two, which might be taken to indicate that the specific contexts and practices within which soft robots are placed can greatly influence and perhaps even determine human interactions with them. That is, in the video of *Alexitimia* (which I discuss in depth in Paper 7) what I dubbed "soft interactions" prevail – i.e. ways of touching the robot characterized by longer sequences of controlled movements that appear relaxed, gentle, and contemplative. Similar attentive, explorative ways of touching recur and figure centrally in the video documentation of *BRALL*. Even though these videos depict interactions between the robots and the artists that produced them, after watching them, I had imagined that such interactions would also be prominent in audience interactions with the artworks, and that they would perhaps also appear in the HRI experiment. Yet, in this experiment, which took place at two public events in a university library, the touches performed onto the soft robots varied a lot more – some were equally gentle, mindful, and patient but others were swift, distracted, and forceful. The interaction experiment, moreover, triggered a significant amount of discourse on possible applications and practical uses of the robots. These differences could be due to the fact that the HRI experiment and the artworks featured different soft robots. But it is likely that the differences in physical interaction are also in part generated by the contexts. That is, no setting can be claimed to be "neutral". Rather both an art gallery and a university library are spaces that come with their own codified sets of behaviors, practices, rules, spatial organizations, and attitudes (see e.g. (O'Doherty 1999)).

The above considerations raise the following issue: To what extent and under which conditions do soft robot aesthetics generalize? Or more precisely – are the qualities, capacities, and meanings of soft robotics within fields of aesthetic practice stable and generalizable to other contexts? Can knowledge gained about the aesthetics of soft robotics within the reception situation of soft robotic artworks be transferred to an HRI context or applications of soft robotics "in the wild" for that matter (and vice versa)? Is a soft robot's aesthetic agency something it holds, or is it generated in its network of relations? Even if soft robots in art and other contexts share the same physical forms and materials, the meanings they are attributed and the actions they generate appear to differ (as in the example given above). This would seem to bolster the assumption, introduced in the first chapter, that an aesthetics of soft robots must be approached in acknowledgement of its constructed and situated character and that it consequently cannot pretend towards claims of universal applicability. Yet on the other hand, the interaction experiment indicated that the material aesthetic of soft robotics influences how humans engage with and interact with the technology, and that soft and rigid robot embodiments generate different kinds of physical interaction. Moreover, it reproduced that touching plays a central role in this, as indicated in several artworks. The conclusion to draw from this seems to be that from soft robotic artworks, roboticists can gain new ideas for soft robot designs and for their interactions with humans, but only a heuristic for what human experiences, meanings, and behaviors the robots will activate.

7.3.3 RQ3: *What influence might the aesthetic qualities of soft robotics technology have on human interaction with soft robots?*

The article on the HRI experiment (Paper 6) argued against describing the aesthetic appearance of soft robots as "natural" or more "natural" than that of rigid robots. The experiment revealed no statistically significant differences in how natural nor appealing the visual, kinetic, and tactile appearances of the soft robots and the rigid robot were rated. However, the experiment indicated that the specific appearance of soft robots influences how they were perceived and physically interacted with. That is, in comparison with the rigid robot, the soft robots triggered greater variety in how people touched them. For the soft “red robot”, several participants also articulated a concern for the safety of the robot, whereas for the rigid robot, participants only expressed concern for their own safety. Taken together, this indicates that soft robotics’ aesthetic can both generate interpretations that soft robots are more fragile than rigid robots, but also that they are more durable.

Comparing the interactions with the two soft robot designs, it was observed that fewer people managed to get the “red robot” to touch them than the “blue robot”. This was attributed to the red robots’ slow movements, which might not have signaled to the interactant that the robot was moving towards the hand. Moreover, the red robot was most often said to resemble a part of an organism, the blue robot was most often said to resemble an animal body part. We argued that using this difference and tweaking the aesthetics of soft robots so that they might reveal their intended purpose would be useful in practical applications.

Even if both the soft robots and the rigid robot had very simple designs and only preprogrammed movement patterns and a rudimentary interactive behavior, this was enough to evoke significant perceptual and cognitive perspective-taking and attribution of mental states and to cause people to speak directly to them.

As noted in Paper 6, the HRI experiment provides ideas about how soft and traditional robots might differ in practice with respect to interactions with humans, and indicates that their aesthetic plays a role in this, yet further work is needed to address RQ3 satisfactorily.

7.4 Further work

7.4.1 Multiple ontologies of softness

The founding assumption of soft robotics is that softness makes certain things possible or easier to accomplish for a robot. However, a central insight that has emerged through the thesis’ transdisciplinary engagements with soft robotics is that in practice the softness of a soft robot can become active and come to matter in many different ways. The thesis papers evince that even when taken to refer to a physical property of a material, and not used as a broader concept or metaphorically, softness works in multiple ways when incorporated into a robot. That is, different versions of softness appear to be actualized within distinct contexts and under specific circumstances, with varying consequences and potentials for how a robot might enter into contact with matter and materials, objects, processes, practices, human bodies, and cultural imaginaries. In an HRI experiment, for instance, softness in a robot can become an affordance for specific types of tactile interaction. In an artwork, it might instead serve as an element in constructing an aesthetic of bio-morphic movement or abet "soft interactions" and impressions of vulnerability or feelings of empathy. In a swimming robot, softness may equally become a means to increase energy efficiency or enable an integration of actuation, control, and computation.

Bearing this in mind, an important question for future research on soft robots to engage with is thus how to make sense of and take into account the different effects that the softness of a soft robot can have. And the task remains to develop a theoretical framework that can adequately describe how different materialities and agencies of soft robots are able to manifest themselves within and beyond the contexts of art and technical research. In Paper 7, I sought to initiate this work by drawing on the theoretical tradition of ANT that takes a view of reality as something that is more than merely physical at its core. It sees reality as something that is constructed in the interplay between human and non-human actors and is emergent from these interactions. Ontology is thus transposed from dealing with the question of what there is to instead dealing with "how things exist", as the ontologies of objects, such as soft robots, are not stable but enacted in contingent more-than-human practices.[38] Within ANT theorizing, the agency of a soft robot, its capacity to act in a given environment, is thus not seen as an essential attribute but a relational network effect. Within new materialism, this perspective is shared by some theorists, whereas others instead view agency as something that materials or objects themselves hold (Colman 2018).[39] As noted in Paper 7, a related way of thinking soft robotic agency, is also found in Isabelle Stengers' notion of approaching things in terms of their "force". By force, Stengers refers to what things "are able to do in particular well-defined circumstances" (Stengers 2005, 190), and as she points out,

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[38] In relation to this perspective and the thesis' subject it should be mentioned that artist Louis-Philippe Demers' PhD thesis on robotic performers is entitled "Machine Performers: Agents in a Multiple Ontological State". Yet the concept of ontology applied by Demers and his argument diverges from the one presented here. For Demers the multiple ontological state refers to how such robots in a performance are characterized by "oscillations between human and machine, animate and animated, subject and object" (Demers 2014, 109).

[39] There is, however, also several different concepts of agency within new materialism (Colman 2018).

> […] experimental science and technology cannot succeed without increasing or heightening what they address, without producing situations where what they address becomes able to do what it could not do in the usual circumstances. (Stengers 2005, 190)

As is evident from the examples given above the force of soft robotics, however, encompasses capacities that are not restricted to mechanical functioning. Hence, these cannot be uncovered by natural science and engineering methods alone. Adopting a performative ontological view of reality may thus serve as an aid to conceptualizing softness beyond Young's modulus and accounting for a much wider set of capacities of soft matter and soft robotics.

7.4.2 'Soft robot studies' – notes on future methodologies for soft robots

The perspective on soft robots outlined above implies that soft robotics is in need of theories that acknowledge and take into account the different effects that softness in a robot can have. In order to fully unfold the potential and engage with the consequences of rendering a robot soft, a transdisciplinary perspective on softness is needed. As noted in the introduction, robots already inhabit numerous contexts and different sites where they are embedded in divergent practices, and soft robotics is imagined to further expand their range of uses (Verl et al. 2015; Rus and Tolley 2015). Hence, at present in addition to more encompassing, adequate, and nuanced theoretical accounts of softness and soft robots, there is an urgent need for accompanying methods and methodologies for implementing and expanding such theorizing in practice.

Inspiration for constructing such methodologies may be found in STS approaches such as those that influenced Paper 7. Yet, STS researchers have traditionally not taken part in constructing artefacts, except as a part of ethnographic fieldwork aimed at generating descriptive, analytical, and theoretical insights or within action-research practices aimed at facilitating change or solving particular problems.[40] The visual arts tradition, on the other hand, has historically always engaged with physical construction and physical materials and their agency. Moreover, in Paper 7 I argue that art methodologies constitute more modest ways of approaching soft matter, not with an ambition of gaining complete control nor a universal and secure knowledge about it, but accepting the unknowability of its physicality. Art practices pay attention to the singular, not just the general,

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[40] At present there is, however, an emerging interest in incorporating art and design into STS (Salter, Burri, and Dumit 2016).

and accept to remain with ambiguities and conditions of not-knowing for an extended period (Borgdorff 2010, 2013). Aesthetic and artistic research practices can thus add a more wholistic view of reality as not just physical but performative and emergent, and additionally provide a means to explore and invent reality through material practice.

In Section 4.4, I have tried to condense the strategies that have been developed through the thesis' attempt to address soft robot aesthetics from an expanded perspective. The approach the strategies constitute is experimental, yet it is still pragmatic, in the sense that it considers the practical effects of softness as a physical property of an object.[41]

Art and aesthetics, in some of their contemporary theorizations, also add ethics and politics to soft robotics – two subjects that also figure prominently within new materialist theorizing. However, I have exclusively addressed this explicitly in Paper 7. Hence, I leave it for further work to provide more in-depth reflections on how to articulate politics and ethics in relation to soft robotics and how to negotiate them in practice.

7.4.3 The relevance of soft robotics as an artistic medium

The augmentation of soft robotics effectuated by conjoining it with art and aesthetics encompasses singular aesthetic processes and experiences that emerge around a soft robotic artwork. These are by nature irreducible to language and can only be approximated in a text. Moreover, they constitute the ultimate answer to a question that the thesis did not pose, but which I hope it has contributed to answering indirectly, namely: Why should art and aesthetics interest themselves with soft robotics? Or – in which ways might soft robotics augment art?

A possible way to approach this question more directly is by asking if soft robotic art might extend existing routes of artistic inquiry or recombine them in novel ways? In Paper 2, I notice that soft robotics share with postminimalist soft sculpture an interest in attaining reciprocity between form and material, and probing of how physical properties can engender specific organizations, forms, and behaviors that are inherent to soft matter. But as an artistic medium, soft robotics connects with numerous other art historical currents where softness figures as a central aesthetic interest – Biomorphic Abstraction, Surrealism, Romanticism, inflatables and pneus, the late-Gothic "soft style", wax sculpture, studies of soft materials in paintings (e.g. folds in fabric in renaissance paintings), and *morbidezza* in 17th century painting and sculpture. Moreover, an aesthetic of

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[41] By experimental I here refer to an understanding of "to experiment" as "to try new actions, methods, techniques and combinations, 'without aim or end'" (Baugh 2010, 93).

softness activates certain broader cultural meanings. Within Western culture, soft is a stereotypically feminine characteristic (Hamilton, Whitehouse, and Wright 2007, 152) as epitomized in poet Alexander Pope's denigrating description of women as "Matter too soft" (Pope 1743). Hence, art critics have also frequently described women's paintings as "soft", "delicate", and "weak" and contrasted them with the "virile" and "strong" paintings made by men (Kramarae and Spender 2004, 873). In the late 1960s and early 1970s, this cultural meaning of softness was even explicitly critically reworked within feminist soft sculpture (Fields 2007, 358). Recently a few initiatives have thus sought to engage with art history through softness, e.g. the collection of essays *La dynamique du mou* (Cadaureille and Viguier 2017) and the seminar held in 2018 at Institut National d'Histoire de l'Art (Paris) on "Le Mou".[42]

The art historical, art historiographical, and gender political implications and valuations of softness are testimony to how softness can become a potent theme of critical artmaking beyond its immediate phenomenological interest. As an artistic material or medium soft robotics holds a potential for reworking and working with the qualities, associations, and meanings of softness in novel creative ways, e.g. by updating them via establishing a connection to robotics and AI software, both of which are currently subjects of increasing societal interest. More narrowly, soft robotic art might also bridge the historical tradition of robotic art and the more recently emerged field of *bio-art* that works with soft organic tissue and often concerns itself with issues related to the borders of life and what is deemed to be life-like.

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[42] See https://arthist.net/archive/17630 (Accessed May 14 2019).

8 Closing remarks

Art can bring new meanings to a subject, create new meanings, but it can also create a subject, or an object, anew. This thesis has explored alternative versions of what soft robotics might be or may potentially become if approached from the point of view of art and aesthetics. I have sought to describe, demonstrate, and propose how art and aesthetics might augment soft robotics as it currently exists, and by adding to it, gradually and reflexively alter its constitution.

The thesis publications have contributed to the fields of media art history, artistic research, evolutionary robotics, and HRI. Hence, even if the thesis overall has attempted to take a transdisciplinary view of soft robot aesthetics, the thesis papers have followed certain conventions and perspectives that are constitutive of these respective academic fields in order for publication to occur. This, of course, involves a compromise in relation to what form the research and its presentation and dissemination can take. But it also provides the possibility for conversations across disciplinary boundaries to happen that might have an effect. My engagements with soft robotics have thus involved a conscious decision of becoming soft or elastic: Being receptive and yielding, yet able to recover, flexible and not anchored in just one mode of thought or discipline. The ambition has been to push at the boundaries of different fields, to reform, not to revolutionize. Again – the research problem was how aesthetics and art might augment, and not simply supplant, soft robotics. If the endeavor has occasionally been critical, it has sought to avoid traditional critical revelatory gestures and direct opposition, in favor of an affirmative mode of critique – in other words by being constructive, i.e. seeking to think and invent things differently from how they are currently.

The thesis has demonstrated a potential for soft robotics to become even more interdisciplinary than it already is, perhaps even transdisciplinary. Yet it has pointed out, that for the latter to occur, it is necessary to cultivate a sensibility towards softness in a robot as something that can take multiple manifestations and that may differ within different practices and contexts.

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10 Appendices

10.1 Artwork: *The Condition* (2015-16)

The artwork *The Condition* was initiated together with Laura Beloff before I started as a PhD fellow and work on it continued into the first half year of my enrolment. Even if not employing any soft robotics technology, some of the work's interests and themes resonate with the practice-based work included in the thesis.

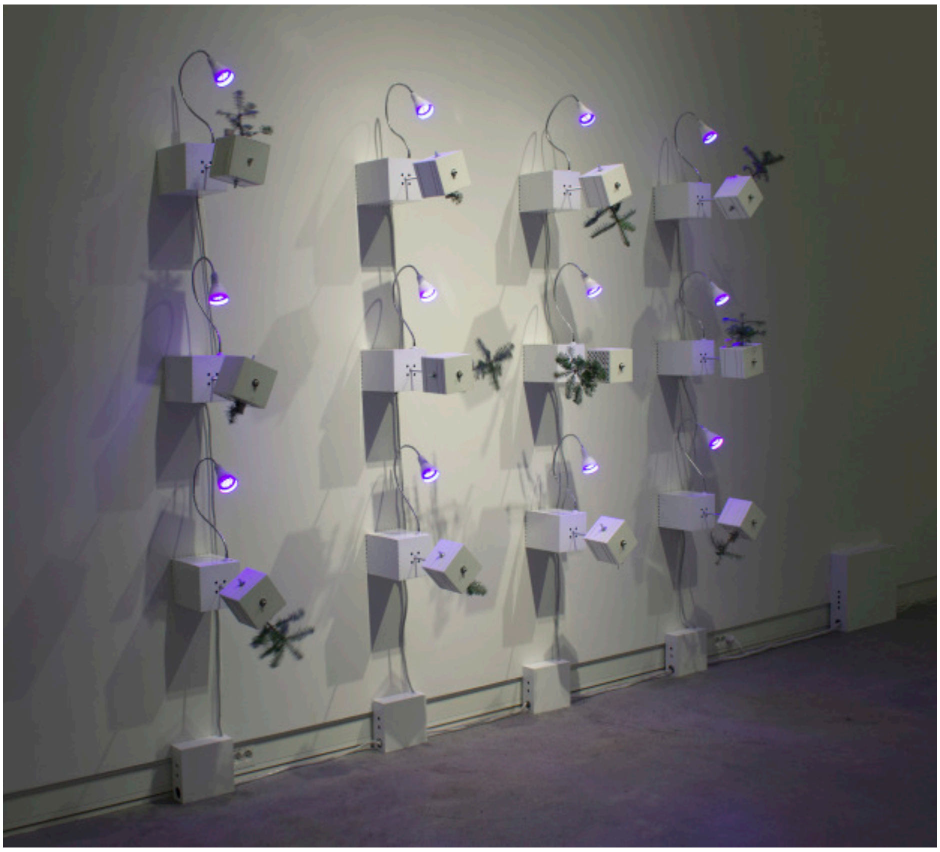

Fig. 20. Laura Beloff & Jonas Jørgensen, *The Condition* (2015-16), mixed media (acrylic boxes, mechatronics, plant lights, plants, networked laptop computer). Installation view at Kunsthall Grenland 2016. Photo: Laura Beloff

Description of the artwork:

> *'The Condition' interrogates the status of organisms in hybrid conditions that result from the entwinement of technological, economic, biological, and cultural factors. The installation consists of twelve rotation boxes that each house a small cloned Christmas*

> *tree. The rotation is governed by a self-organizing map algorithm that takes space weather measurements from a NASA satellite as its input. Plant researchers have shown that when trees are rotating, a micro-gravity condition similar to outer space is produced. The work asks what types of organisms will survive in changing environmental conditions? It ironically questions if a Western cultural icon, the Christmas tree, might endure such changes.*
>
> *The cloned trees used for the installation are of the species Abies Nordmanniana, which has become the preferred Christmas tree for many Europeans. It has gained success through its suitability for growing in the Northern climate and become the economically most important species in Danish forestry, with 10 million trees produced annually. Currently, this species is also being developed through cloning to yield a mass production of trees that all share the same genetic code that produces trees consumers find aesthetically pleasing.*
>
> *'The Condition' explores the adaptability of organisms to changed living conditions, and the messy web of hybrid agencies that emerge when a culturally and technically defined biological species is further embedded in an infrastructure consisting of robotics, AI, and information technology. As the artists behind this work, we have created an artificial environment for a small forest of trees, and in a way continued the process put forward by industry and science when the species was brought from Caucasus to the Danish fields, and, more recently, when cloning methods for a profitable mono-culture production were envisioned. The experiment points towards a present and future that is forming at the intersection of technological and biological evolution and human intervention.*

The work has been exhibited at: Kunsthall Grenland (Porsgrunn, Norway), Nikolaj Kunsthal (Copenhagen, Denmark), Forum Box (Helsinki, Finland), Science Gallery Dublin.

It was recommended for the STARTS Prize 2018 (Grand prize of the European Commission honoring Innovation in Technology, Industry and Society stimulated by the Arts) by one of the award advisors.

The work is described in more detail in:

> Laura Beloff & Jonas Jørgensen "The Condition. Towards Hybrid Agency" in: *ISEA 2016 Hong Kong CULTURAL R>EVOLUTION: Proceedings of the 22nd International Symposium on Electronic Art*. School of Creative Media, City University of Hong Kong, p. 14-19. (ISEA 2016 Proceedings).

Video documentation is available at: https://youtu.be/rufoum6uqmo and https://youtu.be/mWYCfHs19NI

10.2 Artwork: *Beyond Digital Towards Biological (2017)*

During a research residency at Chronus Art Center (Shanghai) funded by *The Danish Agency for Science, Technology and Innovation*, I produced a collaborative installation together with Laura Beloff, Stig Anton Nielsen, David Kadish, and Stavros Didakis. The installation was exhibited at Chronus Art Center in December 2017.

The initial project description for the work (authored by myself and Beloff) reads as follows:

> *The installation constitutes a hybrid ecology or proto-environment, and explores the boundaries between different concepts of life – from artificial chemical life, to biological life, and computational life in silico. Hanging robots deliver fluids that initiate or nurture artificial chemical life-processes in a dialogue with soft robotic elements that embody life-like qualities on the scale of humans and animals and intermingle with plant life. Our research practice seeks to question different taxonomies of life, both artificial and natural. Through the installation we enable conditions for a wide spectrum of life-forms to assemble into novel configurations with unique and emergent dynamics.*

The installation incorporated three groups of soft robots:

1. A translucent tentacle lying on a plinth covered in black fabric
2. A glass cylinder filled with water containing two actuated silicone arms, and two donut-shaped vaporizers that emit fog and green light
3. A number of green pneu-nets and bladder actuators lying in a pile of sand

The three groups of soft robots all have light sensors embedded, and respond to light with movement. The hanging robot, which is the central element of the installation, shines a light on them to interact with them.

An edited video documenting the installation is available online at: https://youtu.be/UX3swR57zUo

Fig. 21. *Beyond Digital Towards Biological* (2017). Overview of the installation. Left (top): The encasing containing the petri dish with chemicals. Left (bottom): The analogue projection of the petri dish. Middle: Two groups of soft robots. Top: the computer visualization generated from footage of the petri dish and the hanging robot. The third group of soft robots is not included in the photo.

Fig. 22. *Beyond Digital Towards Biological* (2017). The soft tentacle.

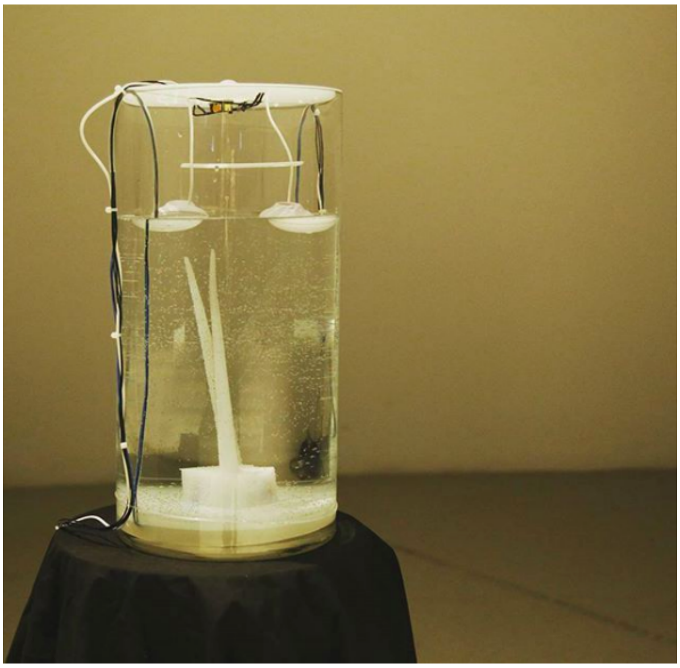

Fig. 23. *Beyond Digital Towards Biological* (2017). The glass cylinder with the two soft arms cast onto the bottom and two floating vaporizers.

Fig. 24. *Beyond Digital Towards Biological* (2017). Left: Visitors watch as the hanging robot interacts with the group of earthbound green soft actuators. Right: close-up showing the green soft actuators in the pile of sand (the microcontroller, pumps, valves, and light sensor were hidden inside the pile).

10.3 Workshop descriptions

I was invited to conduct workshops on soft robotics on a number of occasions.[43] The three workshops that I conducted were aimed at different audiences and had different durations and foci. In relation to the research process they provided an opportunity to experience how people from different backgrounds might approach and take an interest in soft robotics and they helped generate ideas about how the aesthetic of soft robotics can be experienced.

Below I have included brief information on each of the three workshops and their official descriptions.

10.3.1 *Soft Robotics Workshop* (Pixelache festival, Sept. 24-25 2016)

The workshop was conducted together with Frank Veenstra, at the annual *Pixelache* festival for electronic art and subcultures in Helsinki, Finland. It had a duration of two full days and was mainly attended by art students and professional artists.

Fig. 25. Photos from the workshop.

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[43] I was able to accept three of these invitations and had to decline others that did not fit my schedule, including from Interactive Architecture Lab at Bartlett and *Hiperorgânicos 8* symposium in Rio de Janeiro.

Workshop description:

> *Soft robotics is a growing field of research wherein soft and compliant materials replace some or all of the traditional rigid parts conventionally used in robotics. The soft parts can engender properties such as elasticity, full body actuation and delicate object handling which can be beneficial for many different applications. Soft structures can also give robots a more biological appearance and are generally safer in robot human interactions. Materials such as silicone rubbers, for instance, allow movements to become more fluid and "naturally" expressive. A soft surface is also reminiscent of human and animal skin, which some researchers have claimed allows for a higher degree of identification with and feelings of empathy toward robots.*
>
> *Soft robotics has become a field of enquiry for possible applications within areas as diverse as eldercare, prostheses, surgery, rescue operations, and wearable technology. More recently, soft robotics has also been gaining attention from architects, designers and artists. Certain challenges and difficulties, however, emanate when considering the manufacturing processes as well as the rapid prototyping solutions that can be used to produce soft morphologies.*
>
> *In this workshop participants will get a broad introduction to the field of soft robotics. Through hands on practice-based inquiry participants will become acquainted with a number of selected methods for a simple production and control of soft morphologies.*
>
> *The first day of the workshop will focus on the production of basic soft robotic parts and morphologies. An introduction will be given to different types of soft actuators and their usages as part of robot morphologies (PneuNets, tentacles, grippers etc.). A workflow is introduced wherein 3d computer modeling leads to 3d printed molds which are then used with a lost wax casting procedure to yield robot parts in Ecoflex silicone.*
>
> *The second day focuses on the final assembly of the soft robots and different ways of controlling them with pneumatics. We will be using syringes as basic pumps and experimenting with using an Arduino microcontroller to control electrical pumps to generate more complex movement patterns (e.g. gait) and to have the robots respond interactively to sensor readings.*
>
> *Participants are expected to bring their own laptop with Arduino IDE installed (can be downloaded from https://www.arduino.cc/en/Main/Software).*
> *The workshop is open for all interested - prior experience working with robotics, Arduino or 3d modeling is not needed to participate.*
> *Time of the workshop:*
> *24.5. at 10 - 14*
> *25.9. at 10 - 14*

Video documentation of the workshop is available at: https://youtu.be/5gUWRf1ztrA

10.3.2 *Enacting and Encountering Soft Robots* (ICRA 2018, May 24 2018)

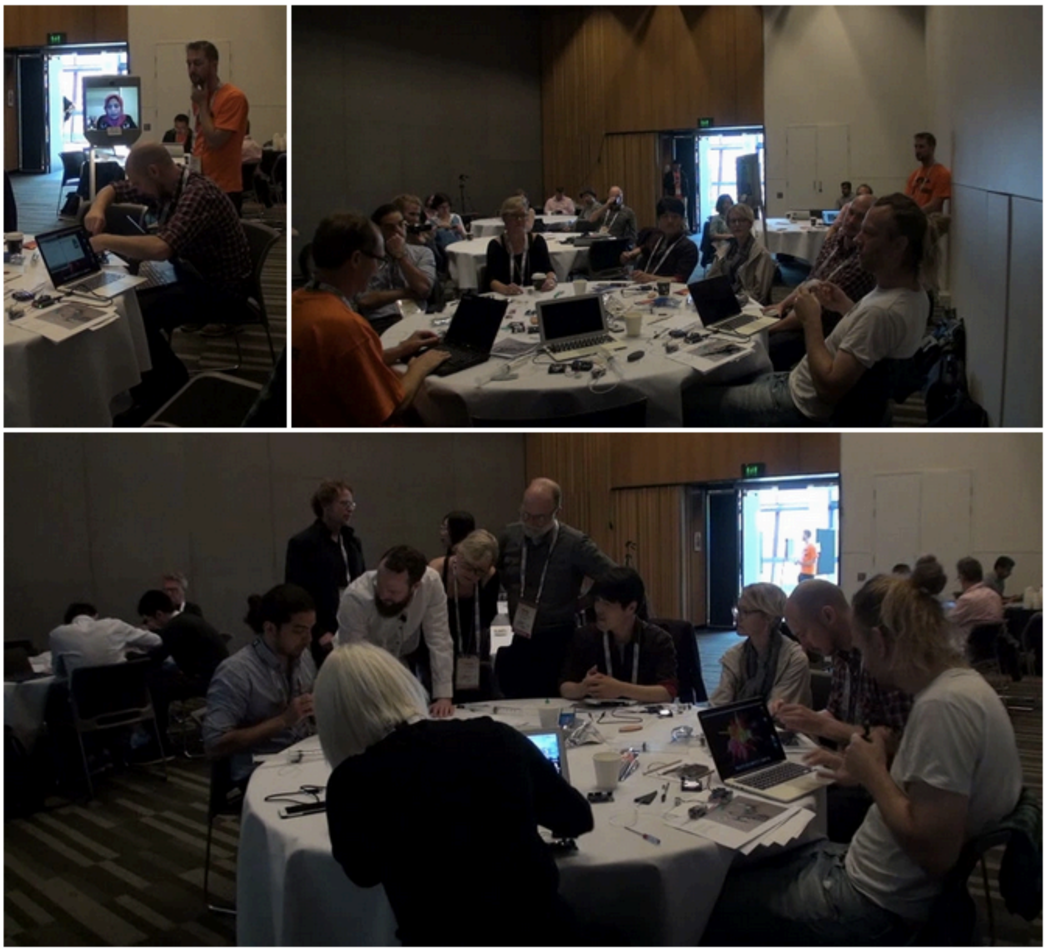


Fig. 26. Photos from the workshop.

The second workshop was conducted at the “Robot Art” Forum at ICRA (International Conference on Robotics and Automation) 2018 in Brisbane, Australia. It had a duration of two hours. It was mainly attended by robotics professionals and invited artists with a background in robotic art including Ken Goldberg, Patrick Tresset, Ingrid Bachmann, and Nathan John Thompson.

Original workshop description:

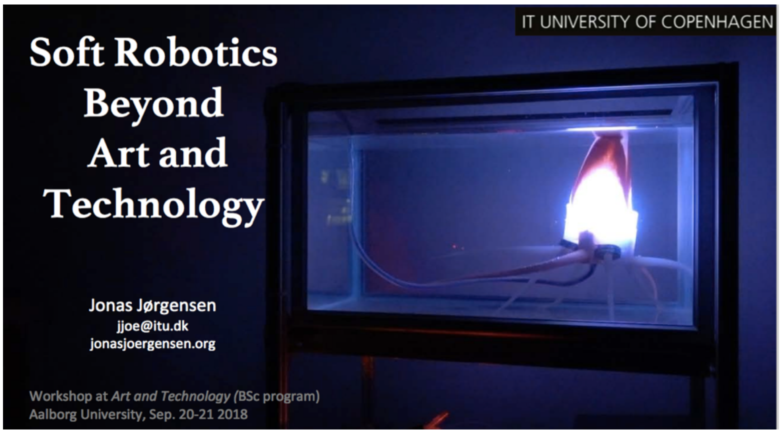
> *In this workshop participants will explore the affordances of softness in a robot through collective practice-based inquiry and reflection on practice.*
> *The workshop introduces basic soft robotic components and their fabrication including different types of silicone-based pneumatic actuators and discusses their possible uses as parts of robot morphologies. We will be using syringes as manual pumps for*

actuation but also control electrical pumps and solenoid valves with an Arduino microcontroller to generate more complex movement and make our soft robots respond interactively to sensor readings.

The workshop is set up as a collective hands-on experimental knowledge production which centers on the basic epistemological question of how to grasp and think about softness in a robot. We will reflect on soft robots as relational and processual objects and draw on technical as well as cultural and artistic interpretations of softness as a concept and phenomenon. With the ambition of cultivating an ecology of practices that spans the natural and technical sciences as well as speculative and experiential philosophical and artistic perspectives, the workshop explores not what softness is, but what softness can do.

10.3.3 *Soft Robotics Beyond Art and Technology* (Aalborg University, Sept. 20-21 2018)

The third workshop was part of a course for fifth semester students in the *Art&Technology* BSc program at Aalborg University, where I was brought in as an external lecturer. It had a duration of two full days (8 hours each) and was an extended version of the ICRA workshop. Following the workshop, the students had to finish the projects they had started on their own and submit them as a part of their exam.



IT UNIVERSITY OF COPENHAGEN

Soft Robotics Beyond Art and Technology

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Workshop at *Art and Technology* (BSc program)
Aalborg University, Sep. 20-21 2018

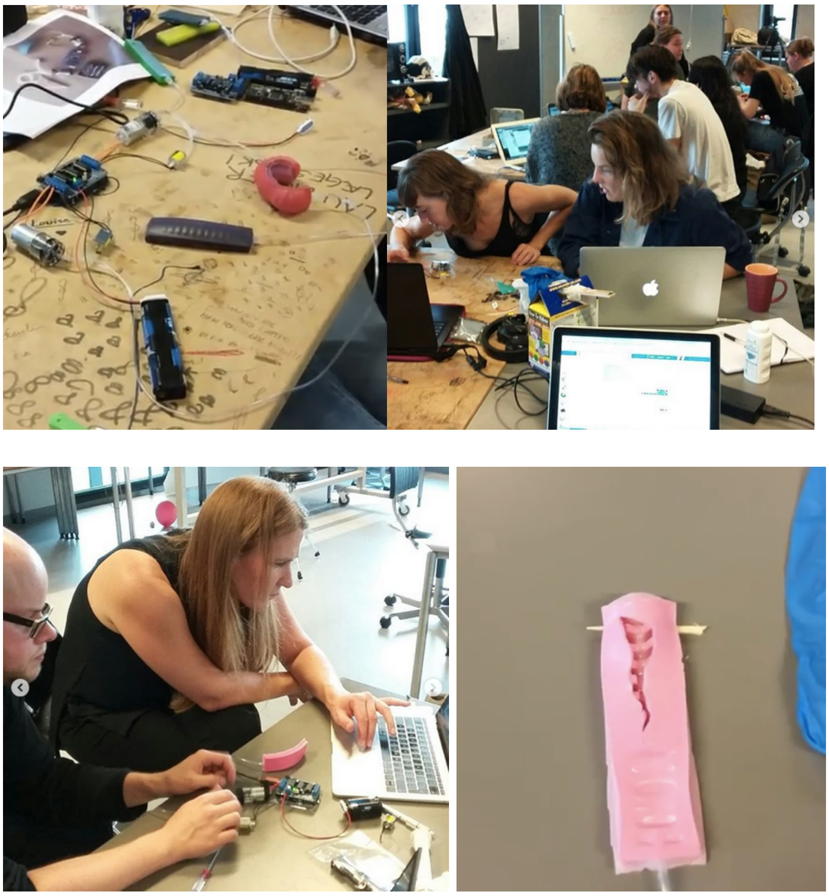
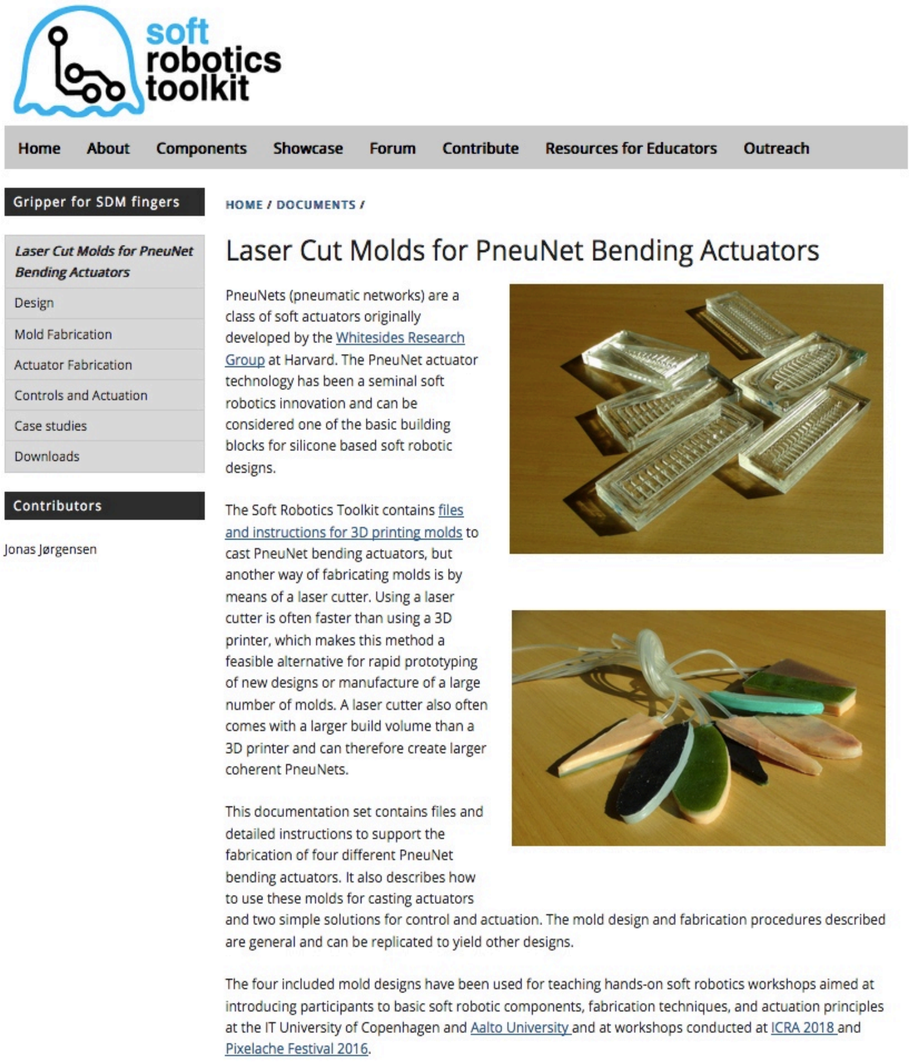


Fig. 27. Photos from the workshop.

10.4 Educational publications

For the three workshops I developed techniques and tools to easily fabricate different pneu-nets type actuators. I subsequently refined the materials and documented how to use them in images, video, and text and submitted two instruction sets to the *Soft Robotics Toolkit*. The *Soft Robotics Toolkit* is a peer-reviewed educational website maintained by Harvard researchers aimed at providing accessible introductory knowledge about soft robotics to a wide audience. Descriptions of the two instruction sets and links can be found below.

10.4.1 Laser Cut Molds for PneuNet Bending Actuators



Laser Cut Molds for PneuNet Bending Actuators

PneuNets (pneumatic networks) are a class of soft actuators originally developed by the Whitesides Research Group at Harvard. The PneuNet actuator technology has been a seminal soft robotics innovation and can be considered one of the basic building blocks for silicone based soft robotic designs.

The Soft Robotics Toolkit contains files and instructions for 3D printing molds to cast PneuNet bending actuators, but another way of fabricating molds is by means of a laser cutter. Using a laser cutter is often faster than using a 3D printer, which makes this method a feasible alternative for rapid prototyping of new designs or manufacture of a large number of molds. A laser cutter also often comes with a larger build volume than a 3D printer and can therefore create larger coherent PneuNets.

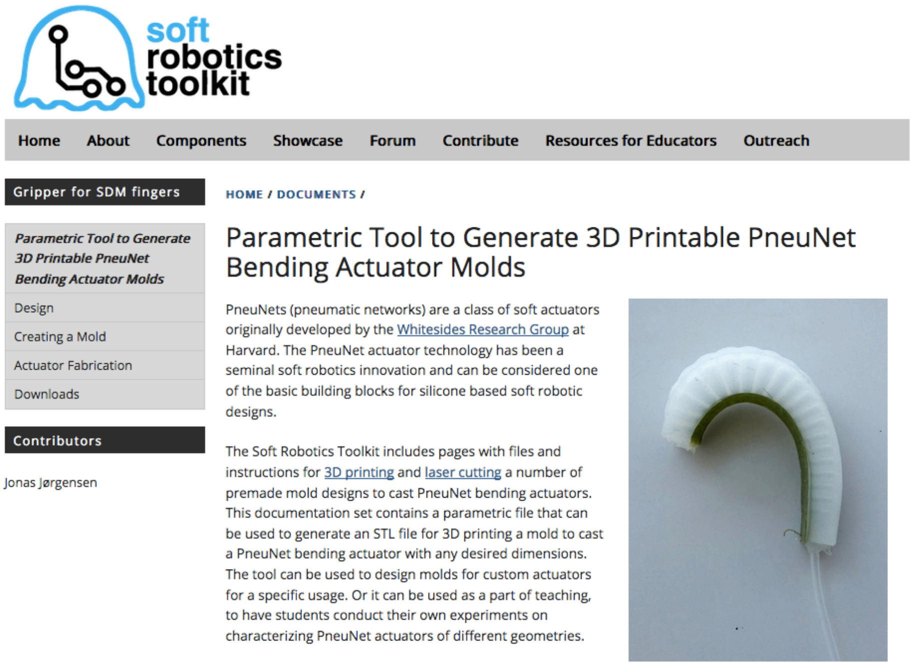
This documentation set contains files and detailed instructions to support the fabrication of four different PneuNet bending actuators. It also describes how to use these molds for casting actuators and two simple solutions for control and actuation. The mold design and fabrication procedures described are general and can be replicated to yield other designs.

The four included mold designs have been used for teaching hands-on soft robotics workshops aimed at introducing participants to basic soft robotic components, fabrication techniques, and actuation principles at the IT University of Copenhagen and Aalto University and at workshops conducted at ICRA 2018 and Pixelache Festival 2016.

Fig. 28. Screenshot of the instruction set webpage.

The instruction set is available online at: https://softroboticstoolkit.com/laser-cut-molds

10.4.2 *Parametric Tool to Generate 3D Printable PneuNet Bending Actuator Molds*



Parametric Tool to Generate 3D Printable PneuNet Bending Actuator Molds

PneuNets (pneumatic networks) are a class of soft actuators originally developed by the Whitesides Research Group at Harvard. The PneuNet actuator technology has been a seminal soft robotics innovation and can be considered one of the basic building blocks for silicone based soft robotic designs.

The Soft Robotics Toolkit includes pages with files and instructions for 3D printing and laser cutting a number of premade mold designs to cast PneuNet bending actuators. This documentation set contains a parametric file that can be used to generate an STL file for 3D printing a mold to cast a PneuNet bending actuator with any desired dimensions. The tool can be used to design molds for custom actuators for a specific usage. Or it can be used as a part of teaching, to have students conduct their own experiments on characterizing PneuNet actuators of different geometries.

Fig. 29. Screenshot of the instruction set webpage.

The instruction set is available online at: https://softroboticstoolkit.com/parametric-tool-3d-printed-molds

10.5 Documentation of fabrication processes

10.5.1 Design and fabrication of the soft tentacles

After having fabricated my first soft robotic tentacle (the “red robot” in Paper 6) by following a published tutorial, I began to think of easier ways of fabricating a tentacle. Casting the tentacle had involved a lot a laborious steps, as jeweler’s wax was used to create the inner compartments.[44] I conceived a solution where no wax was needed. Instead, a 3D printed inner mold part is used that can be pulled out to create the tentacle’s three internal air compartments.

The mold that implemented this technique was used for casting the two robots of the *Phytomatonic* series, the “blue robot” used in the HRI experiment, and the translucent tentacle featured in the *Beyond Digital Towards Biological* installation. Below the process of how to fabricate a tentacle with the mold is documented and described.

The mold parts for casting the tentacle were modeled in OpenSCAD a geometric CAD software program. The modeling was done by parametric programming. This means that the dimensions of the tentacle can be altered (e.g. maximum- and minimum-diameter, length etc.) by changing the variables listed in the file. And that files to 3D print different molds can be output.[45]

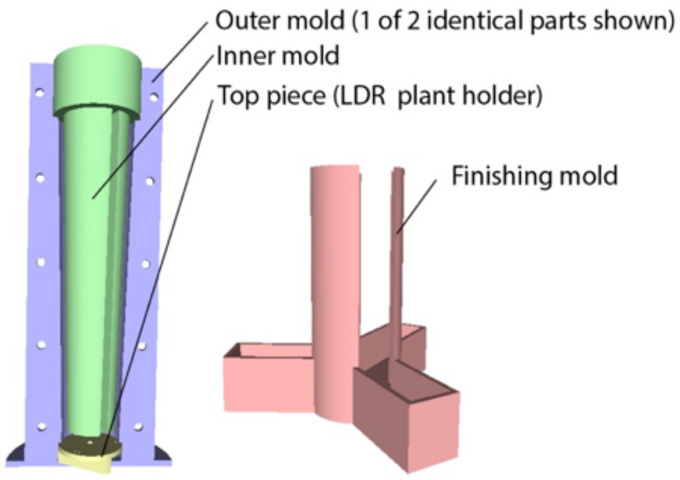


Fig. 30. The mold parts.

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[44] The fabrication process included: 3D printing the mold parts, casting a new mold in silicone from the 3D prints, casting wax parts in this mold, assembling the wax parts by cutting and melting them to fit, inserting the wax parts into another mold, casting the tentacle, and finally getting the wax back out of the tentacle by heating and squeezing it and pouring boiling water inside it.

[45] A GitHub repository containing the OpenSCAD code can be found on: https://github.com/JonasJoergensen/Robots-and-Artificial-Life---extended-project- . This OpenSCAD code was also used to generate the mold for casting the upper body of the cephalopod robot featured in *Tales of C* by changing the dimensions.

The CAD modeled parts were exported as STL files and printed in PLA on an Ultimaker 2 Extended 3D printer. The remainder of the production process is shown below in Fig. 31, Fig. 32, and Fig. 33 with the *Phytomatonic 01* tentacle as example. The production process was similar for the other tentacles cast, except that the “Top piece” was replaced with a solid disc and a round “Finishing mold” was used instead.

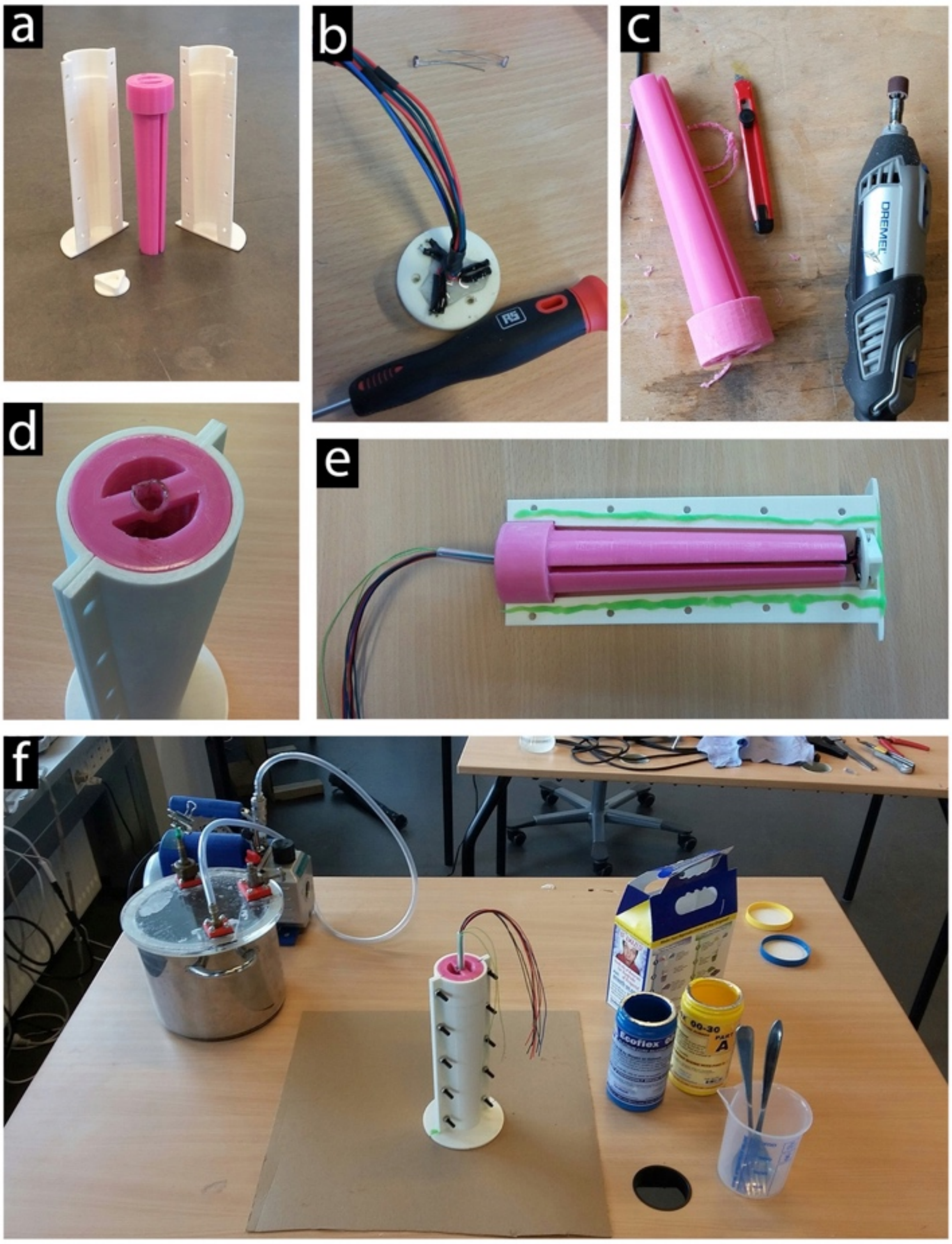

Fig. 31. Preparations for the casting.

Fig. 31 shows the pre-casting process. The outer mold and inner mold parts (a) were brushed with a thin layer of liquefied Vaseline. For *Phytomatonic 01*, the rigid top part was fitted with three light sensors and wires and a layer of epoxy glue was added to attach the wires to the “Top piece” (b). Due to printer inaccuracies, some small corrections had to be made with a Dremel tool and an x-acto knife for the mold parts to fit together snugly (c-d). In next step, a thin layer of (green) Play-Doh was applied to the edges of the mold to seal the contact zones between the two outer molds (to make sure the mold would not leak the liquid silicone) (e). Finally Ecoflex 00-30 was mixed with silicone color and degassed in DIY vacuum chamber (f) to get rid of air bubbles, before it was gently poured through the holes at the top of the inner mold and into the bottom of the finishing mold (Fig. 32a). After 24 hours of curing at room temperature the demolding and bonding of the bottom and top part can be performed as shown below in Fig. 32.

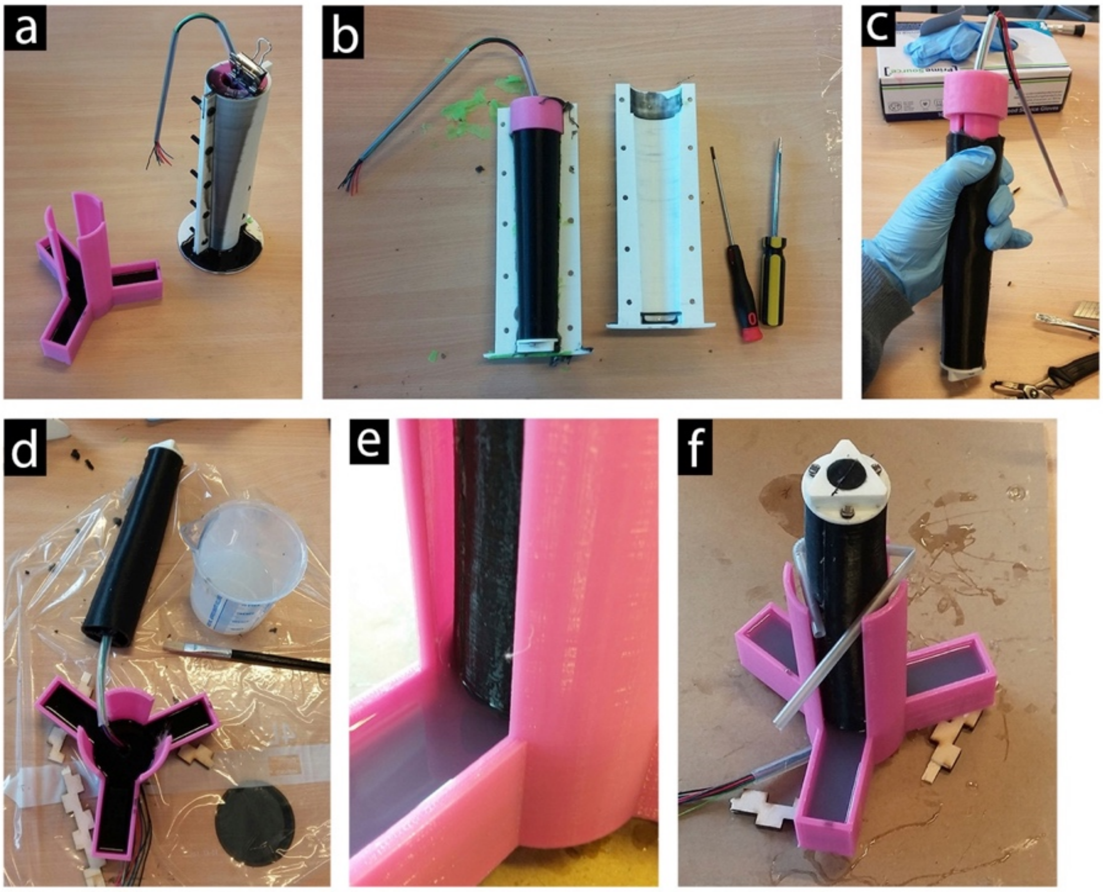

Fig. 32. Molding the tentacle.

The screws are loosened and two outer mold parts are pried apart gently using screw drivers (b). The inner mold is pulled out of the tentacle (c). Liquid Ecoflex is brushed on the contact surfaces between the tentacle and the bottom part that has been cast in the finishing mold (d). A layer of Ecoflex is poured into the finishing mold and the tentacle is placed standing upright in the finishing mold. A bit of air is pushed out of it so that some uncured Ecoflex is sucked inside it, to increase the size of the bonding surface between the two (e-f).

After 24 hours, the tentacle is removed from the "Finishing mold" (Fig. 33a).

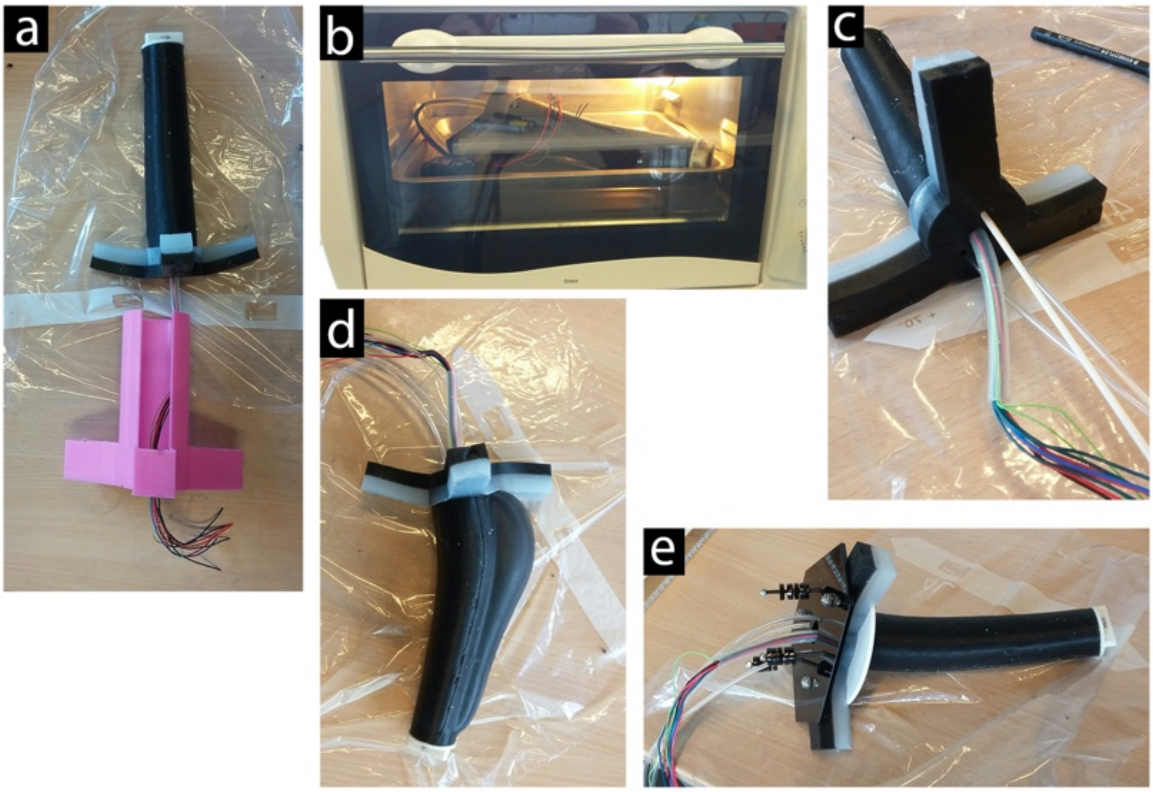

Fig. 33. Finishing the tentacle.

If the silicone at the contact surfaces between the bottom and top parts is not fully cured, the cast is put in a toaster oven at 75 degrees Celsius for an hour (Fig. 33b) to speed up the curing process. After this, holes are poked from the bottom into the three separate air chambers using a bamboo skewer (c) and PVC tubes are inserted into the holes. The tentacle is inflated to test that the three internal chambers are airtight (d) and the PVC tubes are then glued in place with Sil-Poxy glue.

10.5.2 Fiber reinforcing the tentacle

For the “blue robot” used in the HRI experiment, fiber reinforcements were added to the tentacle to prevent radial expansion. This was done as described below.

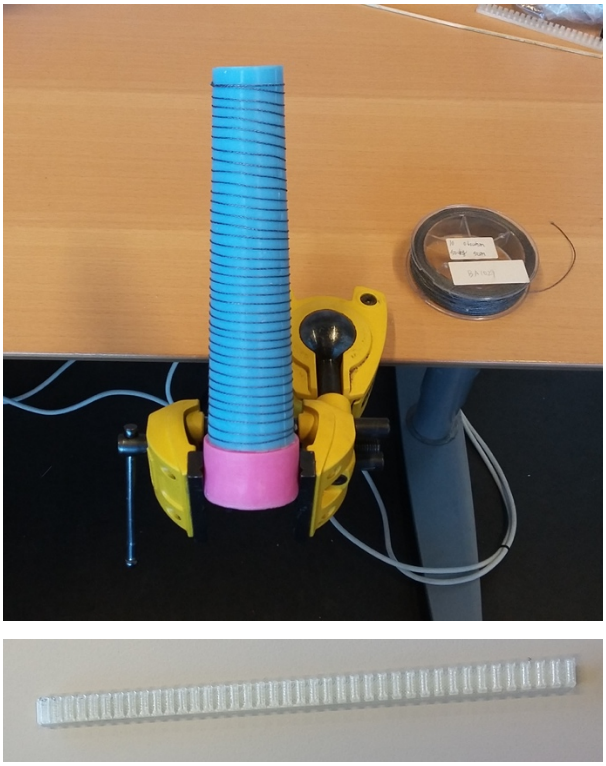

Fig. 34. After the tentacle with the inner mold has been removed from the outer mold, the end of the inner mold is fixed in a clamp. Braided fishing line is wrapped around the tentacle from the bottom. A 3d printed guide with equidistant ridges (lower image) is used to position the windings with an equal distance to each other. The fishing line is secured at the top with a knot and epoxy glue.

Fig. 35. The fishing line is wound around the tentacle from the top to the bottom in the opposite direction of before and fixed with a knot and epoxy glue at the bottom. The overlaps between the windings are aligned to be vertically parallel on opposite sides of the tentacle, and the distance between the windings adjusted with the 3D printed guide.

Fig. 36. Two mixing sticks and rubber bands are attached around the inner mold as shown, in order to lift the tentacle slightly to make room for an extra layer of silicone in the mold. The outer mold is filled with liquid Ecoflex up to about a third full and the tentacle and inner mold is inserted.

Fig. 37. After 24 hours of curing, the tentacle can be removed from the mold and the bottom and tubes can be attached.

10.6 Documentation of additional prototypes

As a part of my research a lot of time went into exploratory prototyping and trying out different techniques and ideas for building soft robots. Below I have assembled documentation and short descriptions of four promising groups of prototypes that were not developed further nor included in the thesis publications.

10.6.1 Posthumanoid series

People often imagine robots as either humanoids or as large industrial machines. Researching casting techniques, I found the mold making material alginate. It comes as a powder to be mixed with water and cures in approx. 15 min. I used alginate to quickly cast molds from my own arms, hands, and toes. With the alginate molds I then cast silicone replicas of these body parts.

I planned to assemble the parts into a kind of posthumanoid robot morphologies, constructed from repurposed human body parts, e.g. the four-legged walker made from five fingertips, an elbow, and the upper side of a hand, shown top left in Fig. 38. The morphologies would be actuated with servo motors attached to the sticks.

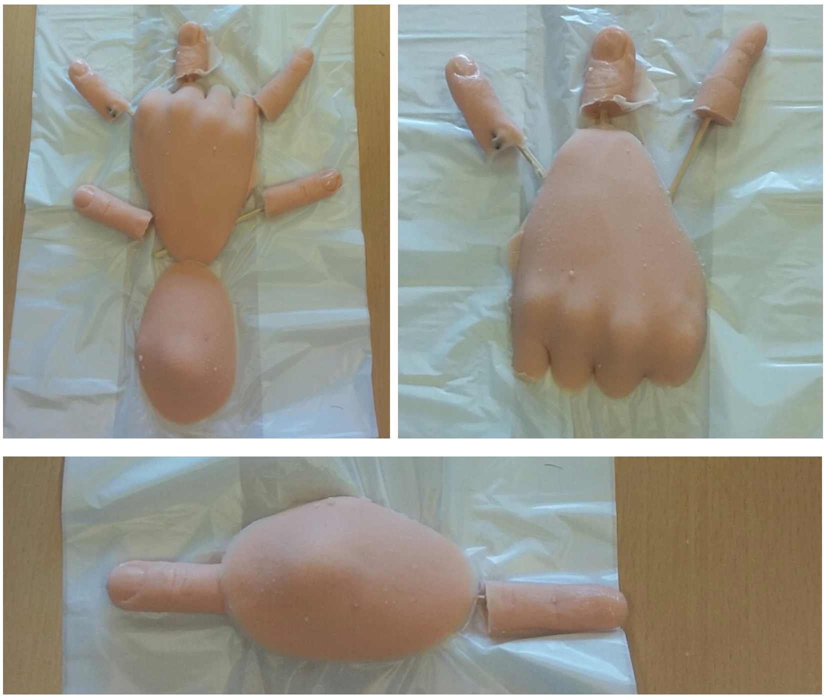

Fig. 38. Cast silicone parts of my hand, elbow, and fingers assembled into posthumanoid morphologies.

Fig. 39. Silicone cast of my toes. The toes can be made to wiggle by pushing the bamboo sticks together.

10.6.2 Dynamic color changing

These prototypes explored mixing silicone with chromo-thermic pigments that changes from blue, red, or black to white when heated up. Kanthal thread was embedded into the silicone. When a current was applied to the thread it would heat up the silicone and cause it to change color.

Fig. 40. Silicone colored with thermochromic pigments heated with Kanthal thread.

10.6.3 Boiling water actuation

This prototype explored using boiling water for pneumatic actuation by expansion.

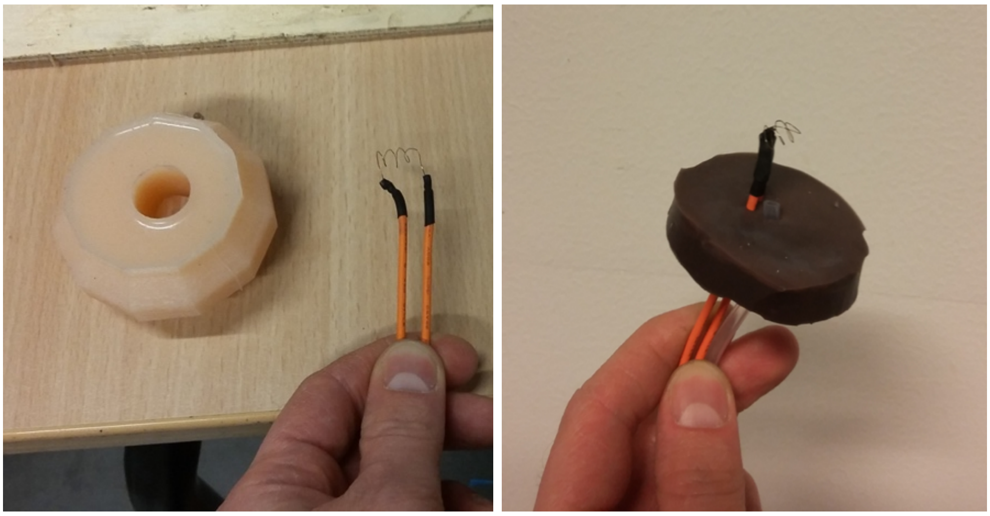

Fig. 41. Silicone compartment and top part and orange wires attached to Kanthal thread.

Fig. 42. Left: The compartment and top part is assembled with water inside and a silicone pouch is attached with a tube. Right: A current is applied to the Kanthal thread, which heats the water. The water starts boiling and the pouch is inflated by water vapor.

A similar idea of creating expansion by boiling a liquid was later published where ethanol was used instead of water and the liquid was embedded as micro-bubbles in the silicone (Miriyev, Stack, and Lipson 2017b).

10.6.4 Flesh-like soft robotic parts

Fig. 43. Flesh-like silicone parts.

As a part of the preparation for the research residency at Chronus Art Center (see Appendix 10.2), I experimented with casting soft robotic parts that were flesh-like in appearance. The flat larger pieces have vein-like structuring in a red tone. Molds for them were laser cut, with the vein-like pattern raster cut onto the bottom. Diluted silicone pigments were poured into the mold and allowed to dry before silicone with skin-colored pigments were poured in.

The pneu-nets actuators shown in the image were instead fabricated by first pouring blue and reddish liquid silicone in thin stripes onto a plate. When the stripes had dried, they were put into a pneu-nets actuator mold, which was then filled with lightly skin-colored liquid silicone. Reddish and bluish liquid silicone was then stirred into the liquid skin-colored silicone and the actuators were left to dry. Because the vein-like colored stripes were embedded inside the actuators they are only visible when the actuators are inflated and the skin-colored silicone has stretched to become more transparent.

11 Papers

Prolegomena for a Transdisciplinary Investigation Into the Materialities of Soft Systems

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Abstract

This paper presents exploratory research on the materiality, aesthetics and ecological potential of soft robots. Within the still emergent paradigm of soft robotics research, bio-inspiration is often hailed as being of central importance. The paper argues that soft robotics should equally be seen as giving prominence to materiality and the enactive and processual potential of soft matter. The paper excavates different notions of materiality within media art that uses soft robots and in technical soft robotics research practices and discourses. Against this background, the author's own practice-based experiments with soft robots are presented.

Keywords

Soft robotics, soft robots, robotic art, bio-inspiration, materiality, ecology

Introduction

The field of soft robotics has in the past ten years become established as an emerging subfield of technical robotics research. A number of different definitions of soft robots exist but in general "soft" is taken to refer to the body of the robot as being constructed of a soft material. "Softness" is most often correlated with a mechanical property known as Young's modulus, defined as the relation between stress and strain for a linear elastic material. Soft roboticists Daniela Rus and Michael Tolley thus define soft robots as "systems that are capable of autonomous behaviour, and that are primarily composed of materials with [Young] moduli in the range of that of soft biological materials" (Rus & Tolley, 2015: 467).

In relation to robotics research in general, the field of soft robotics distinguishes itself by utilizing bio-inspired design strategies (often coupled within an interest in *morphological computation*) as well as an interdisciplinary outlook that seeks to combine research from engineering, computer science, biology and material science (Trimmer et al, 2015). Within soft robotics bio-inspiration has mainly come from soft bodied animals or parts of animals that are soft, e.g. larvae, cephalopods and the elephant's trunk.

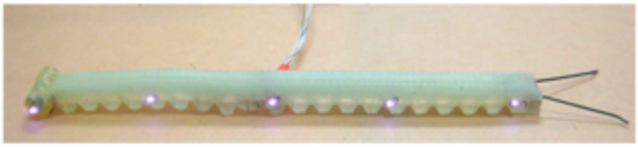

Figure 1. Caterpillar-inspired soft robot by Huai-Ti Lin, Gary G. Leisk and Barry Trimmer. © Huai-Ti Lin, Gary G. Leisk and Barry Trimmer.

Soft robots offer different conditions of possibility for interactions with humans than their more common rigid counterparts. From a naïve realist point of view it seems intuitively clear that this fact hinges upon inherent qualities of the materials from which they are constructed. Within technical and natural sciences research, these can easily be described with reference to the physical properties of e.g. silicone rubbers, which can be reproducibly measured and calculated. Physical descriptions, however, obviously miss the potential of soft robotics as an aesthetic, cultural and ecological phenomenon and elides the sensuous knowledge, cultural imaginaries and fascination the technology is able to conjure up. Approaching soft robots from the point of view of materiality, a first question thus becomes how to think in a way that allows one to escape the trap of a purely physicalist conception of matter (see Stoljar, 2016). And how one avoids its reductionism and violence towards knowledge, percepts and affects hailing from sensory perception or thinking constituted in practices and relations that lie beyond the grasp of positivist science.

Materiality

Within the social sciences and humanities a shift of interest towards materiality and matter has been evident for some time now. It is often described as a swing back from or reaction against the linguistic turn and its emphasis on semiotics and signification. Some of its most obvious manifestations are taken to be the emergence of *object-oriented ontology*, *speculative realism* and a number of so-called *new materialisms* (Atkins, 2016). The term "materiality" is, however, used in very divergent ways in the various contexts, fields and sub disciplines where it has made its presence felt. The theoretical movements just mentioned, for instance, are mainly interested in materiality from ontological and metaphysical perspectives. N. Katherine Hayles has written extensively about matter and materiality and distinguishes between *physicality* and *materiality*. Physicality, according to Hayles, is "similar to an object's essence; potentially infinite" and "unknowable in its totality" (Hayles, 2014: 172). Materiality on the other hand, is what we can know – "the physical qualities that present themselves to us" (ibid.). As Hayles notes, what qualities that "present themselves" obviously depends on how we attend to the object or material in question (ibid.) i.e. our choice of epistemology.

Drawing on this minimal definition of materiality, I will in the following two sections explore how the materiality of soft robots is constituted within two different contexts: the reception situation of contemporary media art and the fabrication and design processes within technical research practices. I review *how conditions are set up that enables the physical qualities of soft robots to be actualized* (i.e. to manifest themselves and be recognized). I also consider *the processes through which this occurs* and *what material characteristics that emerge from them*.

Soft Robots in Contemporary Media Art

A small number of artworks currently exist that make use of technological means that can be considered variations of soft robotic technology.[1] Jonathan Pêpe's installation *Exo-biote* (2015) is a notable example. It was produced in collaboration with soft robotics researchers at Université de Lille. The work consists of a transparent display case that contains several small white rubber parts in geometric and organic shapes, all kept in a very clean and designed commodity aesthetic.

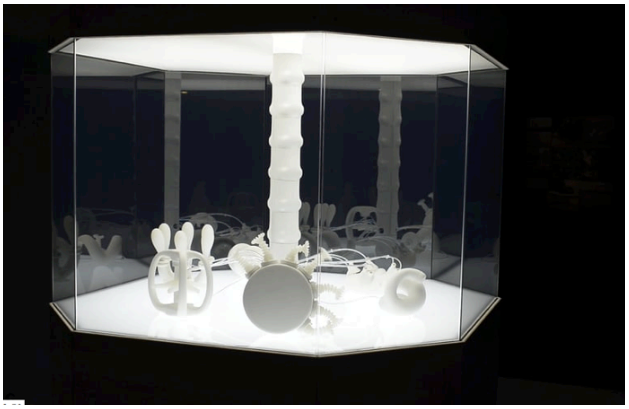

Figure 2. Jonathan Pêpe, *Exo-biote* (2015), Le Fresnoy, National Studio of Contemporary Arts; Neuflize OBC; INRIA, the DEFROST team. © Jonathan Pêpe

Some of the parts are able to pop up and whirl around or expand to provide movement. The piece has been described by the artist as a scenario that presents the viewer with a kind of artificial externalized prosthetic organs that come together as a pneumatic organism. In his view, it suggests a possibility for transhuman enhancement as a new mode of capitalist consumption (Pêpe, 2015).

Another example that is also the result of interdisciplinary collaboration between soft roboticists and an artist is *THE BREATHING WALL (BRALL)* (2015).

Figure 3. Ece Polen Budak and Ozge Akbulut, *BRALL* (2015) (detail), silicone on polycarbonate panel, 145 × 145cm. © Ece Polen Budak and Ozge Akbulut

This installation by Ece Polen Budak and Ozge Akbulut, was constructed in collaboration with Onur Zirhli and soft roboticist Adam A. Stokes from the University of Edinburgh. In the work panels of a silicone foam wall structure

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[1] I only review projects here that were produced explicitly in an art or artistic research context. Moreover, I only include work that makes use of microcontrollers or other means of computational technology in combination with a pliable or deformable soft morphology. There is currently also a burgeoning interest within architecture in utilizing soft robotic technologies. Michael Wihart's *Pneumorphs*, Bijing Zhang and Francois Mangion's *Furl* (2014), the *Sarotis Project* (2016) and Dino Rossi's work are examples of this. Many artworks of course also exists with more traditional uses of pneumatics – spanning the period from ancient China and Greek antiquity until today. Within contemporary art and media art pressurized air has also frequently been used to power piston actuators or McKibben artificial muscles or together with inflatables made of thin plastic. Soft robotic artworks also bear formal similarities to the tradition of *soft sculpture*, from the 1960s where a number of artists started using materials such as synthetic foams, rubber, soft plastic, paper, fabric and different kinds of fibres in their work.

perform a kind of breathing swelling motion. This movement is further augmented with audio recordings of human breathing sounds played through a set of loudspeakers. The audience can physically touch the structure and interact with the system as the large air pockets are inflated in accordance with input from capacitive sensing conductive plates installed behind the panels (Budak et al, 2016).

Paula Gaetano Adi's biomorphic half-spherical autonomous robotic agent *Alexitimia* (2006-2007) is another early example of a soft robotic artwork. Interestingly it was produced before soft robotics had become a prolific research field and it was designed and constructed by the artist herself. Like *BRALL* it interacts with audience members through touch. Here, however, yet another sensorial register is added: The tactile experience of soft latex rubber bending upon impact is accompanied by sensations of wetness as the sculpture responds to haptic stimulation with the secretion of a sweat-like fluid. Gaetana Adi posits the work as an exploration of "artificial corporeality" (as a supplement or alternative to artificial intelligence) and robotic body language (Gaetano Adi, 2007)

Figure 4. Paula Gaetano Adi, *Alexitima* (2006/2007), Autonomous Robotic Agent. © Paula Gaetano Adi

Looking at the artworks I have cursorily presented in this section, it is possible to discern some central aesthetic interests and tropes that seem to cling to soft robotics when constituted as an artistic medium. For one, in the reception situation of soft robotic art we are primarily dealing with a materiality that is accessible through bodily and corporeal engagement. In Budak and Akbulat's work as well as in Gaetana Adi's the viewer is physically implicated with the robotic system via a haptic aesthetics – in order to experience the work we must touch it. Pêpe's installation similarly alludes to touching but via negativa – the pristine white soft rubber parts are warded off from the viewer by transparent glass plates and thus a gratification of the desire to touch it is withheld. The act of touching a soft robot is, arguably, an experience that carries with it, if not uncanniness, then at least an amount of cognitive dissonance: We are all familiar with pliable soft surfaces that respond to our touch, but from living bodies not artificial entities. In this sense, there exists a cognitive contiguity between soft materiality and animatedness. This contiguity is also evoked in the breathing expansion motion that is used in *BRALL* but also in a number of other soft robotic artworks including Paula Gaetano Adi's *Anima* (2009) and Ingrid Bachmann's series *Pelt (Bestiary)* (2012). The swelling motion of a soft structure here serves as not just a signifier of liveness, but a simulation of its basic unit – the breath, in what amounts to a kind of primordial production of presence.

Through their use of touch and/or rhythmic expansive movement the reviewed works manage to stage and present select physical qualities of soft matter in expressive ways that conjure up their centrality in organic life processes in general. This is done through modes of presentation that rely on a direct interlinking with the human sensorium. Being that this occurs in the institutionalized art space the soft materiality of the works also inevitably expands to encompass cultural connotations of softness: Vulnerability (a quality also explicitly mentioned by Gaetano Adi when speaking of her work), weakness, the feminine (cf. the likeness between Gaetano Adi's robotic agent and a pregnant belly).

In the following section I will look at how the materiality of soft robots is constituted within technical research practices and discourses. As will become clear, technical soft robotics research brings questions of material transformation to the fore as both a resource and a matter of concern for robotics research.

Technical Soft Robotics Research

In technical research on soft robots the issue of materiality figures prominently as a key question has been which materials to use and how to most efficiently design and construct soft morphologies (Marchese et al, 2015; Rus & Tolley, 2015). The aim of developing new materials and reliable fabrication procedures has in fact served as a crux for an import of knowledge to the field from material science and also for its further development of existing rapid prototyping technologies.

Unlike traditional robots, soft robots are generally fabricated as continuous morphologies, rather than as assemblages of discrete components. This opens up the possibility for a different design and fabrication approach than when confined to assembling rigid mechanical parts as is usually the case for roboticists. A soft morphology is most often cast in a mold from a soft material such as silicone rubber. It might be tempting to see this procedure as being a version of the *hylomorphic scheme* as described by Gilbert Simondon. That is: as a fabrication procedure that is conceived as mind actively imposing a form on a "raw" matter that is inert and passive (Simondon, 2005). This is, however, misleading, I posit, as the two central points of Simondon's critique of hylomorphism are actually inherent to current soft robotic design and fabrication practices, namely that: 1. matter is not passive (but rather capable of contributing to the generation of its own form), 2. matter (in fabrication) is not raw but always prepared and produced.

Process and Material Transformation as a Part of the Fabrication and Functionality of Soft Robots

Some of the early pioneering soft robotics research came out of chemistry research in microfluidics, most prominently from the Whitesides Research Group at Harvard. In a number of soft robotics projects the capacity of matter to react with other kinds of matter and to transform given the right conditions is therefore an essential aspect. This is the case for what was promoted as the first fully autonomous soft robot and published in the prestigious *Nature* journal in 2016. It was fabricated by depositing various materials using a modified 3D printing platform equipped with syringes. Some of these materials would gradually evaporate to yield microfluidic air channels used for pneumatic actuation of the finalized morphology (Wehner et al, 2016). The design and fabrication scheme thus relied on transformational properties of matter, e.g. the capacity of fugitive inks to auto-evacuate. But what is more, the cyclical movement pattern enacted in the finalized robot was also accomplished by a pneumatic logic circuit driven solely by chemical reactions and no electronics. The robot's operation was rooted in making two fluids react to create a gas and a resulting pressure differential between the inside and the outside of the morphology's surface.

The research that is being done by the Soft Robotics Group at the Bristol Robotics Laboratory is another example of how the transformational properties of matter are being leveraged as not just a part of the fabrication process but for the actual functioning of soft robots. Here experiments are being conducted with biological means of generating electricity to drive soft robots by relying on microbial fuel cells and organic matter that is abundant in local ecologies. Moreover, rather than using silicone, which is manufactured though an energy demanding and elaborate process from sand and hydrocarbons and is very durable, the researchers are experimenting with using biodegradable materials such as latex rubber and gelatine. This is done to yield autonomous soft robots that may assimilate to and eventually perish in natural environments without causing damage to them. This visionary approach to soft robots highlights the fact that actual robots do not exist in an ahistorical vacuum of time, but have a life span and an entwinement with larger flows of matter that needs considering.

The Mangle of Practice

From the examples of technical soft robotics research I have surveyed in the previous paragraph it becomes clear that the enactment of a processual and dynamic chemico-biological materiality is central to the fabrication and functioning of certain state-of-the-art soft robots. If we look at descriptions of the creative process of designing soft robots, materiality also plays a vital and dynamic role here.

In a seminal article on soft robots from 2011 that introduced the *PneuNets* (*Pneumatic Networks*) actuation technology, which has since been widely used in soft robotics (and patented by the authors to be commercially exploited by their company), for instance, the authors write:

> "We used a series of parallel [air] chambers embedded in elastomers as repeating components. Using intuition and empirical experimentation, we stacked[31] or connected these repetitive components to design and test prototypical structures that provide complex motion." (Ilievski, 2011: 1891)

For the authors, who were all working in the Whitesides chemistry research lab, an embodied and situated knowledge combined with active material experimentation formed the substrate from which their invention sprung. The final design of the robot, it seems, was negotiated between human and non-human material agencies – both natural and historically contingent ones.

In a similar manner, a lot of soft roboticists look to nature as a source of inspiration. But soft robots are more often bio-inspired than biomimetic. That is, rather than being copies or technical remediations of biological mechanisms aimed at exact replication they extrapolate these, following their virtual lines of flight. The bio-inspired mechanics are then iteratively prototyped, using rapid prototyping tools, to arrive at a desired level of functionality in the final design (see e.g. Kovač, 2013). The translation of a mechanical principle observed in nature into technology is thus evidently negotiated through a series of entwinements between contemporary social needs and desires, technology and matter. This dialectic between *resistance* (obstacles on the path to a goal) and *accommodation* (the revision of conceptual models) is what Andrew Pickering has described as *the mangle of practice*. According to Pickering, it is the emergent process that gives structure to scientific research through an interplay of material, conceptual and social practices (Pickering, 1994: 262-3.

Experiments Toward Soft Robotic Ecologies

My own approach to soft robotics is characterized by an interest in the aesthetics of interaction between soft robots and humans also characteristic of the soft robotic artworks I have reviewed in this paper. This includes how softness affords a specific expressivity, how soft robots are perceived differently than rigid ones and how the cultural, symbolic and meaning making potentials of soft materials play into this. My focus is, however, not solely on human-robot interaction or the structure of the experiences it may give rise to. Soft robots are part of and shaped by a multiscalar material ecology that is physical as well as social and cultural. I aim to explore how acknowledging this fact may contribute to envisioning robots anew. Adopting an ecological framework, the task becomes to determine what the wider assemblages are that soft robotics couple with or make possible and how their materiality conditions or gains traction on experience, social forms, knowledge and politics and rearticulates them at different scales. I have been exploring this in a number of prototypes, some of which I will briefly present.

Entropy

Entropy is an early prototype constructed from silicone, silicone glue, wax and various found waste materials. It was constructed in a mold made of soil as a counteroffer to the sleek mass-produced commodity aesthetics characteristic of technical soft robots and as an insistence on a grounded non-idealizing aesthetic. The morphology performs a breathing motion at irregular intervals.

Figure 5. *Entropy* (2016).
Video: https://www.youtube.com/watch?v=y3MTcC0x5-g.
© Jonas Jørgensen

The prototype was one in a series of material experiments in combining highly elastic silicone with other materials.

Figure 6. Examples of material experiments. Left: Coloured EcoFlex silicone and beads of hydrogel were submerged in water. The beads become transparent, swell and expand the silicone. Middle: Silicone embedded with kitchen salt then cured in an oven and placed in water overnight to dissolve the salt. The resulting structures were easily compressible and sponge-like with perforated holes all the way through which allows air to pass from one side to the other. Right: Cured sheets of silicone doped with carbon black to yield electrical conductivity (the attempt was unsuccessful). © Jonas Jørgensen

The Fluid Medium

A number of more recent prototypes have been relocated from atmospheric air to an aquatic milieu – a future other organisms might face as the planet deteriorates further. These prototypes carry a technical interest in *morphological computation* (how soft materials can obviate the need for extensive computation in the control loop of a robot) over into aesthetic concerns: viscosity is explored as an *affordance* (Gibson, 1986) for silicone that enables biomorphic life-like movement. They also speculate on how a productive interplay between a specific milieu and a soft body can occur and how softness exists as an intermediate state between liquid and solid.

Figure 7. Physical coupling between a silicone appendix (cast onto a servo motor) and its containing medium (water). The arm produces fluid motion with gradual biomorphic bending when submerged in water but flaps clumsily around when in the air. Video: https://youtu.be/ifLChDLxdjE. © Jonas Jørgensen

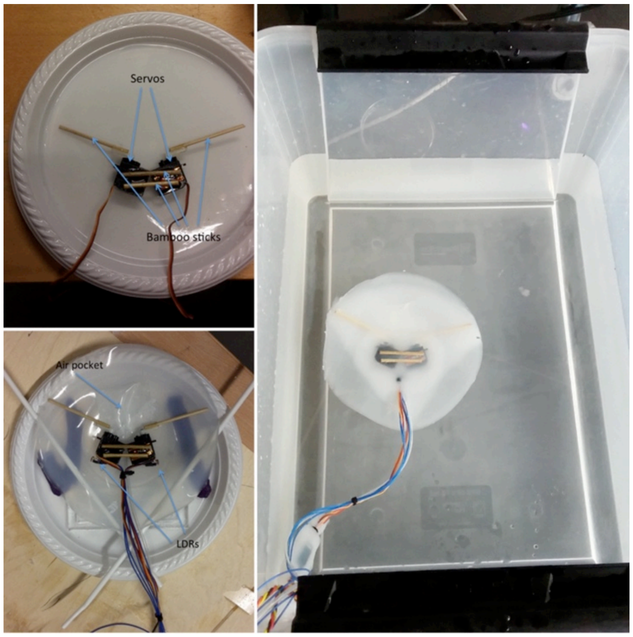

Figure 8. An improvised fishlike soft prototype was fabricated from silicone, bamboo sticks, epoxy, two servo motors and two light-dependent resistors. I plan to experiment with using evolutionary algorithms to evolve its swimming behavior. Video: https://www.youtube.com/watch?v=U7c0oTtsseU. © Jonas Jørgensen

Soft Robot-Plant Ecologies and Biohybrids

Phytomatonic is a series of prototypes that explore how soft silicone might afford an artificial agent other relations with biotic elements in an environment than rigid materials. The series also relates to questions on how we can speak and think about biological organisms and robots coming together in ways that go beyond instrumentality and anthropocentrism.

Figure 9. Soft robot-plant interaction. Video of the robot: https://www.youtube.com/watch?v=BO9zXX_XHr4
© Jonas Jørgensen

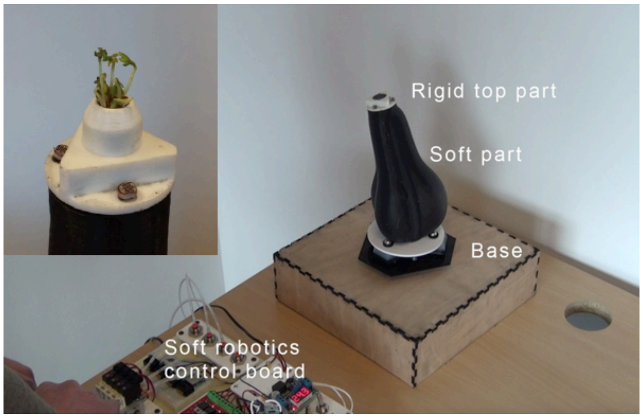

Figure 10. *Phytomatonic 01* (2016).The robotic part of the system and the rigid tip of the robot with the three LDRs and cress plants. © Jonas Jørgensen

The central element in the prototype *Phytomatonic 01* is a black soft robotic tentacle. This soft body is equipped with three light-dependent resistors (LDRs) at its tip that allow the robot to detect incoming light. Directly below each LDR are three separate air chambers that can be inflated with an electrical pump to actuate the robot and make it move. At the tip of the robot, ordinary cress plants are placed. The robotic part of *Phytomatonic 01* replicates characteristic aspects of a growing plant by means of soft robotics technology. More specifically: its phototropic behavior and the mechanism by which directional change is accomplished through cell elongation on the shady side of the stem (triggered by an accumulation of the plant hormone Auxin). The robotic part's mode of functioning thus echoes the working of the plants at its tip and the robot's light-seeking behavior evokes notions of a common desire for light shared by both the biological and technical part of the system. The technological part of the system succeeds in replicating a biological mechanism through the use of soft robotics technology but for a goal that from a practical viewpoint may seem entirely redundant: The robot is programmed to position the plants in the direction of the incoming light – something that the plants are perfectly able to accomplish on their own.

Figure 11. An overview of the prototype *Phytomatonic 01*. Video: https://www.youtube.com/watch?v=-awxAXI035E
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Conclusion

The embrace of soft materials by roboticists has the potential to radically change not only the appearance of their creations but also how they are able to relate to and interlink with their environments and other agents. This will obviously have consequences when the robots are brought out of research labs into "the wild". How will cultural narratives and imaginaries of softness, robots and artificial life conjoin in the encounter with a pliable robot? What meanings and modes of relating will emerge from soft materiality combined with artificial intelligence? Through the line of arguing and the examples presented in this paper, I hope it has become clear, that both artistic practices and technical research are important vehicles to address questions like these.

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From Soft Sculpture to Soft Robotics: Retracing Entropic Aesthetics of the Life-like

I. Introduction

Around the late 1960s a group of artworks were produced that have been historicized under the heading of *soft sculpture*. The epithet refers to Claes Oldenburg's Pop Art sculptures, but also to works associated with Postminimalism, Process Art, and Anti-Form. Straddling several art historical traditions, soft sculpture as a category collects together an ensemble of works that is internally divergent in many respects. And soft sculpture operates with several different notions of softness: Some works index a physical process involving molten or plastically deformed parts, others use pliable, yielding, or lightweight materials, some merely have visual cues that indicate a possibility of deformation, while others still are made of elastic rubbers.

When reading descriptions of works of soft sculpture, it is remarkable to notice that their similarities with living organisms and bodies are so frequently emphasized as a central tenet of their aesthetic, though most are nonfigurative and motionless.[1] Oldenburg's sculptures, for instance, are said to 'take on their own life' (Babington and Owens 2009). The felt compositions of Robert Morris 'allude to the human body through their response to gravity and epidermal quality' (Blessing n.d.) and have 'human qualities' (MoMALearning n.d.). Richard Serra's rubber strips in *Belts* (1966–67) are imbued with an 'anthropomorphic quality' (Spector n.d.), and Lynda Benglis' polyurethane foam accumulations attributed biological drives of their own when claimed to embody an 'erotics of Anti-Form' and 'movement of a (…) Dionysian sort' (Edelman 2004).

But why is soft sculpture so frequently described as life-like? Might this be a direct consequence of or somehow related to their soft materiality or is something else at play? Soft and pliable materials indeed figured prominently within an earlier tradition of crafted objects that explicitly sought to not just imitate, but to simulate organic life, namely the fraction of European automata that Jessica Riskin refers to as 'eighteenth century wetware' (Riskin 2003). As Riskin writes,

> These machines all reflected the assumption that an artificial model of a living creature should be soft, flexible, sometimes also wet and messy, and in these ways should resemble its organic subject (Riskin 2003, 112)

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[1] A few kinetic soft sculptures from the period exist. These include Keith Sonnier's inflatables (Lippard 1966; The National Exemplar 2018) and Oldenburg's *Ice Bag -- Scale B, Yellow* (1971).

The intuition that soft matter plays a central role for the functioning of living bodies, has, moreover, recently started to assert itself within the technical research field of *soft robotics*. Here, efforts are made to construct robots from materials such as silicone, often by drawing explicit inspiration from the bodily mechanics, control strategies, and abilities of soft or partially soft animals.

In this essay, I interrogate an apparent contiguity between softness and what for lack of a better term, I will refer to as *the life-like*. By this, I designate experiences and descriptions of non-living entities and material processes that ascribe to these physical dynamics and qualities characteristic of living organisms.[2] The line of questioning pursued originates from a syncretic ambition, as it seeks to integrate the historical and aesthetic perspectives of media art history with the description of life within physics and with recent technical research on soft robotics. The extensive question that the essay revolves around is thus, what connections can be drawn between softness and the process of life, beyond the obvious observation that most lifeforms (that we know of) are composed of soft matter. This question is approached by way of analyses of a number of selected works of soft sculpture and robotic art. In terms of the wider interests of this anthology, the essay can thus be said to deal with softness, and its changing status as an interface for an aesthetics of life.

To begin with, I focus on postminimalist soft sculpture and its conceptual underpinnings and reception, to explore the different ways in which such works conjure up impressions of the life-like.[3] Doing so, I aim to explicate the kinds of liveliness postminimalist soft sculpture can be seen to enact. Secondly, I proceed to two recent artworks from a burgeoning strand of contemporary media art that appropriates soft robotics technology for an artistic end. And finally, as a way of concluding, I discuss how the relations between softness and life, unearthed through the analyses, relate to measures currently taken in order to imitate natural organisms within technical soft robotics research.

The underlying thesis of the essay is that the concept of *entropy* and the physical description of life as a process of entropy evasion can be used to analyze the different notions of life evoked by soft sculpture. And I argue that accounts of postminimalist soft sculpture as life-like actualize what I term *an entropic aesthetics of the life-like*, wherein life is envisioned as processual and the living organism's physical intertwinement with its environment is stressed. This aesthetics, I further argue,

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[2] I have chosen to use the term 'life-like' as it is less anthropocentric than the discourses on 'anthropomorphization'. It is also preferable to 'animated' as this term usually refers to a qualitative aspect (something that is endowed with life or the qualities of life). The term 'life-like' is better suited for the transdisciplinary interest of this essay, as it is not tied to a qualitative epistemology, but is also compatible with a physical description of life.

[3] It should be noted here that the reading of postminimalist soft sculpture that this focus and approach produces is, of course, highly selective and largely neglects the historical and political contexts within which these works were produced.

can be extended to also encompass two contemporary soft robotic artworks through a historically bound reworking of the entropy concept that emphasizes an understanding of entropy as sameness.

II. Forces Become Process

The question of why soft sculpture is so frequently described as life-like obviously has more than one answer. In some works of soft sculpture, we find so-called natural materials such as fur, wool, jute, or hemp, that have connotations of life because they derive from living organisms. In others, the belts by Serra for instance, there is something about the scale and proportions that come close to the human body. But in the subgroup of works where softness is introduced via pliable materials or physical deformation, the sense of life-likeness also appears to hinge on a reflexivity between the sensuous apprehension of soft matter that is part of the viewer's own body and soft matter within its proximity. In Lucy Lippard's "Eccentric Abstraction" essay, which mentions several works of soft sculpture, she insightfully remarks that for sculpture

> The use of a flexible instead of a fixed medium opens up an area somewhere between kinesthetic and kinetic art in which moving or movable elements are extremely understated. (Lippard 1966, 106)

In flexible sculpture, movement is thus arguably implied in a subtle manner that seems to implicate the kinesthetic. Kinesthetic experience relates to the sensations we have of our own living bodies. They involve an embodied knowledge of the effects that physical forces and gravity have upon the type of matter we inhabit from the inside, namely soft matter. But from Lippard's observation, the inference can be drawn that soft sculpture also appears to trigger kinesthetic responses, hence, this might in part be what compels the viewer to empathetically attribute soft sculptures a liveliness of their own.

The coexistence of movement and non-movement, observed by Lippard, also brings up how soft matter in general seems to exist in between set categories. Soft matter mediates between not just the fixed and the moveable, but also between liquids and solids, the stable and the unstable, the structured and the unstructured. In many respects, soft bodies are characterized by being receptive to forces coming from their outside and hence they are also tied to process.

In his programmatic text "Anti-Form", written in 1968 the minimalist aesthetic of 'object-type art' which he had previously pursued, Robert Morris famously announced an aesthetics of process that was to become central to postminimalism. For Morris, the painting practices of Jackson Pollock and Morris Louis provided a point of departure for rethinking artistic creation. 'The stick that drips paint', Morris wrote, 'acknowledges the nature of the fluidity of the paint' (Morris 1968, 43). Hence, compared to the brush 'it is in far greater sympathy with matter because it acknowledges the inherent tendencies and properties of that matter' (Ibid.). Against an idealist focus on form, which Morris took to be a ‘conservative enterprise’ (Ibid., 45), he proclaimed process a ‘more direct revelation of matter itself’ (Ibid., 44). Hence in his works from the period, Morris explored a balance of flexibility and stiffness in materials that included soft industrial felt.

Fig. 1. Robert Morris, *Untitled*, 1969, felt, 459.2 x 184.1 x 2.5 cm.

The credo of Morris and other postminimalists, such as Richard Serra, that sculptural form should be derived from the inherent properties of materials, is related to the notion of ‘truth to materials.’ Yet in postminimalist practice, this notion was radicalized and became an ambition of bringing matter and form into a condition of mutuality: The forms and the physical relations between parts should be generated from and made possible by the specific physical characteristics of the materials used. This is evident in Serra’s bent sheet of vulcanized rubber upheld by forces of friction in the work *To Lift* (1967). But even more elegantly displayed in *Right Angle Prop* (1969) where a bent piece of lead alloy is used to balance another piece of the same material against a wall, something that is made possible by the specific density, friction, and stiffness of the material.

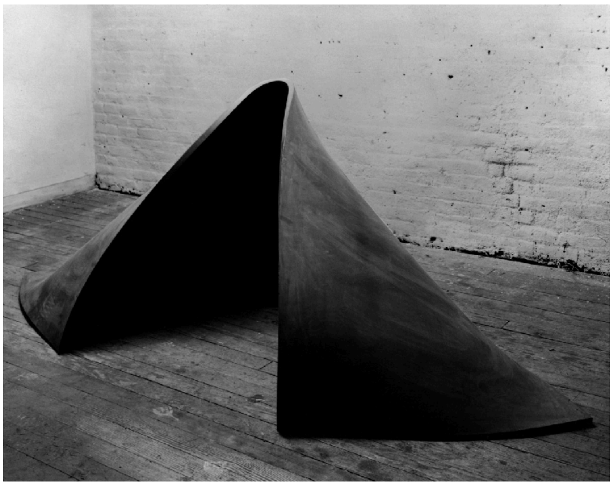

Fig. 2. Richard Serra, *To Lift*, 1967. Vulcanized rubber, 91.4 x 200 x 152.4 cm.

Fig. 3. Richard Serra, *Right Angle Prop*, 1969, lead antimony, 182.9 x 182.9 x 86.4 cm.

III. Entropy and Life

In Morris' and Serra's works, the force of terrestrial gravity enters the artwork to become a co-constitutive element of sculptural composition. In this way, an indispensable link between the artwork and its surroundings is established that echoes the subjection to gravity that all earthly organisms must endure. In other postminimalist works, a physical connection between organism and environment is also thematized, but in a different way that can be more directly brought to bear on a physical processual view of life.

From a physical perspective, acting as a catalyst of process can be interpreted as letting entropy lead. As a concept, entropy originates in thermodynamics, but it also became a frequent reference of late 1960s art discourses and is explicitly mentioned by Morris in "Anti-Form". Defined technically in statistical physics as related to the number of microstates of a given system, and thus an expression of its number of degrees of freedom, entropy is often interpreted as a measure of disorder, even if such an interpretation does not always hold (Piazza 2011, 80).[4] Entropy is relevant in relation to the life-like because life seems to evade the second law of thermodynamics, which implies that all physical processes yield a net increase in entropy. Given the physical description of life as being, at its core, anti-entropic, it might seem paradoxical that postminimalist and Anti-Form works with soft materials that are based on letting physical processes run their due course, and usually appear somewhat disorganized or haphazard, are frequently described as possessing qualities shared with living organisms. However, Erwin Schrödinger (2012[1944]), and before him Ludwig Boltzmann (1974[1875]), have pointed out that living organisms only evade the decay to thermodynamical equilibrium by continually exporting entropy to their surroundings. Within the physical description, the locus of life is therefore not just the living organism itself. Instead, life is seen to inhere in the relation that the organism continually sustains with its environment. The living organism is considered an *open system* (in the physical sense) that exists in a state of continual exchange of entropy, energy, and matter with its environment. Interestingly, this ecological perspective on life also runs as a latent current through the associations conjured up by postminimalist soft sculptures by Eva Hesse and Lynda Benglis.

In the text on Hesse's work *Tori* on Philadelphia Museum's webpage, for instance, it is stated that Hesse 'imbued a subtle eroticism and a sense of human presence in her sculptures' (Philadelphia Museum 2018). The nine forms that make up the work are, moreover, described as 'organic and rigid, fleshy and repellent, corporeal and otherworldly' (Ibid). And the organization of the piece is referred to as a 'casual arrangement' that looks 'more like something discovered by chance than deliberately set in place' (Ibid).

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[4] Entropy is a concept that arguably has many different meanings. It has gone through considerable reworking and has been redefined on its travel from thermodynamics to statistical physics, information theory, and beyond. Entropy has previously been applied to art and aesthetics on a number of occasions (see Jones 1973). Gestalt psychologist Rudolf Arnheim's *Entropy and Art. An Essay on Disorder and Order* (2010[1971]) and artist Robert Smithson's writings are probably the most famous instances of this (Smithson 1996). The use of entropy within this essay differs from how the term is used by Arnheim and a number of other theorists' where it serves as a theoretical basis for developing a naturalizing aesthetics rooted in natural science (Rapkine 1970[1945]; Mandelbrojt 1970; Monod 1970). Within these accounts, entropy is associated with disorder and figures as an opposite of order and information that is privileged by way of a classicizing aesthetics. Compared to such theorizing, the scope of this essay is narrower. I do not intend to apply entropy to aesthetics or aesthetic judgement in general, but instead I use the concept as a prism through which to articulate the life-like aspects of soft sculpture and soft robotic artworks. Within this usage, order recurs as a characteristic of life and living bodies, but it is the dynamic physical imbrication of organism and environment, announced by the negentropic physical description of life, that I take as my leitmotif.

Fig. 4. Eva Hesse, *Tori*, 1969, polyester, resin, and fiberglass on wire mesh, largest of nine units 119.4 x 43.2 x 38.1 cm.

In the description, the nine sculptural elements are thus likened to a group of organisms or parts thereof (being ‘fleshy’, ‘corporeal’). But they also take on the role of a kind of elements in the environment that appear as if organized, perhaps for some purpose or from some previous activity, and hence their organization also comes to index the past presence of one or more living creatures. It is thus both the frailness of the parts and the balanced disorder with which they are arranged that imbue the work with a life-like quality. The elements in *Tori* also resemble the shed skin of a snake. Within the reception, Lynda Benglis’ polyurethane *pours* are frequently associated with a comparable discarding of bodily matter and bodily fluids, that are imagined to leave the body to be cast off to the environment (Chadwick 1996).

Fig. 5. Lynda Benglis, *Night Sherbert A*, 1968, Dayglo pigment, phosphorescence and poured polyurethane foam,12.7 x 121.9 x 153.7 cm. (View from above).

In such readings, the works come to reflect a process of *abjection*, described by Julia Kristeva as the expulsion of bodily matter, a shedding of 'the me that is not me' (Kristeva 1982). When read through this prism, Hesse and Benglis' works allude to the fact that entropy does not just vanish in organisms but is exported to the environment through a transfer of matter and energy. They acknowledge that life is not simply anti-entropic, but rather a modulation of entropic flows that envelop both the organism and the environment. Matter must continually enter the body and leave it again in a more entropic state, in order for the body to maintain its structured organization. And we can take Kristeva literally when she writes that 'These body fluids, this defilement, this shit are what life withstands (…) Such wastes drop so that I might live' (Kristeva 1982, 3).

In line with the above reading, author Darian Leader has noted a tension between a kind of unruly matter that constitutes the living body and this body's highly organized character as a general theme within Hesse's work. As Leader writes,

> When we look at Hesse's three-dimensional work, we are looking at ourselves (…) Hesse shows us that the body itself is a tension between imposed, regulating structures and a substance that is never entirely subsumed by them (Leader, 2002).

To summarize and conclude, the critical reception illustrates how soft sculptures by Morris, Serra, Hesse, and Benglis can come to appear life-like in the sense that they may be read as analogies that parse different aspects of the relation through which a living organism is inscribed into its physical environment. Although they are explicitly preoccupied with process, Morris and Serra's works predominantly channel this relation via a focus on physical forces, notably gravity, and their effects on soft materials, and analogously soft bodies, as well as the potential of such forces to generate specific inherent organizations of different kinds of soft matter. Hesse and Benglis' work is instead associated with a transformation of biological matter, and processes wherein matter is passed between organism and environment. Albeit rooted in an analogy between artwork and organism, the perception of soft sculpture as life-like evoked by these works differs from the Romanticist notion of the artwork as a *quasi-organism*. For within that analogy, it was the holistic unity of all the parts of the artwork, and the resultant "self-organization", that was essential and proclaimed a source of the artwork's beauty (Gorodeisky 2016). Postminimalist soft sculpture, in contrast, propels *an entropic aesthetics of the life-like*. Within it, life is portrayed as processual and as intimately tied to its physical surroundings. Organisms and bodies are rendered permeable to outside forces and enrolled in material flows and transformations, within a dynamism of forces of chaos and order. Following Rosalind Krauss' writings on *the formless*, this aesthetic can be described as entailing a blurring of the boundary between organism and milieu, or in art historical terms—a dissolution of the figure/ground relationship (Krauss 2000, 75).

Within a number of recent soft robotic artworks, the theme of physical intertwinement between organism and environment also recurs. Yet in these works, the viewer-become-user is confronted not just with a soft object or a sculpture, but surroundings that have themselves become life-like. In the following sections, two such works will be analyzed.

IV. BRALL

The Breathing Wall (BRALL) (2015) is an interdisciplinary project by artist Ece Polen Budak, engineers Onur Zirhli and Ozge Akbulut, and soft roboticist Adam A. Stokes. The installation consists of nine silicone foam tiles mounted side by side on an upright panel. The tiles have different organic surface structures and a porous sponge-like surface—a few are endowed with a layered appearance reminiscent of Benglis' foam pours, while others are characterized by saggy folds. Each tile possesses its own air compartment and has a separate sensor implemented underneath. The structure as a whole 'responds to touch by modulating its breathing' (Budak et al. 2016), and when one of the silicone tiles is touched, the tile will start to inflate and a playback of recorded sounds of human breathing is triggered.

Fig. 6. *BRALL*, silicone on polycarbonate panel, 145cm × 145cm, 2015. (© Ece Budak and Ozge Akbulut. Photo © Baris Dervent, Murat Ugurlu).

In their paper on *BRALL*, Budak and her collaborators state that the work 'investigates the tactile possibilities of human interaction with synthetic biomorphic surfaces' (Budak et al. 2016, 162). And they claim that by way of its responsiveness to touch and its 'breathing', the work 'engages the viewer in a similar fashion to that of a living organism' (Ibid, 163). They believe this 'foster[s] greater responses on the part of the user', so that 'the interaction [with the installation] will be closer to that of organic life' (Ibid.). And they further quote research to support the notion that the presence of biomorphic shapes in an environment 'can serve to enrich human emotional experience' (Ibid., 162).

Like the soft sculptures discussed earlier, *BRALL* evokes an entropic aesthetics of life, both by implying exposure to the forces of the surroundings and by way of the installation's use of breathing. From an art historical perspective, the gesture contained in *BRALL*, of rendering a wall soft, can be seen to reiterate Oldenburg's practice wherein rigid objects, such as a fan or a typewriter, were replicated in pliable materials. The resulting soft versions of these objects would often collapse under their own weight, and hence came to appear blatantly non-functional, and softification thus became a means of effectuating a defamiliarization or estrangement from otherwise well-known mass-produced commodities and technologies with a fixed function. In relation to a wall, the operation of rendering soft perhaps even more directly negates the intended functionality. That is, it effectively cancels out the wall's traditional architectural functions of supporting the roof of a building and of shielding against the outdoors. If a wall is soft, instead of a clear separation between the domestic interior and the outdoors, one gets a correspondence and connection. The wall becomes permeable and the human dwellers become exposed to the forces of nature.

The simulated breathing used in the work is a recurrent feature of artworks with soft robots.[5] Breathing is the definitive sign (or index) of life, 'life depends on breathing', as Despina Kakoudaki puts it (Kakoudaki 2014, 93). However, breathing is equally one of the basic mechanisms through which it becomes evident that we are never just ourselves, alone, in isolation from our surroundings. It is an occurrence that transgresses on the borders between the inside and the outside of the body and connects the organism with its environment in an intimate manner. The body is literally reproduced differently with each breath it takes, as oxygen molecules from the atmospheric air enter the lungs and from there the bloodstream, and as entropy is exported via respiration. The way the breathing mechanism is accomplished in *BRALL*, where exhalation is achieved by passive elastic contraction of the tiles, is also in itself an entropic mechanism. For elasticity, the property that in general seems to endow soft elastomers with a life of their own, has an entropic origin. The inherent tendency of a rubber band to return from a stretched state is predicted by the second law of thermodynamics within statistical physics, as the contraction maximizes the number of possible configurations of the polymer chains of which it is composed, thereby increasing entropy (Piazza 2011, 83).

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[5] See Jørgensen (2016). Breathing automatons were also popular in the late 18th century. Jacques Vaucanson's android *Flute-player* (1738) is an early example that was followed by other famous breathing automatons such as the Jaquet-Droz family's *Lady-musician* (1774) and *Draughtsman* (1772-1774) (Riskin 2003).

V. Synthetic Seduction

Synthetic Seduction is a collaborative exhibition by Stine Deja and Marie Munk that consists of individual works by the two artists assembled as a joint installation.[6] The installation is described as 'a futuristic laboratory setting, simulating the proverbial hospital room' (SixtyEight Art Institute n.d.). Within this setting, two video works by Deja and four interactive sculptures by Munk are on display. The largest sculpture, entitled *Skin-to-skin* (2018), consists of a soft slouching circular base on which smaller oblong parts are also lying. Some parts are attached to the base with umbilical cord-like tethers and the different parts all share an uncannily illusionistic appearance that makes their surfaces resemble those of human bodies – bluish vein-like protrusions are visible under the skin-like surfaces as well as belly button-esque crevices.

Fig. 7. Stine Deja and Marie Munk, *Synthetic Seduction* (2018), installation view from Annka Kulty's Gallery. Photos courtesy of the artists and Annka Kulty's Gallery.

The sculptural pieces are constructed from silicone stuffed with a soft foam material that makes them yield to the touch. And *Skin-to-skin* is positioned so as to function as a recliner to sit on or lie on while wearing headphones and watching Deja's video work *The Intimacy Package* (2018) on a large screen.[7] Two of the smaller sculptures produce heartbeat-like sounds when compressed and some of *Skin-to-skin*'s tethered elements also have moving parts below their 'skins' that are reminiscent of the kind of rigid wheels mounted on rotating spokes found in massage chairs (Marie Munk, email to author, November 14, 2018).

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[6] The exhibition has been presented in different formats, first at Annka Kulty's Gallery, London (Feb. 21- March 24, 2018), then at SixtyEight Art Institute, Copenhagen (June 8 – Aug. 4, 2018), and subsequently also at a number of other venues. In my analysis, I refer to the exhibition at SixtyEight Art Institute, which I visited.

[7] I was told by gallery staff of this intended function while visiting the exhibition .

Despite possessing visual and haptic qualities that call to mind the soft, moist, and wet character of biological life, *Synthetic Seduction* perhaps less obviously aligns with the thematic of physical exchange between organism and environment that connects *BRALL* with the earlier works of soft sculpture. The installation thematizes artificial corporeality and softness as a means of achieving physical (artificial) intimacy (SixtyEight Art Institute n.d.). Through allusions to the mother-infant relationship (umbilical cords, skin to skin contact, the breast-like appearances) notions of physical dependence or symbiosis with an enveloping artificial (m)other are evoked. The relationship between infant and mother is a symbiotic relationship between two organisms, but it is not symmetrical—in terms of survival, the child obviously needs the mother more than she needs it. In a sense, the mother can thus be said to constitute the child's immediate physical surroundings that sustain it. However, within the installation as a whole, the mother-like interactive sculpture *Skin-to-skin* attains a strange kind of presence. On the one hand, it is a center and the anchor piece, and its appearance, as well as its movement and sound, arguably draws attention to it and encourages active physical exploration on the part of the viewer. Yet when it is used to sit or lie on in order to watch the video work, it is relegated to having only a kind of ambient presence and to exist at the periphery of perceptual awareness, as a piece of furniture. *Skin-to-skin* thus oscillates between encountering the viewer via what Don Ihde terms an *alterity relation* and a *background relation* (Ihde 1990). Within the former, the sculpture attains a subject-like status as a *quasi-other*, whereas in the latter, it functions as a context for human existence, but is not at the center of experience itself. The soft settings envelop the viewer as she lies down and then become less noticeable as she is absorbed by the video, thus evoking an experience of having merged with an artificial (m)other.

VI. Entropic Aesthetics and 21st Century Soft Robotic Media Art

In the previous two sections, I have sought to articulate in which respects two more recent soft robotic artworks may be said to extend the entropic aesthetics of life latent in postminimalist soft sculpture. Yet, in *BRALL* and *Synthetic Seduction*, we can also discern a reformulation of the entropic aesthetic. To unpack it, we might start from the theorization of entropy that occurs within the writings of Robert Smithson, who extends the entropy concept from the physical domain to also encompass aesthetic and cultural phenomena. In Smithson's writings, which were closely tied to his artistic practice, the interpretation of entropy as 'sameness' dominates (Smithson 1996). This is a meaning that originates in thermodynamics, where the second law predicts that when two closed systems are put into contact, they will gradually attain the same temperature. But also, that this phenomenon will eventually manifest on a much vaster scale, resulting in the so-called *heath death*, a condition of maximum entropy wherein the Universe will have attained an even temperature and all macroscopic movement ceases to exist. Smithson reinterprets and applies this gloomy teleology on a cultural scale with a critical bent, as entropy becomes tied to a diagnosis of cultural and aesthetic uniformity but also to an affirmation of facticity within contemporary minimalist art that he sees as taking part in developing a new kind of monumentality.

But where can this entropic sameness be located today? Given that soft robotics can be conceived of as an intermingling of computing, sensing, and actuation technologies with soft matter, it seems logical to start by looking at the physical computing technologies that the soft sculptural medium is augmented with as it transforms into soft robotic art. From a contemporary perspective, Smithson's notion of entropy, as descriptive of a qualitative sameness that pertains to facets of cultural practices, art, and the built environment, is also obviously missing a crucial component, namely an account of the effects that the proliferation and implementation of computational technologies on a planetary scale over the past couple of decades have had. The contemporary lifeworld is permeated by and saturated with computational media, software programs, algorithms, as well as networks of sensors and actuators assembled as a still expanding *internet of things*. Terms such as *pervasive computing* and *ubiquitous computing* (*ubicomp*) are often used to describe this phenomenon (Ekman et al 2015). A number of theorists have taken note of how this development has rendered computational processes ambient and atmospheric, and consequently established a dispersed environmental computational agency. Mark B.N. Hansen, for instance, argues that

> Through the distribution of computation into the environment (…) space becomes animated with some agency of its own (Hansen 2012, 33)

And that this sets new requirements for adequately thinking through the relationship between humans and technology. As he puts it,

> We must reconceptualize the coupling of human and technics beyond the figure of the 'technical object.' (Ibid., 51)

The animation of space of which Hansen speaks, can arguably be seen to have endowed the environment as a whole with life-like qualities, in the sense that the surroundings have attained what appear to us as both intelligences and autonomous agencies of their own. That is, within experience, the physical environment may be attributed abilities and a mode of being that were traditionally reserved for living beings within the modern scientific worldview. And, as Hansen argues, the fact that the forms of intelligence and agency the surroundings manifest can no longer be traced back to a single origin (a subject or an object), but are dispersed and networked in character, makes them troubling and hard to adequately conceptualize and come to terms with.

BRALL and *Synthetic Seduction* are emblematic of this contemporary condition of ubiquitous computing, I argue, wherein architectural elements (a wall) and domestic settings (a couch) via technological augmentation come to attain phenomenal qualities that were previously the preserve of living beings, and as a consequence start to appear semi-living. In these works, we are presented with sessile technical entities that are embedded into an environment, yet resemble living bodies visually, haptically, and auditorily. The living figure has merged with the ground, one might say, to extend Krauss' phrasing. The works thus take part in a dramatization of the sameness and indistinction between humans, technology, and environment that ubicomp has brought about, i.e. the interlacing of human existence with a set of intelligent and agential technologies that have begun to spill out into all parts of the human habitat. In doing so, the artworks attain an uncanny quality in the sense that they seem to reactivate a suppressed knowledge of the increasingly central role played by technology and technological agencies within everyday life. In a hyperbolic manner, they appear to give a missing body to ubiquitous computational processes, intelligences, and agencies, that, despite the recent focus on materiality and infrastructure within media theory, often tend to be conceived as abstract and dematerialized. Compared with the sophistication of the machine learning algorithms that have intertwined with contemporary everyday life, they appear strangely analogue and anachronistic, donning an almost vulgar corporeality. Their artificial soft bodies appear crude, perhaps even unintelligent, as they are reduced to only displaying basic bodily functions similar to those controlled by the autonomic nervous system (breathing and intra-bodily motion). It is tempting to think of the works as reversals of Mark Weiser's original vision of ubiquitous computing as the becoming invisible of computing technologies (Dourish 2004; Weiser 1991) and the subsequent notion of unobtrusive *calm technology*, he took part in developing (Brown and Weiser 1997). Yet *BRALL* and *Synthetic Seduction* derive their aesthetic effects from a calming and casualizing of human interactions with strange embodied technological entities, that at first sight might appear repulsive, via switching back and forth between enrolling them and the viewer in background and alterity relations.

VII. Onwards from Soft Sculpture to Soft Robotic Art

This essay has addressed the question of how softness can be seen to afford impressions of the life-like within postminimalist soft sculpture and contemporary soft robotic art, and what conceptions of soft life these two strands of works activate. I have proposed that the concept of entropy can serve to elucidate aspects of this phenomenon as it unfolds within the critical reception of postminimalist soft sculpture. Extending this analysis, I argued that with a reworking and expansion of the entropy concept that emphasizes entropy as sameness, it also has analytical purchase in analyzing more recent artworks wherein soft robotic life-like entities merge with their surroundings.

In conclusion, and in order to return to the broader interest stipulated at the outset about a possible connection between softness and the process of life, the question I raise is what might soft sculpture and soft robotic art add to soft robotics research that explicitly seeks to replicate soft bodies of living organisms in a technical medium? By posing this question, I do not mean to insinuate that art must measure up to purposefulness as a yardstick, nor that the value of art lies in its potential as a driver of innovations that eventually become useful. Instead, the question is posed from a commitment to transdisciplinarity in acknowledgement of the historicity and contingency of the modern distinction between art and science/technology (Guattari 1995) and the onto-epistemic potential held by artistic practices.

The obvious and straightforward art historical answer to this question is the traditional avant-garde reply wherein the potential of art is postulated to lie in its criticality and ability to subversively scrutinize cultural tendencies and positions. And this answer also resonates with the contextualizing reading I proposed of *BRALL* and *Synthetic Seduction*. Soft robotic artworks, such as *BRALL* and *Synthetic Seduction*, can indeed be said to add vital reflections to more instrumentalist technical research agendas by probing the ramifications of contemporary technologies on human and non-human life. But also by going further and introducing a *naturecultural* (Haraway 2003) perspective by drawing attention to the fact that the biophysical process of life can no longer be imagined to unfold within a 'natural' environment, but is set to evolve within augmented technical settings and on a planet whose state and constitution is tied to human culture and activities.

However, other answers to the question are also possible. In retrospect, the postminimalist aspiration of attaining reciprocity between form and material, and the associated intensive probing of how physical properties can engender specific structural organizations and behaviors that are inherent to soft matter, can be seen to anticipate a central conceptual pillar of technical soft robotics research. I am referring to the idea that the implementation of pliable materials can serve to greatly simplify a robot design or make a robot perform some tasks more easily or better (Laschi and Cianchetti 2014). That is, specific material properties can contribute to attaining specific functionalities. This principle, roboticists claim, is already implemented in the soft bodies of natural organisms whose designs have been optimized by the process of natural evolution. The notion of life as being processual and entwined with the physical environment, contained in an entropic aesthetics of life, is also central to research on biodegradable robots occurring at the fringes of soft robotics. Here, a more ecological view of robots than that which is generally the order of the day in robotics, prevails, and robots are envisioned to have life-cycles and sustain themselves through exchanges with specific physical environments (Rossiter et al. 2016). Hence, actuators and other parts are constructed from biodegradable materials such as gelatin but also latex, a material that was also favored by Eva Hesse, who was well aware of its eventual degradation over time. However, such overlaps and shared interests between art and soft robotics research seem to have almost vanished within contemporary media art that uses soft robotics technology. This strand of artworks instead tends to work in the vein of the historical tradition of robotic art.[8] That is, the main impetus is usually an interest in an aesthetic of robotic behavior, conceived of as embodied actions and interactions that unfold on a humanly perceptible time scale. This allegiance serves to extend the interests of the tradition of robotic art found within the broader field of media art. But it would be interesting, I posit, to see artists treating soft robotics less as a fixed technology that is an extension of traditional robotics, and more as a medium or affordance in its own right, with singular capacities and modes of composition that must be invented, and continually reinvented, physically and aesthetically from scratch. Perhaps postminimalist soft sculpture can provide some inspiration for undertaking this work.

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[8] See Kac (1997), Wilson (2003), Whitelaw (2004), Penny (2013), and Shanken (2014).

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Leveraging morphological computation for expressive movement generation in a soft robotic artwork

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ABSTRACT

The paper describes the design of a cephalopod-inspired soft robot that is part of the art installation *Tales of C* (2017). Two soft modules for movement are presented, one actuated by a servo motor the other with pneumatics. It is shown that dynamic biomorphic movements can be realized with these modules using simple control signals (linear and constant changes).

CCS CONCEPTS

• **Applied computing → Arts and humanities**; Media arts • **Computer systems organization → Embedded systems**; Robotics • **Human-centered computing → Human computer interaction (HCI)**

KEYWORDS

Soft robotics, robotic art, aesthetics, morphological computation, robotic movement.

ACM Reference format:

J. Jørgensen. 2017. Leveraging morphological computation for expressive movement generation in a soft robotic artwork. In *4th International Conference on Movement Computing Proceedings, London, UK, June 2017 (MOCO'17)*, 4 pages.

1 INTRODUCTION

Within the research fields of Social Robotics, Human-Robot Interaction (HRI), Cultural Robotics, and Entertainment Robots the issue of how to generate and utilize expressive robot movement has surfaced as an important area of inquiry [1]. Research on soft robotics has on the contrary directed its main attention at the two other fundamental types of robotic movement: locomotion and manipulative movement [2]. This paper seeks to connect soft robotics research with research on expressive movement design for robots. It aims at shifting the focus on practical applications in soft robotics research towards the aesthetic potential of soft robotics as an expressive medium.

The paper shows by example that soft materials can offer a shortcut to generating expressive biomorphic robotic movement. It contributes a modular design of a cephalopod-inspired soft robot based on the concept of *morphological computation* commonly used to describe how pliable morphologies may obviate the need for extensive computation in the control loop of a robot [3][4]. This principle is leveraged for designing the soft robot "with expressive movement in mind" [1]: The expressive movement generation is delegated to the mechanical properties of the soft silicone morphology and its interaction with its surrounding medium (water). It is shown that with the design simple linear changes in control signal over time result in highly biomorphic movement dynamics.

The presented system is based solely on open source hardware and software and easily lends itself to modifications. It has a low cost of materials (around EUR 20 to construct the entire morphology excluding the control board and the embedded LED ring). STL files for the molds used to cast the morphology as well as the microcontroller code used to generate the movement are included as supplementary materials, making it possible to replicate or expand on the design for applications in other robotic artworks, creative robotics, entertainment robots or animatronics.

2 BACKGROUND

The practice-based artistic research project *Tales of C* (2017) by the author explores the ethology and aesthetics of cephalopods as metaphors of twenty-first century computational media dynamics. In its current form the installation consists of an aquarium containing a cephalopod-like robot, installed in an enclosure alongside the pneumatic and electronic systems that support the robot, a PC laptop, and an active loudspeaker.

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MOCO '17, June 28-30, 2017, London, United Kingdom
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ACM ISBN 978-1-4503-5209-3/17/06...$15.00
http://dx.doi.org/10.1145/3077981.3078029

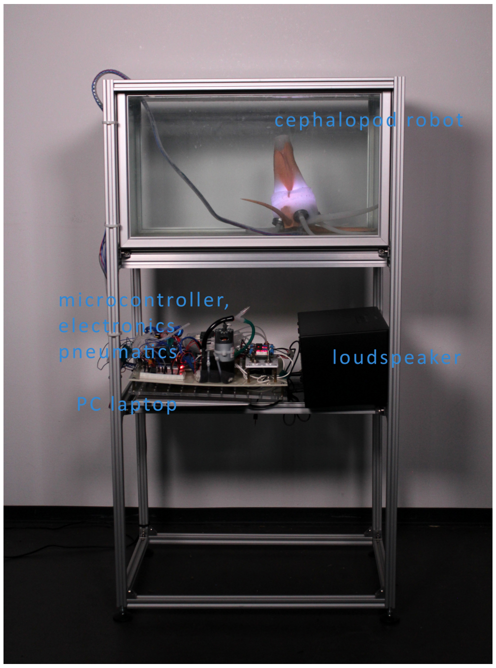

Figure 1: *Tales of C*, mixed media, 2017, approx. 135 x 65 x 40 cm. The installation setup photographed in daylight. (© Jonas Jørgensen. Photo: Jonas Jørgensen.)

An important aspect of constructing the installation was to design the cephalopod-like robot so that it would be perceived as embodying both “technological” and “biological” qualities. To accomplish this it was decided to fabricate it in soft silicone but to keep its shape as a combination of simple geometric forms (cones, tubes, and boxes).

Figure 2: *Tales of C* (2017). The artwork photographed installed in a darkened room running in exhibition mode. A video of the installation can be seen here: https://youtu.be/B4S0E5D4zck (© Jonas Jørgensen. Photo: Jonas Jørgensen.)

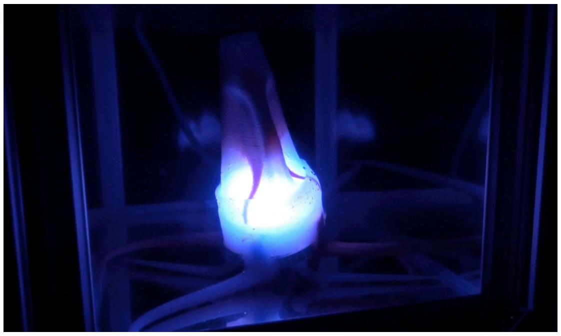

Figure 3: *Tales of C* (2017). Close-up of the soft robot. (© Jonas Jørgensen. Photo: Jonas Jørgensen.)

A number of soft robots exist that are inspired by cephalopods. These are, however, either based only on parts of the animal’s anatomy (often a single arm) or relatively complex systems aimed at fulfilling the specific task of locomotion either by way of crawling or pulsed-jet swimming. The design presented here was inspired by arm and leg designs from the OCTOPUS and PoseiDRONE projects [5], but uses only one hobby servo motor for actuation of each arm rather than pull-string or crank mechanisms. For the purpose of the installation this more simple system that would still fulfill the aim of displaying biomorphic dynamic movement was preferable.

3 DESIGN

The robotic morphology is based on two previously fabricated prototypes: The first a conical “arm” constructed from highly elastic and soft Ecoflex 0030 silicone cast onto the horn of a 9g hobby servo motor (TowerPro SG90). With this prototype, it was observed that the servo arm was able to move unhindered from side to side at angle variations of up to approx. 45 degrees even if cast into the silicone (see Fig.4). Moreover, the design was waterproof and servo sweeps (linear increments in servo angle over time followed by linear decrements) resulted in biomorphic fluid movements of the arm when submerged in water (video at: https://www.youtube.com/watch?v=ifLChDLxdjE).

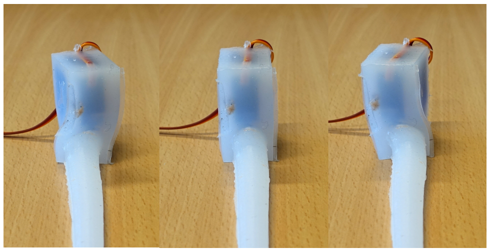

Figure 4: A servo motor with a silicone arm attached embedded in silicone. The servo angle is set to 45, 90, and 135 degrees (left to right) respectively. The softness of the enclosure makes it possible for the servo arm to deform the material and move unhindered to both sides. (© Jonas Jørgensen. Photo: Jonas Jørgensen.)

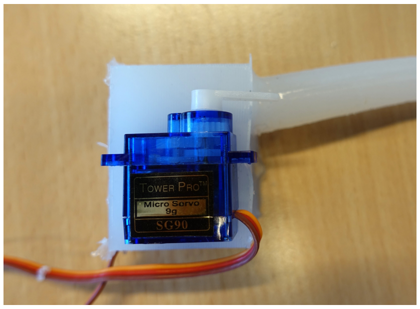

Figure 5: A servo motor placed on top of a servo enclosure to illustrate where the motor and the servo arm are located inside the enclosure. (© Jonas Jørgensen. Photo: Jonas Jørgensen.)

The second prototype was a pneumatically actuated three-chambered silicone tentacle. Experimenting with it revealed that the volume of this structure could increase significantly upon inflation. This led to the idea that it might be used as a controllable floating device.

The cephalopod-inspired morphology was conceived as a modular design that integrates four arms derived from the "arm" prototype. These active arms are combined with an inflatable top part based on the tentacle design. A further four passive arms without any actuation were added to the design.

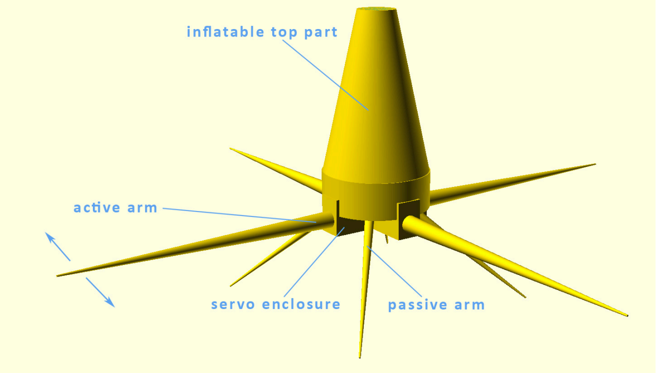

Figure 6: A CAD rendering of the complete robot morphology. The height of the robot's body (measured from the top of the inflatable part to the bottom of the servo enclosures) is 192 mm. The active arms are approx. 235 mm long (measured from tip to servo enclosure) and 15 mm in diameter at the widest part (© Jonas Jørgensen. Illustration: Jonas Jørgensen.)

4 FABRICATION

The fabrication process of the morphology involved casting the silicone parts separately in 3D printed molds with the needed electronics (servo motors, an LDR sensor, an LED ring) embedded. Casting the servo motor inside the silicone was successful in 8 out 10 cases (two motors were not working after the procedure). The molds were designed in OpenSCAD and exported as STL files. They were printed in PLA on a consumer-grade FDM 3D printer (Ultimaker 2 Extended) and sliced using the free Cura software. The cast parts were assembled by using uncured Ecoflex 0030 and SilPoxy adhesive to bond them together.

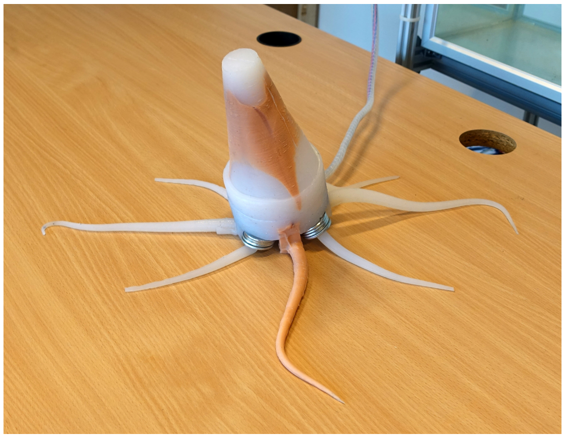

Figure 7: Photo of the assembled soft robot. Four iron washers were attached at the base of each of the passive arms with zip ties in order to increase the weight of the robot to prevent it from floating. (© Jonas Jørgensen. Photo: Jonas Jørgensen.)

5 CONTROL AND MOVEMENT IMPLEMENTATION

5.1 Control hardware

The morphology is controlled with the *Fluidic Control Board* that is part of the open source Soft Robotics Toolkit [6]. It is programmed in the Arduino IDE. The three chambers of the inflatable top part are connected to push fit pneumatic connectors on the board with 3mm (outer diameter) PVC tubing. The servo motors and the LED ring embedded in the morphology are powered from an external power supply with 5V and their control signals generated using PWM pins on the Arduino MEGA microcontroller.

5.2 Movement concept

Through experimenting with the prototype three expressive motion primitives for arm movement were discovered empirically:

a) Slow sweeps with the same backwards and forwards speed (a probing relaxed gesture)
b) Fast sweeps with the same backwards and forwards speed (movements suggestive of locomotion)
c) Sweeps with high speed in one direction and low speed in the other (an aggressive kind of twitching)

The movement concept underlying the programming of the robot is based on the idea that the robot should perform only subdued motion that is just enough to maintain notions of liveness when the synthetic voice (coming from the laptop and the loudspeaker) is narrating the installation. When the narration stops, the robot should react with more energetic behaviors and after this go back to the subdued movement pattern. Inspired by the interpretations of the movement primitives (listed in parenthesis above) and the findings of Inderbitzin et al [7] that the speed of body movements are correlated with arousal level, type a) movements were chosen for the first situation and type b) and c) for the latter. The energetice movement pattern also includes inflation of the top part, which makes the robot ascend, and dynamic light changes on the LED ring.

5.3 Movement programming

The control of the arms occurs with a function called "servoSweeps()". It is called with four control variables: The number of sweeps to perform, the delays in ms before incrementing or decrementing the servo angle 1 degree, and the maximum displacement angle of the servo arm from the equilibrium position of 90 degrees.

The Arduino microcontroller is set up as a slave that communicates with a C++ program running on the PC laptop over serial connection via ÙSB. When the microcontroller does not receive any signal the servoSweeps() function is called with a low angle and high delays (for one or all four motors) yielding movements of type a). Every time the speak is concluded on the PC laptop a signal is sent over the serial connection. This triggers either inflation, changes in lighting, or more energetic flapping of the arms for a period, i.e. servoSweeps() calls with shorter delays and a higher servo angle displacement corresponding to movements of type b) or c). The variable values used for the function calls are all overlaid with some randomization noise, i.e. the values are not fixed but confined to specific intervals corresponding to a call of type a), b), and c) respectively. This was done to achieve variation in the robot's movement that was deemed essential to creating an illusion of animatedness

6 RESULTS AND DISCUSSION

Albeit a simple system it was possible to create biomorphic movement with some variety. Emergent changes in functionalities that contribute variation in behavior were also identified when the system was running. These include a shift from the servo motors flapping the arms in the water to them moving the body from side to side when the robot drops to the bottom of the tank. But also a bending backwards of the arms when the robot is ascending (due to their softness).

Informal preliminary user interviews (N=4) conducted in the lab with the robot running movement patterns without speak revealed that subjects frequently used the terms "natural", "fluid", and "lifelike" to describe it. The movement patterns were, however, perceived as repetitive and predictive after a couple of minutes, suggesting that more contrast and variation might be beneficial to sustaining an illusion of animatedness.

7 CONCLUSION

This paper has described the design of expressive movement in a simple cephalopod-inspired soft robot. Using linear servo sweeps in combination with constant rate inflation it was possible to achieve biomorphic movement with the morphology. The design was successful in this task by leveraging the inherent movement dynamics of a thin arm constructed from Ecoflex 0030 submerged in water and changes in the morphology's density accomplished by inflation.

SUPPLEMENTAL MATERIALS

- Movement code for Arduino MEGA 2560 and STL files for 3D printing the molds: https://github.com/RobotisMollis/TalesOfC-github

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[5] http://sssa.bioroboticsinstitute.it/projects/OCTOPUS and http://sssa.bioroboticsinstitute.it/projects/PoseiDRONE.

[6] http://softroboticstoolkit.com/

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Tales of C: Cephalopodic Aesthetics and Computational Media

Jonas Jørgensen

Abstract

This paper presents central ideas formed in the process of constructing the artwork *Tales of C* (2017) and contextualizes the work in relation to the central sources of inspiration. It describes the author's experimentation with how to create a cephalopod robot that is adequate to the cephalopodic as a naturecultural force and aesthetic, and hence goes beyond merely trying to replicate the biomechanics of this animal class. The project develops the intuition that the cephalopodic and computational media processes share certain defining characteristics, and that the intermingling of cephalopodic bodies with information technology inherent in contemporary *soft robotics*, is prefigured in other contexts. Consequently, the project seeks to reenact, expand, and problematize the notion of an artificial cephalopod by drawing on a wider range of practices and cultural imaginaries surrounding cephalopods that are absent in its current instantiations within robotics research.

Prologue

In the beginning there is the arm. The arm, unlike the brain, is replaceable and modular. It can be put into a vat. It can be assembled with other parts of a body in different numbers. One arm, two arms, four arms, or eight.

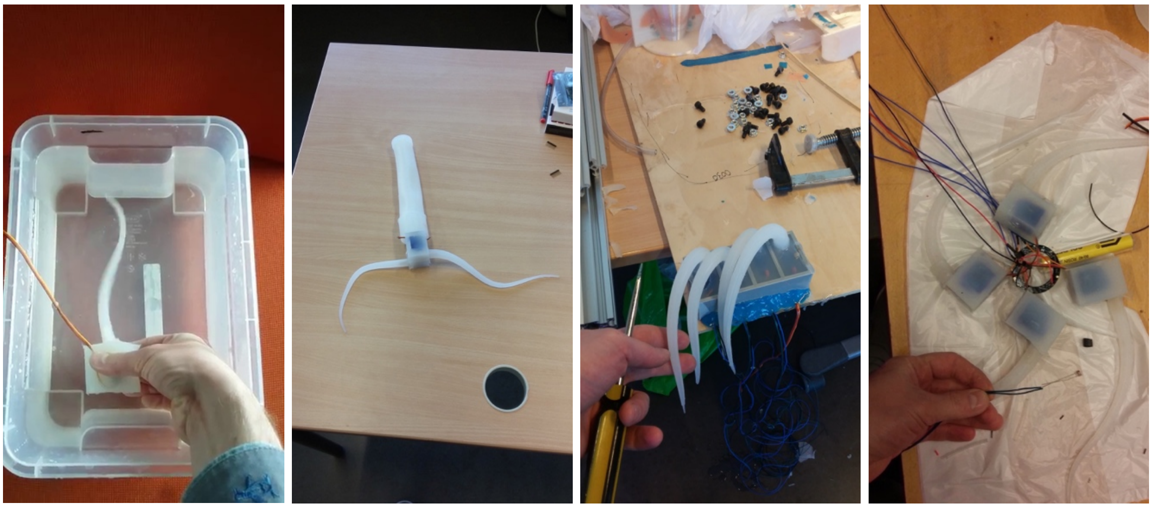


Fig. 1. Arms in different configurations. The arm to the left is submerged in water. (Photos: Jonas Jørgensen)

In cephalopods (members of the molluscan class *Cephalopoda*, which counts, among others, the squid, cuttlefish, octopus, and the chambered nautilus), the separation between the brain and the arm is not sharp. The brain slips into the arms, thus partitioning itself, separating itself from itself, metamorphosing into something else that leaves us ‘moderns’ dumbfounded. ‘[T]he octopus is like the Internet, whereas we are stuck with individual CPUs’, a researcher recently declared with reference to the fact that two thirds of the octopus’ neurons are distributed throughout its arms that seem to operate somewhat on their own in a decentralized manner, performing routine tasks without communicating with the central brain (Courage 2013).

An arm is an effector, it manipulates objects in an environment. Its actions are composed of movements that can be decomposed further into smaller segments with a chosen granularity. Yet when working efficiently, an arm acts fluently and appears as if working both in accord with itself and its environment. The movement is not in the arm, nor is it in the water. It subsists in the coupled system.

Cephalopoda

The iconographical meanings attached to cephalopods are many and representations of the animals stretch back from Greek vase paintings of the second millennium BC to Japanese woodcuts of the 19th century and more recently activist digital media. Among the prominent cephalopodic cultural topoi, media scholar Melody Jue lists the cephalopod body as a depiction of ‘unchecked power, greed, or libidinal energy’ notably in critiques of imperial, colonial, and corporate entities (Jue 2014, 83). Cephalopods are equally used to invoke notions of action at a distance and, on a more positive note, to signify interconnectivity between individuals, and flexibility in movement or communication. Their bodies are historically tied to the erotics of touch and a sexuality that transgresses the borders between biological species, as in the example of Katsushika Hokusai’s *Dream of the Fisherman’s Wife* (1814), but also the contemporary anime/manga genre Hentai bear witness to. ‘[T]he figure of the cephalopod drifts between opening and closing channels of material interconnection’, Jue writes (Jue 2014, 83). But cephalopods do more than that: they manipulate, control, and move or affect in myriad ways that often seem to escape human apprehension and epistemological capture. The fascination that they hold for technologists, for instance, is often rooted in the preciseness of the control they exert over objects in their environment in combination with what is perceived as a strong-willed and highly inventive mind: they routinely manage to escape from aquariums in unanticipated ways or from jars by twisting off the lids from the inside. In fact, certain species can even handle childproof bottle-caps (Courage 2013).

Cunning

Within Western culture, the intelligence of cephalopods has historically been considered as closely linked with their ability to blend in with and assimilate to their environment. Cephalopods are polymorphous, they may change configuration and adapt their body to specific tasks. In Greek mythology, such shape-shifting capabilities were associated not just with changes in the physical body but also with a specific ontology and modes of fluid thinking and being that are characteristic of water deities and their aquatic milieu. '[The] power of metamorphosis possessed by the Old Man of the Sea and the goddesses of the sea is associated with a particular type of intelligence compounded of craftiness, cunning and trickery which comes into play when, instead of contemplating the immutable essences, one has to come to grips with the shifting, multiple and unpredictable entities of Becoming', historians Marcel Detienne and Jean-Pierre Vernant write (Vernant and Detienne 1991, 144). And, they continue, 'In this world of constant change what is necessary is a mind which is *pantopóros*, fertile in inventiveness, capable of devising a plan … suited to the circumstances of every occasion, and of finding a way out and expedient, *póros*, to escape from the *aporía* or … to be able to find clever ways out from impossible situations.' (Vernant and Detienne 1991, 144). The Greeks referred to the kind of wisdom, skill, or craft described here by Detienne and Vernant as *mêtis*. Besides deities, certain animals also possessed it, they maintained, including the cuttlefish and the octopus, in which it was perceived as strongly linked with their polymorphic powers (Vernant and Detienne 1991).

Calculation

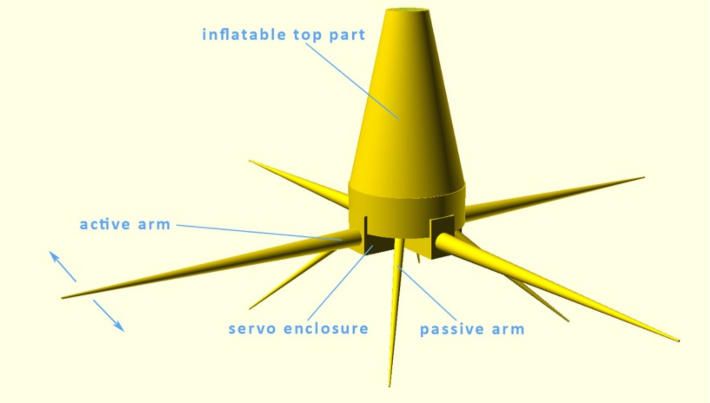


Fig. 2. CAD rendering of a cephalopod-inspired soft robot

Craftiness and cunning are usually cynical and calculated efforts, but perhaps this is not the case when carried out by cephalopods. Calculation implies abstraction and distance, autonomy, cold-gazing, the ability to picture oneself as separate from the fabric of the world. Calculated moves are founded on logical reasoning combined with an acute attention paid to the dynamics and relations that envelop people and other entities. The success of such moves is predicated on one's ability to precisely extrapolate the consequences of a specific intervention from the current state of things, to master black-boxed dynamics – given this input, what will the resulting output be?

Within the past ten years, soft robotics has become established as an emerging subfield of technical robotics research (Bao et al. 2018). Cephalopods have by far been the most paradigmatic animal models from which its bio-inspired robot designs have been derived. The first autonomous soft robot, published in 2016 in the pages of *Nature*, thus took the shape of an octopus not for functional reasons but as an homage to this animal in recognition of its importance as a driver of soft robotics research (Wehner et al. 2016). The interest of technologists in the dispersed or networked intelligence found in cephalopodic bodies dovetails with a shift away from symbolic 'good old-fashioned AI' towards the bottom-up and connectionist approaches that underlie the most recent advances in machine learning. However, roboticists have also taken to utilizing the concept of *morphological computation* to describe how the mechanical properties of its simple pliable limbs may, in themselves, obviate the need for extensive computation and heavy calculations in the control loop of a robot's software. Morphological computation has been theorized mathematically by showing that the mechanics of soft elastic bodies are equivalent to mass-spring systems, and that such systems perform a complex filtering of a given input of mechanical forces (Hauser et al. 2011). The ontological import of this physico-mathematical description is easy to miss, but has important implications for considering the link between cephalopodic bodies and intelligence in relation to computing and robotics. What the mathematical theory of morphological computation highlights is the capacity of soft materials to compute. It posits that soft matter can process information (signals received as incoming forces) in ways that are equivalent to procedures composed of logico-mathematical operations. In the context of a computational theory of mind (the notion that the mind is in essence an information processing system and that thinking is a form of computing), this would seem to indicate a latent capacity for intelligence inherent in soft matter.

In its idealized abstract theorization, the intelligence of soft matter is rendered comprehensible yet also unlike that of natural brains. It is without history and memory and hence purely reactive. It is elastic rather than plastic:

> While plastic material holds its form and cannot return to its initial state once it has been configured […] elastic material does return to its initial form and loses the memory of the deformation that it has undergone. (Malabou 2012, 177)

Co-evolution / Compliance / Chthulucene

Despite the fact that the octopus was described as a pneumatic machine by Victor Hugo (Hugo 2007), cephalopods' ethologies are far from mechanical. Much like contemporary biopolitics or soft power, these animals manage to thrive by inhabiting and redirecting the vital forces, dynamics, and currents that are already present in accordance with their own agendas. Thus, what the mathematical theory of morphological computation misses in relation to cephalopods is to account for the importance of intelligently inhabiting and relying on one's surroundings. But 'where does the mind stop and the rest of the world begin?' (Clark and Chalmers 1998)

In Félix Guattari's *The Three Ecologies*, he describes an experiment with a living octopus that was broadcast on live TV in France (Guattari 2008). The octopus was caught in the polluted waters of the Marseille port and put in a tank containing some of this water. At first, it appears lively and well. It is then moved to another tank filled with unpolluted seawater. After a few seconds all movement stops and the creature falls to the bottom, as it has died.

Fig. 3. An octopus stranded in a Miami Beach parking garage after a tide in November 2016. (Photo: Richard Conlin)

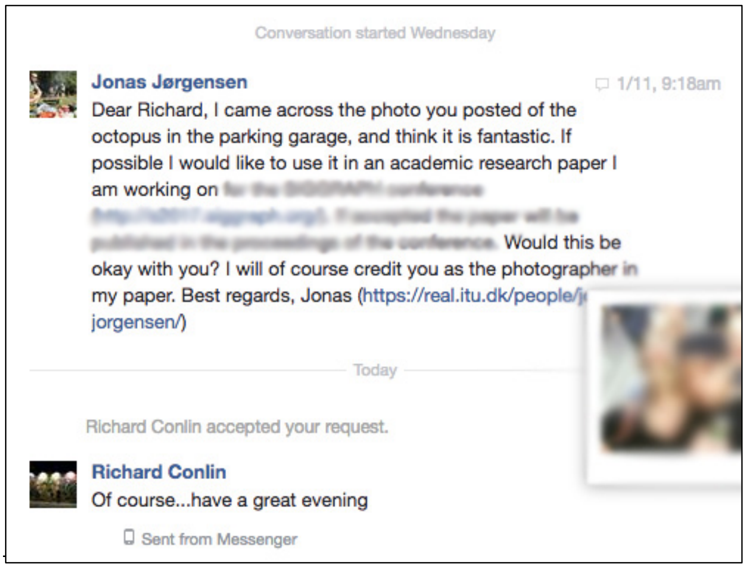
The contemporary situation of the cephalopod is riddled with an ambiguity similar to the one contained in Guattari's anecdote. Many cephalopods have died, in fact the extinct member species of the animal class by far outnumber the ones currently living. Yet cephalopods have been thriving in recent years and have steadily increased in numbers since the 1950s, which researchers hypothesize is due to warmer oceans and the adverse effects of man-made climate change (Doubleday et al. 2016; Monahan 2016). In Donna Haraway's most recent writings on the 'Chthulucene', she thus mentions cephalopods articulating a 'tentacular thinking' aimed at engaging with our damaged and still deteriorating planet. 'The tentacular are […] nets and networks', tentacularity is about 'life lived along lines […] not at points, not in spheres' (Haraway 2016), she makes clear.

C Media

Morphological computation casts soft elastic bodies as inherently mediatic. Solely by virtue of their mechanics, they are always already physically enrolled in the transmission and processing of information. In *Vampyroteuthis Infernalis* (the Vampire Squid from Hell) (1981), Vilém Flusser presents a fable that poses as a scientific treatise on the cephalopod species with this unflattering name. Extrapolating from a base of scientific evidence about the animal available at the time of writing, Flusser constructs a highly speculative but equally compelling narrative of, among other things, its art and culture, in which media models of communication also figure prominently. By way of a phenomenology and a psychology constructed on inference from its biology, Flusser arrives at a conception of the life-world of the Vampyrotheutis, which somewhat resembles the understanding of cephalopods in Greek mythology described earlier.

According to Flusser, Vampyrotheutis does not transmit its history through inscriptions on objects as humans have historically. Moreover, he claims that durable stable objects are anathema to its philosophy, as its perceptual field is inscribed in a fluid field and comprises fleeting phenomena: ‘He [the Vampire Squid] is not Platonic, he is organismic. It is not philosophical contemplation, but philosophical vertigo and its posture.’ (Flusser 2011, 79). Flusser also remarks that, having no verbal language, an important communicative means for the animal is the chromatophores found on its skin that allow it to change color, which Flusser claims is integral to attracting mates (Flusser 2011, 85). In fact, this performance must, in Flusser’s view, be seen as the substrate of its art, which involves not the creation of objects but seduction. ‘[W]hen he creates, Vampyroteuthis does not experience the resistance of the object but the resistance of the other.’ (Flusser 2011, 109). The creative act, Flusser bluntly states, necessarily involves ‘deliberate deception, artifice and lies’ (Flusser 2011, 111).

In Flusser’s text, the Vampyrotheutis throughout serves as a kind of distorted mirror image of the human. Part of the philosopher’s interest is thus to use the creature to shed new light on human culture by emphasizing divergences but also overlaps with Vampyroteuthian culture. Flusser finds a crucial example of the latter in the human ‘communication revolution’, which he ultimately sees as consisting ‘of a diversion of the existential interest stagnating in objects back toward the other’ (Flusser 2011, 114). Recently, we have thus reconnected with the squid: ‘Our communicational structures are being fundamentally transformed, in the sense of becoming constituted by ephemeral and transient media that allow the other to be informed without the need of objects. It is as if humanity, after a multi-millennial turn through the objective world, has now reencountered the vampyroteuthian path.’ (Flusser 2011, 114).



Jonas Jørgensen 1/11, 9:18am

Dear Richard, I came across the photo you posted of the octopus in the parking garage, and think it is fantastic. If possible I would like to use it in an academic research paper I am working on [redacted] Would this be okay with you? I will of course credit you as the photographer in my paper. Best regards, Jonas (https://real.itu.dk/people/j jorgensen/)

Richard Conlin accepted your request.

Richard Conlin

Of course...have a great evening

Fig. 4. My communication with Richard Conlin.

Albeit writing at a time when the preeminent example of ‘the communication revolution’ was flow TV, the themes introduced by Flusser are prescient of twenty-first century media conglomerations such as the internet and social media. Mark B.N. Hansen is one of a number of media theorists that have written extensively about how computational media have ushered in a novel technological regime. It is anchored in, on the one hand, micro-computational processes occurring on a time-scale so minuscule that they are inaccessible to human perception and cognition, and on the other hand, vast amounts of big data – an ocean of information that equally escapes us.

According to Hansen, ‘twenty-first century media is characterized first and foremost by the capacity for capturing information that directly concerns our behavior and tendencies but to which we ourselves lack any *direct* access.’ (Hansen 2016, 39). He refers to this as the ‘precognitive vocation of twenty-first century media’ and sees it as ‘deeply imbricated with the operation of global capital’. Contemporary technology allows for ‘predicting … behavior *before it actually happens*’ (just think of the sometimes uncannily intriguing suggestions of recommendation algorithms online).[1] Consequently, by utilizing computational media '[c]ontemporary capitalist industries are able to bypass consciousness – and thus to control individual behavior' (Hansen 2016, 40) [22]. In Hansen's theorizing of this process, which is described as having a 'feed-forward' structure, central tenets of the Vampyrotheuthian aesthetics thus resurface: artifice, deception, distraction, and capture.

'It's flashing now?' 'Yes, it's been doing that all along' [2]

The installation *Tales of C* consists of an aquarium in which an artificial cephalopod resides (video available under 'Supplementary Materials' below). The tank is installed in a frame furnished with the pneumatic and electrical systems that support the creature.

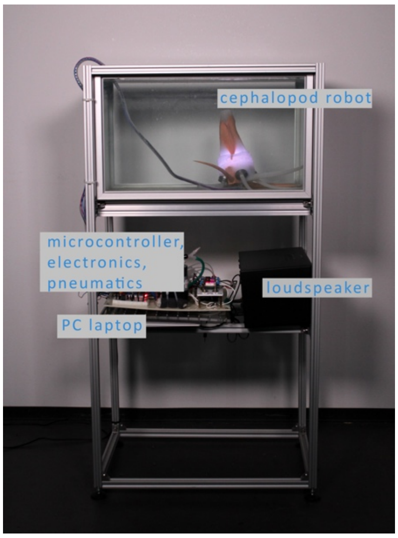


Fig. 5. Tales of C*, mixed media, 2017, approx. 135 x 65 x 40 cm. The image shows the system photographed in daylight. (Photo: Jonas Jørgensen)*

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[1] Another recent cultural example of this is the film *Ex Machina* (2014), wherein the robot Eve, based on biometric analysis, declares to the male protagonist that he is in love with her, yet he has not himself become aware of it.

[2] Comments from audience members when encountering the installation *Tales of C*.

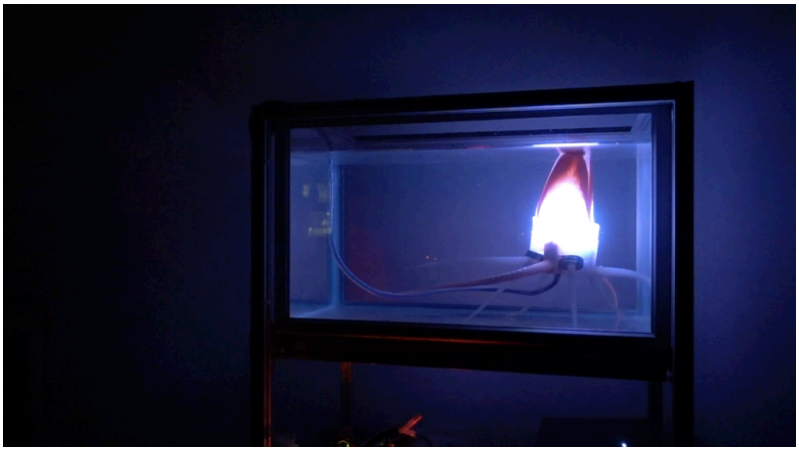

Fig. 7. Tales of C*, mixed media, 2017, installation view (detail). (Photo: Jonas Jørgensen)*

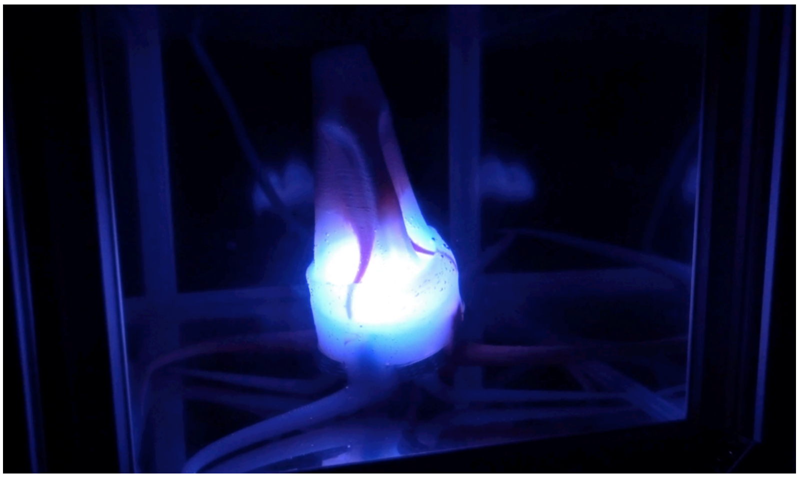

Fig. 8. Tales of C*, mixed media, 2017, installation view (detail). (Photo: Jonas Jørgensen)*

The cephalopod changes the intensity and hue of the light it emits and its arms move fluently. A loud noise, can be heard when the creature's body expands and it surfaces. Interchangeably with this, a synthetic voice recites a text generated by a computer program. The text consists of fragments drawn from a repository file, which contains excerpts from literature on cephalopods – from news stories, fiction, science articles, anthropology, and philosophy. Quotes from these sources are interspersed with text that the program continuously retrieves in real-time from Twitter posts mentioning the word 'cephalopod'.[3] A text paragraph is

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[3] This is done with an R script that runs on a laptop computer and stores tweets to a text file.

randomly selected every time the narration restarts. Some are dense, evocative, and linguistically well-crafted, while others come across as trivial or arbitrary. The serial juxtaposition of dislocated text fragments produces an unfolding narrative, yet one that continually breaks down in moments of disjuncture, reminiscent of the hiccups in conversational software agents and virtual assistants.

'What does it react to Anton? I don't think it reacts to us' [4]

Fig. 9. Mace Ojala and I were staged in lab coats together with the cephalopod by the IT University of Copenhagen's photographer for photos to be featured on the university's website and in social media (November 2017). (Photos: Martin Nedergaard Møller)

Artificial neural networks (ANNs) can be trained from a time series to predict future values of given variables of systems that are complex or chaotic, for which no analytical solution exists. The cultural phenomenon of 'Paul the Octopus', which unfolded a couple of years back, saw a common octopus predict the winners of all seven of Germany's matches in the 2010 World Cup. Visualizations of an ANN's structure resemble the cephalopodic body morphology, and, in fact, the physiological understanding of the *action potential*, the mechanism by which neurons generate and propagate nerve impulses, originates from

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[4] Comment from audience member when encountering the artwork.

experiments carried out with Giant Squid axons (Wang 2015). The ANN implemented in the artificial cephalopod was evolved through training with a data set that contains ocean temperatures from the past 60 years. The network takes the generated text along with readings from a light sensor as its input, and its four output neurons control the movement of the creature's arms.[5]

Closure

It is still out there. That is how tales of the sea normally end to withhold closure. But in this case, the pronoun is left dangling and the location would also seem to be unspecified – nowhere and everywhere. Its identity and properties are not easily fixed, and herein lies part of its power. It is a harbinger, it is thinking, action, and subjectivity gone formless, to the point of being nauseating, inside and out. A machine that reflects on itself, yes perhaps, but it bleeds into us, you C.

Supplementary Materials

Video: https://vimeo.com/334447890

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[5] The implementation of the ANN is temporarily suspended until I find a suitable collaborator to help me finish this work.

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Evolution of Fin Undulation on a Physical Knifefish-inspired Soft Robot

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ABSTRACT

Soft robotics is a growing field of research and one of its challenges is how to efficiently design a controller for a soft morphology. This paper presents a marine soft robot inspired by the ghost knifefish that swims on the water surface by using an undulating fin underneath its body. We investigate how propagating wave functions can be evolved and how these affect the swimming performance of the robot. The fin and body of the robot are constructed from silicone and six wooden fin rays actuated by servo motors. In order to bypass the reality gap, which would necessitate a complex simulation of the fish, we implemented a Covariance Matrix Adaptation Evolution Strategy (CMA-ES) directly on the physical robot to optimize its controller for travel speed. Our results show that evolving a simple sine wave or a Fourier series can generate controllers that outperform a hand programmed controller. The results additionally demonstrate that the best evolved controllers share similarities with the undulation patterns of actual knifefish. Based on these results we suggest that evolution on physical robots is promising for future application in optimizing behaviors of soft robots.

KEYWORDS

Soft Robotics, Evolutionary Algorithms, Covariance Matrix Adaptation Evolutionary Strategy, Evolution of Physical Systems

1 INTRODUCTION

Despite recent advances in evolutionary robotics, the reality gap [15] is still a prevalent issue. Especially in the emerging field of soft robotics it becomes more difficult to simulate the physical properties of soft materials accurately [25]. In cases where this was accomplished successfully, it required high computational power and complex algorithms [6]. For aquatic robots, the integration of flexible materials can lead to increased performance by the principle of morphological computation, i.e. by exploiting that dynamic interactions with the environment can be useful for achieving a desired behavior efficiently. The complex mechanics of silicone and its hydrodynamic interactions are, however, computationally heavy to simulate, especially when the morphology is driven by multiple actuators. For these reasons, we propose an evolutionary approach of directly evolving physical systems [24] as a feasible alternative method to evolve efficient behavior of a bio-inspired soft robot. To the best of our knowledge, this is the first paper to use an evolutionary algorithm to evolve a behavior directly on a physical soft robot without prior simulation.

Soft robots have been proposed for a number of applications that include exploration and search and rescue operations. For such tasks high maneuverability is usually necessary. Since the family of ghost knifefish (Apteronotidae) contain examples of dexterous aquatic animals capable of high multidirectional maneuverability at low speeds [20], we chose this fish as our model whose control will be subjected to evolution. Knifefish are able to produce thrust in many directions by undulating a single anal fin located underneath the body. By generating propagating waves across their fin they can easily move backwards and forwards depending on the directionality of the wave [9]. Vertical thrust is accomplished through sending counter-propagating waves towards and away from the center of the fin canceling out longitudinal forces. In undulatory swimming the thrust is produced through a reaction force on the fluid adjacent to the body or fin surface. Bending of the body part, in our case the fin, enables wave propagation. The combination of the lateral forces produced on both sides of the fin should cancel out each other to produce a net forward thrust [2].

1.1 Evolution of Soft Robots

The evolutionary robotics approach to soft robotics has thus far only been implemented in simulation environments such as VoxCAD [3, 4, 8, 16] or off-the-shelf physics engines where morphologies are represented by tetrahedral meshes and the controls and morphology have been evolved [23]. Computational power is, however, a major constraint when using simulations. Computational requirements scale proportionally to the amount of tetrahedra and voxels simulated, usually exponentially, increasing the computational power needed when more are used. Morphologies found through the VoxCAD approach have only been replicated physically by means of soft volumetrically expanding materials that require changes in the pressure of the surroundings for actuation [14].

Controllers for simulations of existing partially soft morphologies have also been evolved in simulation environments and in some cases transferred to hardware. A genetic algorithm with a "lumped" dynamic model simulation has been used to evolve the gait of a soft caterpillar-inspired robot and has resulted in an increase in performance of a physical prototype [26]. In another instance, both an objective-based and a novelty-driven (*novelty search* [17]) approach have been utilized to optimize the design of a crawling

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[*] These authors contributed equally to this work.

octopus by discovering self-stabilizing dynamic gaits [7]. A differential evolution algorithm was used to optimize a model-free adaptive controller (MFAC) in a simulation of a robotic fish with a flexible caudal fin [5]. For the same morphology an evolutionary multiobjective optimization technique (NSGA-II algorithm) found morphological and control parameters in simulation that maximize the swimming speed and minimize the power usage with subsequent validation in hardware [5]. However, in this approach it was found that the "best speed" parameters were considerably faster in simulation than in the experiments due to hardware limitations. This illustrates that although reasonable performance can be transfered from the simulation to reality, discrepancies are still persistent. In the above examples the evolution of soft robot morphologies and controllers was made possible by confining the search space to highly abstracted morphologies (fish where only a simple tail is flexible, caterpillar-like shapes) or by decomposing the morphologies into a finite number of voxels. While such approaches have yielded interesting results, they are still lacking in relation to realizing the full potential of soft robotics technology as they limit the design space to very simple or highly abstracted shapes. By evolving the controller in the physical hardware instead, one is able to reap the benefits of having both a bio-inspired design that mimics a natural model closely and an automated discovery of its most optimal behavior.

1.2 Knifefish-inspired Swimming Robots

Due to their unique morphology, knifefish have served as inspirations for a number of research robots. Building on the work of Low et al. [18, 19], Siahmansouri et al. constructed an untethered robot with 6 fin rays capable of regulating the direction and depth of swimming by moving the fin relative to a buoyancy tank [28]. Curet et al. built a knifefish-inspired robot with 32 individually actuated fin rays and were able to show that its optimal actuation parameters were similar to the ones of the black ghost knifefish [10]. They were also able to generate upward forces on the robot with counter-propagating undulation waves [9]. Sfakiotakis et al. devised a linear slide equipped with a fin composed of 8 individual fin rays and implemented open-loop velocity control and closed-loop position control [27].

A common denominator of the previous work on knifefish-inspired robots is the use of sinusoidal functions as an undulation pattern for the fin. This occurs despite the fact that a sine function is only an approximation of the actual undulation pattern of the species, which could be reproduced more accurately[30]. The design of our robot also departs from the earlier work as it is an integrated silicone morphology constructed with contemporary soft robotics fabrication techniques. This approach simplifies the fabrication of the fin and fin rays significantly. Moreover, elasticity is added to the fin, which has been hypothesized to be a means of increasing energy efficiency [18].

2 METHODOLOGY

We designed a soft swimming robot with a single undulating fin inspired by the anatomy of the black ghost knifefish[1]. To be able to evaluate its swimming speed with different motion patterns, we constructed the experimental setup shown in Figure 1. As we only evolve the forward swimming speed, the robot is fixed on a linear slide. It is not submersible and kept at a level of neutral buoyancy. The robot (E) is placed in the water surface of a 100×40×40cm aquarium. It is tethered with power and signal cables for its 6 servo motors. It is attached to a cart (F) with four ball-bearing wheels that is mounted on a T-slot beam linear slide (C) atop the aquarium. A plastic attachment piece (D) connects the cart to the linear slide and prevents the robot from turning. The slide is equipped with two IR sensors to measure when the beginning and end of the slide has been reached. For the evaluation of an undulation pattern, the robot starts on the left side of the track at the first IR sensor. During evaluation a swimming pattern is played on the robot and an ultrasonic distance sensor (A) measures the distance to a plastic plate (B) on the cart. The cumulative sum of the distance readings are used directly as the fitness value for the undulation pattern that was evaluated.

2.1 Mechanical Design of the Robot

The main parts of the robot are its hull, frame, and fin rays (see Figure 2) [2]. The hull and fin of the robot were constructed from Ecoflex 00-30 silicone (Young's modulus approx. 0.1 MPa, Shore A hardness 00-30) [22]. The uncured material was degassed after mixing and poured into a three part 3D printed mold (two sides and one inner part). The inner mold part holds the fin rays in place during casting and blocks out a compartment for the rigid inner frame, which was mounted after casting. The inner frame is constructed from laser cut acrylic parts that were glued together. The servo motors are held in place with bolts and nuts.

Six bamboo sticks (approx. diam. 3mm) serve as fin rays. With 6 fin rays it is theoretically possible for the robot to hover and to move forward, backward, up, and down by generating traveling and counter-propagating waves [9]. Each fin ray is attached to a servo motor via a servo bracket. The servo motors used were initially six H-KING HK 15148 mini servo motors. Due to malfunctions three of them were replaced with two TowerPro SG90 and one EMAX ES08AII. The servo motors are connected to the fin rays with a crank-like mechanism (Figure 3). The angle of a fin ray ϕ as a function of the servo angle α is given by:

$$\phi(\alpha) = \tan^{-1}\left(\frac{\sin(\alpha)\ \cdot 21}{30 - \cos(\alpha)\ \cdot\ 21}\right) \tag{1}$$

where the constant 21 is the distance (in mm) from the center of rotation of the servo to the piston that connects to the fin ray and the constant 30 the distance from the center of rotation of the servo to the approximate center of rotation of the fin ray (see Figure 3).

This equation, however, does not take into account the additional angular deflection caused by slack between the pistons and the fin ray, and the elasticity of the soft body resisting rotation (see Figure 4). The maximum angular excursion was therefore close to 28 degrees instead of the approximately 45 degrees that were calculated when not taking into consideration these issues.

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[1] A video of the robot and our setup can be found at https://youtu.be/3XjgZbs0t2g

[2] The CAD files for the design can be accessed at https://cad.onshape.com/documents/51d2c0394f6e3aa7b3fc06b3

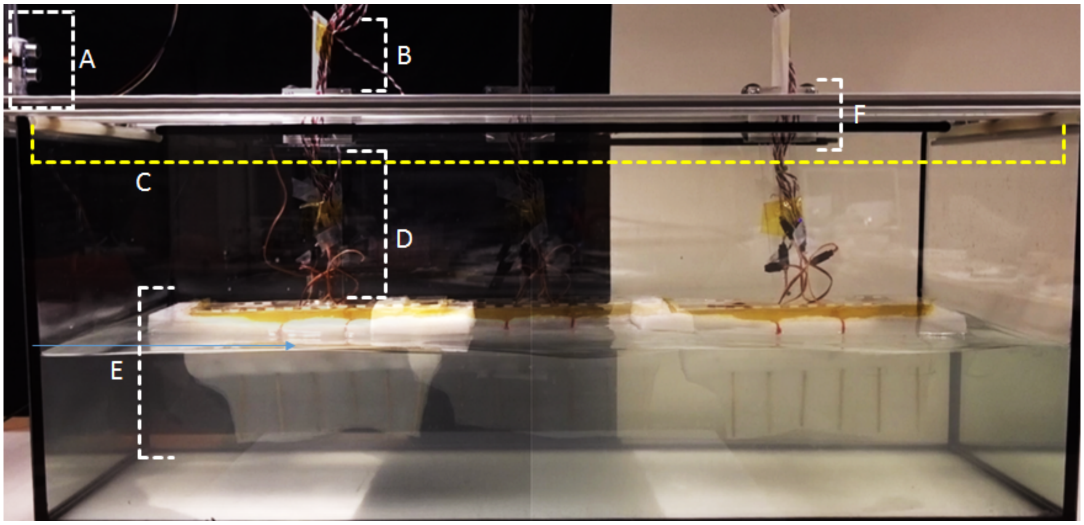

Figure 1: Experimental setup. (A) Ultrasonic distance sensor, (B) plastic plate for bouncing back the sound of the ultrasonic sensor (C) T-Slot linear slide, (D) plastic plate connecting the robot (E) to the cart (F). The evolutionary goal is to move the robot as fast as possible along the slide from the left to the right side of the aquarium.

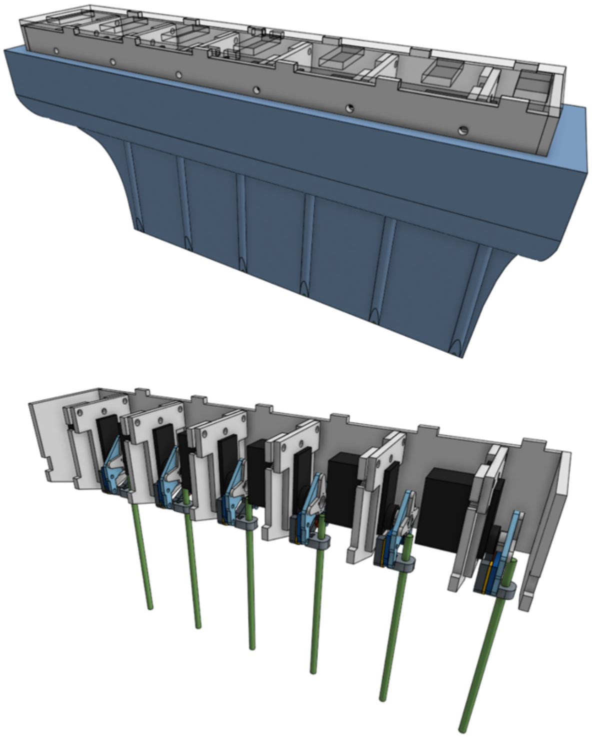

Figure 2: CAD design of the robotic knifefish. The white parts represent the laser cut acrylic parts, the blue part is the silicone part (top), the black parts depict the 6 servo motors that were used to actuate the fin rays. The bamboo sticks that serve as fin rays are displayed in green. The robot's full dimensions are 272x60x136mm and the fin is 70mm high and 210mm long. The fin rays are each spaced 40mm apart.

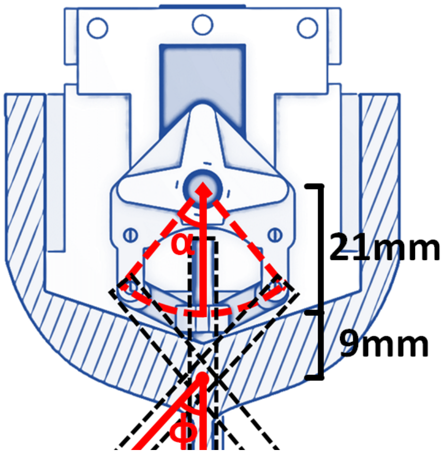

Figure 3: Cross section of the robot fish design. The red arc depicts the range of motion from the center of rotation of the servo motor to the plastic part that is connected to the crank mechanism. The red dot at the bottom in the hull depicts the approximate center of rotation of the fin ray.

2.2 Evolutionary Experiments

In our pre-experiments we implemented a generational evolutionary algorithm without crossover to create the genome for our robot controller. Due to the long evaluation time of the generational evolutionary algorithm, and servos being prone to overheating, we decided to implement Covariance Matrix Adaptation Evolutionary Strategy (CMA-ES) [12, 13] instead, to quickly find the basin of attraction and thereby speed up the evolutionary process[3].

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[3] Our full implementation and the source code of the evolutionary algorithm and Arduino code can be found at https://github.com/FrankVeenstra/Knifefish_GECCO2018

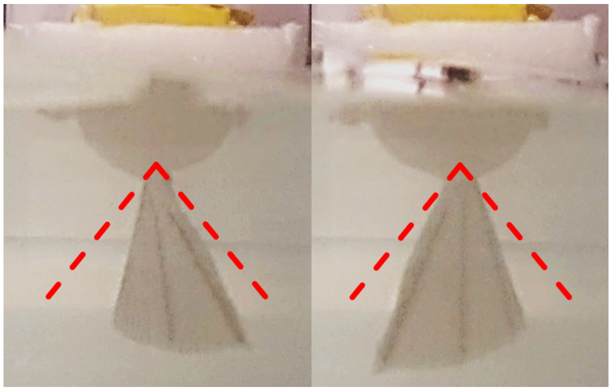


Figure 4: Angular deflection of the fin. Front view of the robot showing the angular deflection of the fin. The actual maximum angle of the fin can be seen to be less than the calculated angle (red dashed lines)

2.2.1 Encoding. The genome we created for an individual is composed of a string of 15 bytes. Each triple of three bytes translates into a sinusoidal function with a specific frequency, phase, and amplitude. The total of five sine functions are summed to yield the first five terms of a standard Fourier series. With this function we can approximate an arbitrary continuous periodic function and use it as a fin undulation pattern on the robot to be evaluated. The mutable parameters were the amplitude, phase, and frequency of each sinusoidal function. These parameters are converted into servo angles α_n for the 6 servo motors with the following function:

$$\alpha_n(t) = (\frac{g_1}{255} \cdot \theta_{max}) \cdot sin((g_3 \cdot t) + (g_2 \cdot n)) \tag{2}$$

where g_1, g_2 and g_3 represent the mutable parameters of a genome triple as bytes. θ_{max} is the maximum angle that the servo motors are allowed to move. n stands for adjacent servo motor numbers (values from 0 to 5) and t represents the time steps.

2.2.2 Evolutionary Algorithm. The evolutionary approach was divided into a control system and an evolutionary algorithm. The evolutionary algorithm made use of functions from the Distributed Evolutionary Algorithms in Python (DEAP) library which included an implementation of CMA-ES [11]. The CMA-ES implementation implemented a population size of 10 and ran for 20 generations. We found that CMA-ES was able to find similar solutions in 20 generations as running a normal generational evolutionary algorithm for 100 generations which was advantageous for limiting the duration of the experiments. Our CMA-ES implementation included an initial standard deviation value of 50 and a centroid value of 125 for every gene (half the max value of the bytes in the genome).

2.2.3 Controller System. An Arduino Mega 2560 controlled the robot by actuating the servo motors and received the sensor readings of the ultrasonic distance and infrared sensors. Through serial communication a genome is uploaded from a PC running the evolutionary algorithm to the Arduino Mega. The Arduino Mega evaluates an individual using the genome it received. This evaluation consists of:

1. Move robot to the starting position (by using a manually coded swimming behavior)
2. Move the servos to a central position and wait for six seconds (this delay was implemented to prevent overheating of servos and reduce waves in the tank)
3. Evaluate genome for 10 seconds
4. Send back a fitness value based on the distance the robot has traveled within the 10 seconds

All steps take roughly between 20-30 seconds for one individual depending on how far the robot was able to swim. When the same genome was evaluated multiple times the error difference in fitness was negligible (standard deviation of samples of size 4 was less than 1% for each run). Each individual is therefore only evaluated once.

A 20 ms delay was inserted between each time step for updating the servo angles. 500 time steps were done for each individual. The fitness value of each individual is calculated as a summation of the ultrasound distance measurements at every consecutive update of the servo positions. At each time step the ultrasonic distance sensor initiates a sound pulse and measures the time difference between the pulse and echo. This time interval becomes higher the further the robot moves away from its initial position. The fitness value for a controller that is not moving the robot lies around $100 \cdot 10^4$. At the start of the evaluation of a genome, the entire wave pattern for each servo is calculated for each time step. This requires six arrays to store 500 byte values derived from the genome. Although this takes up a lot of memory on the Arduino Mega, it circumvents doing calculations on the spot that might have caused an additional delay between every time step. A small delay is, however, caused by the ultrasonic sensor which requires an 8 microsecond delay for measuring the distance.

2.2.4 Experiments. Since earlier examples of robotic knifefish have been able to swim with only a single sinusoidal wave function as a control signal for the fin, we conduct experiments where the genome is reduced to three bytes that translate into the frequency, phase, and amplitude of a single sine function. We test if evolution is able to efficiently optimize these three parameters for increased swimming speed. Our second set of evolutionary experiments evaluate functions that are generated from all 15 mutable parameters, and yield the first five terms of a Fourier series. This is done to see whether an arbitrary periodic function can increase the performance compared to a single sine wave. For both sets of experiments we also test whether evolution will find swimming behaviors similar to the ones of actual knifefish, and if the performance of the evolved controllers can rival a manually programmed controller.

For both the sinusoidal and the Fourier series approach, 5 evolutionary runs were done with the exact same hardware setup. Since the slightest change in hardware and the environment can influence the evolutionary runs drastically, all the 10 runs were done consecutively. A manually coded swimming behavior is used as a baseline to compare with the evolved controllers. This behavior was the fastest swimming behavior we were able to find by manually adjusting the genome parameters during a two hour trial session with the platform. Its control function is:

$$\alpha_n = 40 \cdot sin((64 \cdot t) + (100 \cdot n)) \tag{3}$$

These control parameters correspond to a genome with the following three bytes: 255 for the amplitude, 64 for the phase, and 100 for the frequency.

2.3 Comparing Behaviors of the Robot with Actual Knifefish

Bale et al. [1] found that a diverse group of aquatic animals that use median/paired fin swimming, including knifefish, have evolved a similar optimal swimming strategy. More specifically, the result of dividing the length of an undulation on the fin by the mean amplitude of undulations along the fin, during steady swimming, consistently yields around 20. This wavelength, which maximizes the force generated by the body and the swimming speed, is referred to as the optimal specific wavelength (OSW). We therefore calculate the specific wavelength (SW) of our evolved undulation patterns to compare them with the swimming behaviors of knifefish. The SW is calculated by dividing the wavelength of undulation λ by the average amplitude of oscillation $\tilde{a}$. In general, this average amplitude $\tilde{a}$ is given by

$$\tilde{a} = h_{mean} \sin(\theta_{max}^{avg})/2 \tag{4}$$

Where θ_{max}^{avg} is the mean maximum angle of excursion of the fin rays and h_{mean} is the mean height of the fin.

3 RESULTS

3.1 Performance Analysis

After running CMA-ES for 20 generations using the sinusoidal and the Fourier series approaches, different wave patterns were acquired. Both evolutionary progressions of the 5 runs of each approach (Figure 5) evolved decent swimming behaviors though the Fourier series evolutionary progressions seem to have more variation in performance and did not plateau as clearly as the sinusoidal evolutionary progression. This corresponds to a larger, perhaps more convoluted, search space when evolving Fourier series.

The periodic control signals that have evolved in the sinusoidal approach are similar to each other while the best individuals of the Fourier series exhibit more erratic wave patterns (Fig. 6). Looking at the individual wave patterns and their corresponding fitness values, the best individual evolved in the Fourier series has a significantly higher fitness value than the others.

In Table 1 we compare the evolved swimming behaviors of our best candidates to see if the OSW ratio also applies here. The approximate wavelengths of the traveling waves have been obtained from ventral view video recordings of the robot with the best candidates and the manually coded behavior controlling its swimming. The average amplitude of oscillation was calculated from Equation 4 using a maximum angular excursion of 28 degrees (derived from video recordings) and that the fin height is 7 cm. The average travel speeds were also measured from video recordings (of the manual behavior and the best evolved individuals being replayed on the robot). Our inspiration the black ghost knifefish has a SW of 18.03 [1]. From Table 1 it can be seen that the best evolved sinusoidal controller has a specific wavelength of 16, i.e. it approximates, but is lower then, the optimal specific wavelength found by Bale et al. Although our manually programmed controller has a SW of 17 and comes closest to the actual knifefish, in reality it performed considerably worse than most of the evolved controllers (see Table 1).

Table 1: Specific Wavelengths and Travel Speeds of Behaviors. The evolved behaviors resulted in wave patterns with varied wavelengths and speeds. (Wavelength of Four. (Run 4) has been omitted as the wave function was to erratic for it to be measured from video recordings.)

Genome	Wavelength	SW	Speed (cm/s)
Manual	28 cm	17	3
Sine (Run 1)	26 cm	16	8
Sine (Run 2)	23 cm	14	6
Sine (Run 3)	26 cm	16	6
Sine (Run 4)	23 cm	14	6
Sine (Run 5)	24 cm	15	8
Four. (Run 1)	26 cm	16	4
Four. (Run 2)	26 cm	16	2
Four. (Run 3)	24 cm	15	5
Four. (Run 4)	-	-	5
Four. (Run 5)	22 cm	13	1

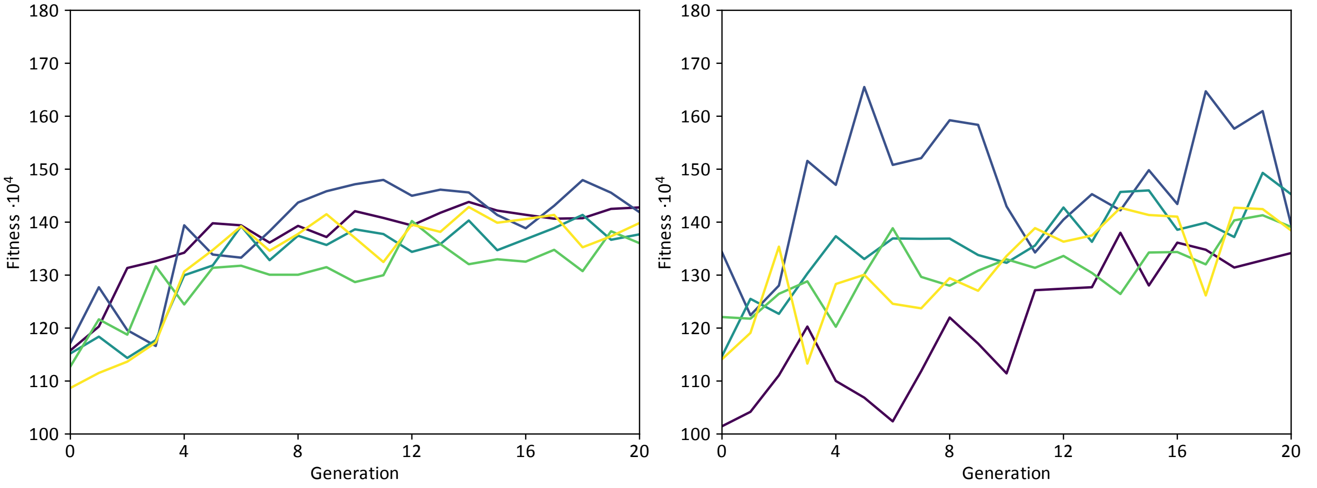
Being able to evolve wave patterns to control the swimming behavior of the robot is of limited use if their phenotype cannot be reproduced. Since the robot was slightly worn down after a lot of different experiments and several malfunctioning servo motors had been replaces, we evaluated the performance of the evolved wave patterns again. When comparing the evolved Fourier series wave patterns with the evolved sinusoidal wave patterns it can be seen that the sinusoidal wave patterns also outperform the manually encoded wave pattern significantly in terms of fitness value (Figure 7). Though this could have been caused by many factors, it seems that a sinusoidal function is a more robust general approach that might be suboptimal but resilient to morphological/environmental change

3.2 Phenotypic Analysis

To analyze the type of behaviors that evolved, the position of the tip of each fin ray was tracked in the best evolved individuals using footage taken from a ventral view of the robot (Figure 8). This tracking was done to analyze the actual undulation patterns across the fin as opposed to the calculated control patterns. Looking at the best evolved individuals from both the Fourier series and the sinusoidal approach, the wave propagates strikingly similar along the fin of both individuals. The phase and frequency are different for the two individuals but the sinusoidal wave pattern generates roughly the same wavelength as the Fourier series only with a higher frequency. The sinusoidal wave pattern makes roughly six undulations while the Fourier series makes five within the same time interval.

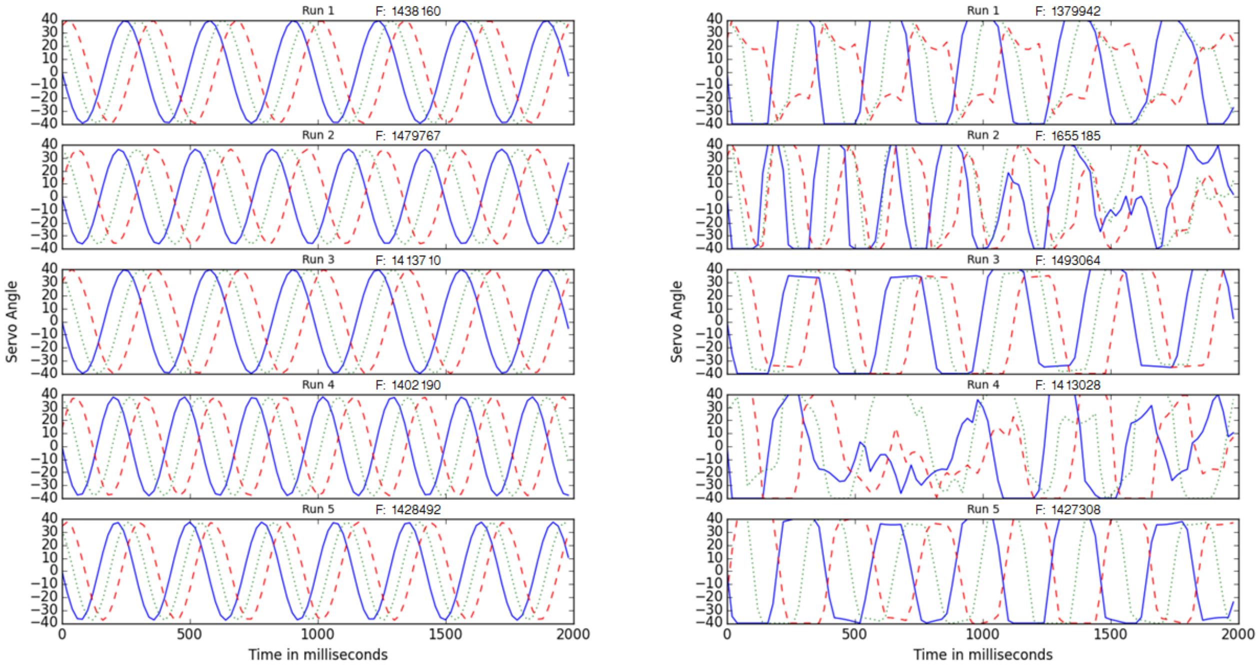
4 DISCUSSION

CMA-ES proved an efficient method for automatically evolving the swimming behavior of our soft robot whose morphology was inspired by the ghost knifefish. Although the search space was quite small, failing hardware was a problem that in general makes



(a) **(b)**

Figure 5: Evolutionary progressions of five runs . The sinusoidal approach (a) and the Fourier series approach (b) showing the maximum fitness (hall of fame) of the evolutionary runs.



(a) **(b)**

Figure 6: Evolved control wave patterns. The best evolved wave patterns in 5 distinct evolutionary runs using the sinusoidal approach (a) and the Fourier series approach (b). The graphs show two seconds of a resulting wave from each genome. The blue line represents the trajectory of the first servo motor while the green dotted and red dashed lines depict the positions of servos two and three respectively. The trajectories of servo four, five and six are not depicted. The difference in the wave of different servos visible in some of the Fourier series is due to including potentially high frequencies and querying the function every 20ms.

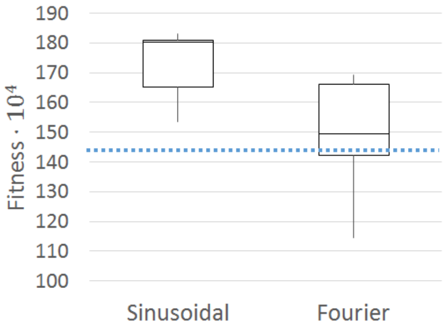


Figure 7: Performance difference between the best evolved sinusoidal and Fourier series individuals. The box plot shows the quartiles of the best individuals of the 5 runs of the sinusoidal approach and the Fourier series approach. These results were obtained from replaying the best genomes of the different approaches using a patched up version of the robotic fish (i.e. where the servo motors had been replaced). The blue dotted line represents the baseline performance of our manually encoded genome.

evolving physical robots arduous. Predefining the controller by only utilizing periodic wave functions and only running CMA-ES for a brief period was enough to generate efficient swimming behavior. One of the main challenges when evolving physical robots is about how to deal with malfunctioning hardware. Considering a death toll of 17 servo motors during these experiments, using CMA-ES seemed a lot more viable compared to initial experiments with a generational evolutionary algorithm that took almost five times longer to get to results compared to the CMA-ES approach.

The robotic platform presented in this paper is constrained by predefined functions and the limited movement sets acquired in the evolutionary runs. However, the presented robot fish could potentially evolve many different behaviors that the knifefish is also capable of. This could make it a viable model for autonomous underwater vehicles. A next submersible iteration of the fish could evolve vertical thrust by sending counter-propagating waves towards and away from the center of the fin canceling out longitudinal forces as discussed by [9]. A selection of these behaviors could be evolved and encapsulated in a fixed environment, removing manual programming of the behavioral repertoire.

Zoological studies of knifefish kinematics have shown that the wavelength of the propagating wave varies across the fin during steady swimming [30]. Given that the swimming behavior of the knifefish has been optimized through natural evolution, implementing this feature in the encoding of the controller could probably lead to better performance. This could be accomplished by using a *compositional pattern-producing network* (*CPPN*) [29] with servo number and time as inputs. A similar approach has previously been used successfully to generate the oscillatory controller for a quadruped robot [21]. To discover a greater variety of controllers that perform well, novelty search [17] or other diversity enhancing methods can also be applied instead of a goal directed approach which is often prone to premature convergence or over-fitting. Another aspect worthy of further inquiry is the materials used for the fin. It is possible that a material with another elastic modulus might better exploit the interactions with the water to facilitate the emergence of dynamics that aid the swimming.

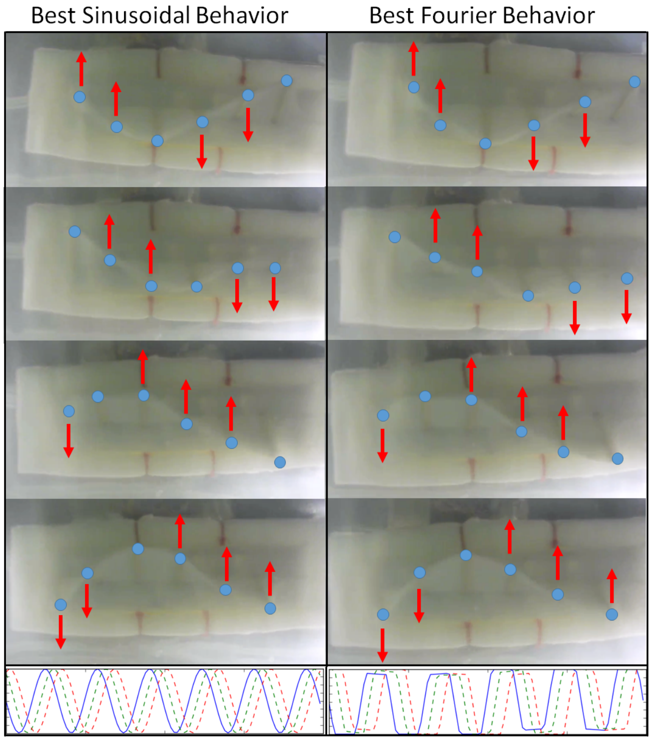


Figure 8: Evolved robot wave patterns. The wave patterns of the best (highest fitness) evolved sine wave and Fourier series seen from below. Both propagating waves are almost identical to one another and have a wavelength that is slightly longer than the length of the fin. The blue dots illuminate the tips of the fin rays while the red arrows depict the motion of the individual fin rays. The function plots below correspond to the fin undulations depicted above and are the best *reproducible* evolved wave patterns shown in Figure 6 (Sine (Run 1) and Fourier (Run 3))

With our robotic platform we are able to automatically evolve the behavior of an intuitively functional soft robot using CMA-ES. Considering the increasing advances of automated manufacturing methods and readily available materials to create detailed robots with various features, we think this evolutionary approach on physical soft robots can become viable as a tool for directly optimizing the behavior of the physical systems.

5 CONCLUSION

In this paper we demonstrated that evolving the controller for a knifefish-inspired soft robot is feasible directly on the physical robot. The majority of the evolved behaviors outperformed a hand-designed controller in terms of speed. Additionally evolution was able to exploit the dynamical properties of the flexible material to produce feasible swimming strategies for the robot that have similar phenotypes but different genomes. We posit that evolutionary experiments on physical robots, which have so far only been applied to traditional rigid robots, are especially relevant for soft robots that are difficult to simulate computationally. In the future the presented approach could be combined with more explorative search methods such as novelty search and different fish models, to solve tasks for which even a simple hand-designed controller is an infeasible option.

ACKNOWLEDGEMENTS

This project has received funding from "Flora Robotica", a European Union's Horizon 2020 research and innovation program under the FET grant agreement, no. 640959.

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Is a soft robot more “natural”? Challenging the perception of soft robotics and perceived naturalness in human-robot interaction

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Abstract

Soft robotics technology has been proposed for a number of applications that involve human-robot interaction. This study investigates human perception of and physical interaction with soft robots as compared with rigid, mechanical robots. We focus in particular on the perceived naturalness of soft robot design and its impact on user preference. In a between-subjects study, participants were asked to interact with either a soft robotic tentacle or a rigid, mechanical robot of a similar shape. The interactions were video recorded, and data was also obtained from questionnaires (N_{video}=90, N_{quest}=94). We found no significant differences in how appealing or natural the robots were rated to be. Appeal was positively associated with perceived naturalness in all cases, however we observed a wide variation in how participants define and understand the word “natural”. Although participants showed no clear preference, qualitative analysis of video data revealed that soft robots and mechanical robots elicit different interaction patterns and behaviors. The findings highlight the key role of physical embodiment and materiality in human-robot interaction, and challenge conventional assumptions that link soft materials with perceived naturalness.

Keywords: human-robot interaction, soft robotics, embodiment, tactile interaction, human factors, naturalness

Acknowledgements
The authors would like to thank Sara Á. G. Nielsen and Anna Sabine Nielsen for their help in conducting the interaction experiments.

1. Introduction

Over the past ten years, the field of soft robotics has produced a novel class of robots that possess a radically different appearance and aesthetic than traditional robots [1–3]. Soft robots have bodies constructed from pliable and elastic materials such as silicone rubbers with elastic moduli comparable to soft, biological matter. Soft robot designs are often inspired by animals or parts of animals that are soft, rather than human anatomy [3]. A primary benefit of soft robotics is increased safety through passive compliance. Because of their pliability, soft robots potentially present fewer dangers to humans, especially for tasks that require close, physical contact. Hence, soft robotics have been claimed to increase the future potential for human-robot interaction (HRI) and enable new applications [3, 4]. While still an emerging field, soft robotic systems have already been implemented in industry for high-speed pick and place tasks [5]. Applications have also been proposed within health care, human assistance, disaster relief and collaborative work. To ensure successful deployment where robots interact closely with humans, more knowledge is needed about people's perceptions and appraisal of soft robots. Such knowledge is crucial for designing safe and intuitive interactions with soft robots. Because of their material similarity to biological organisms, soft robots are widely accepted as having a more "natural", and therefore more pleasing, aesthetic. However, there is scant research on how people actually perceive soft robots and the proposed relation between perceived naturalness and appeal.

A central endeavor of HRI research has been to investigate how people perceive social robots and their behavior [6–8]. Physical embodiment has been shown to measurably impact task performance between robots and humans [9–11], while other studies have demonstrated a link between a robot's materiality and the perception of robots as social agents [12–16]. A robot's material design sets the boundaries for interaction and can elicit specific attributions of social agency, even for non-anthropomorphic robots. Moreover, a robot's aesthetic properties (its appearance, movement qualities, tactility etc.) is closely related to its perceived affordances. For instance, a robot's physical appearance has repeatedly been shown to affect human perception of its capabilities and to influence interaction [17–19]. Yet with only a few exceptions [20–24], studies on the effects of physical embodiment on HRI have been restricted to conventional rigid robotics technology. To our knowledge, no studies directly comparing human perceptions of silicone-based soft robots and rigid robots have hitherto been conducted.

One argument for using soft robots or soft robot parts is that soft materials promote safety due to their passive compliance. However, soft materials can also be more fragile and delicate than rigid robots, and therefore more likely to be damaged by improper contact than conventional robots. As with every tool, the aesthetic design of a soft robot implicitly communicates relevant information about its affordances, such as how, where, and in what manner interaction should occur. Conventional industrial robots visually communicate information about their power and potential safety risks, and people take precautions when interacting with them. How might soft robots convey similar levels of information about their affordances, safety and risk? Could the organic design of soft robots make them appear more robust, more proficient, or more suited for human contact than they actually are? As with conventional robots, a nuanced understanding of how people perceive and respond to soft robots could help robot designers reduce the chance of producing misleading designs that may inadvertently harm the human or the robot. In short, a soft robot's design should match the robot's capabilities and facilitate proper interactions.

This case study was designed with two primary purposes: 1) To question the claim that soft robots are perceived as more natural and more appealing than conventional robots; and 2) To gain insights into people's perceptions of soft robots and the spontaneous interaction behaviors that soft robots elicit. We designed and carried out an interaction experiment to address the following research questions:

- Are soft robots perceived as more natural than traditional mechanical robots?
- Is there a correlation between how natural and how appealing a robot is perceived to be?
- What specific types of human-robot interaction behaviors do soft robots elicit? Do these behaviors differ from those elicited by a comparable rigid robot?

As soft robots are thought to have more natural and fluid movements [25, 26], to "enable soft and natural human-robotics interactions" [26, 27], and to be "capable of soft movements and soft interaction with people"[1], we chose to focus on the appearance, movement, and haptic qualities of soft robots. We tested three robots: two silicone-based soft robotic tentacles and one rigid, mechanical robot of the same shape and with a similar movement range. By comparing interactions and ratings of the two soft robots with those of the rigid robot, we set out to understand whether materiality alone determines user perception and interaction patterns. We chose to include two soft robots with different design aesthetics in order to test whether two different soft robot designs would be perceived and appraised differently by users. Finally, we aimed to uncover possible inconsistencies or incongruencies in how people define, identify and experience "natural" in relation to robots, a term that we generally find problematic when assessing people's responses to machines (soft or otherwise).

Following previous experiments with social robots in public settings [14, 28, 29], we conducted the experiment using an open-ended interaction scenario that would prompt participants to engage in exploratory behavior. Evaluating interactions in public settings opens up a rich space for observing how people intuitively respond to robots. Studies conducted in public settings that capture bystanders and passersby give researchers insight into the perception and preferences in ways that go beyond the limits of questionnaires and self-reporting in laboratory settings [30]. The open-ended interaction scenario (as opposed to a task-based interaction) further reveals how different embodiments yield different interaction patterns in specific settings. This data is useful for understanding how people intuitively respond to physical interactions with robots.

2. Methodology

The study uses a mixed methods design and data obtained from self-report questionnaires and video recordings of HRI. We utilize quantitative statistical analysis combined with qualitative analysis of written answers and qualitative analysis of transcriptions of the video recordings.

2.1 Experimental Design

A between-subjects study was chosen in order to measure initial reactions to a specific robot design and to avoid carry-over effects after exposure to another robot. We reasoned that most people had not previously encountered a soft robot, and we wanted to investigate whether the two different soft robots would provoke different responses. The choice of a between-subjects design was also motivated by pragmatic considerations: as the trials would take place during two public events, it was estimated that a short interaction interval would assure a high number of participants and more reliable self-reporting. Hence, it was preferable that each participant interacted with just one robot.

Participants interacted with either one of two silicone-based pneumatically actuated soft robots, or a rigid robot comprised of servo motors, which were all constructed specifically for the study (Fig. 1). The soft robots were of the same type but had different design aesthetics (color, material, and the rigidity and shape upon inflation). The rigid robot purposely resembled the shape of the soft robots to act as a baseline for comparison.

We chose to have participants perform an open-ended interaction without any explicit task, a decision that was meant to focus the participant's attention on the robot's aesthetics and the experiential aspects of the interaction, rather than the usefulness or feasibility of the platform.

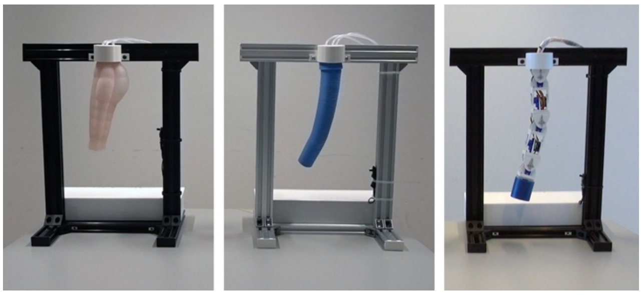

Fig. 1 Study participants interacted with either one out of the two silicone-based, pneumatically actuated soft robots (left and center) or a conventional, rigid robot (right) built specifically for the experiment. The rigid robot was designed with the same overall shape as the soft robots and programmed with similar movements

2.2 Participants

The study was conducted in accordance with the Danish Code of Conduct for Research Integrity and Danish Data Regulations. The participants that interacted with the two soft robots were recruited at a public event. Participants who interacted with the rigid robot were recruited separately at another public event. During the trial with the soft robots, children under the age of 18 were allowed to enter the premises accompanied by a parent or legal guardian who, in accordance with Danish law, could provide informed consent on their behalf.

A total of 94 non-randomized participants, comprising of 49 men and 45 women with an average age of 32.6 years (SD = 11.9 yrs, range 19-70) completed the written questionnaire, of which 54% self-reported no prior interactions with robots. Video data for 90 participants was included for analysis. None of the participants were paid for their participation.

2.3 Materials

We designed a custom soft robotic platform for the experiment, as no soft robots that would suit the purpose of the study are yet commercially available. We chose a tentacle morphology as it would allow participants to experience the three aesthetic modalities (appearance, movement, reciprocal touch) we were investigating. Moreover, soft robots of this type are currently being developed for applications that involve close HRI within collaborative robotics (cobots) and assistive robotics (see Fig. 2).

Fig. 2 Examples of soft robots based on tentacle designs developed for scenarios that involve close interaction with humans: the Festo BionicSoftArm cobot (left) and the I-SUPPORT system for assisted bathing (right). Credits: Image of BionicSoftArm ©Festo AG & Co. KG, all rights reserved, used with permission. Illustration of the I-SUPPORT system used with permission from the I-SUPPORT project [31].

2.3.1 Soft robot platform

The soft robotic platform consists of a three-chambered silicone tentacle that is pneumatically actuated (Fig. 3). By controlling the inflation of the three chambers, the tentacle can to bend in all directions around its central axis. The silicone tentacle is mounted on a T-slot aluminum frame with mounts that were 3D printed in PLA plastic. The tentacle is supplied with pressurized air via 4/2mm OD/ID silicone tubing. It is actuated with three low noise electrical pumps (MITSUMI R-14 A213). Solenoid valves (Uxcell Fa0520D 6V Normally Closed) are implemented to facilitate the release of air from the chambers. The morphology is controlled by an Arduino Pro Mini microcontroller supplied by an external power supply (6V, 2A). Two H-bridge chips (L292D) drive the valves and pumps. The tentacle is equipped with an infrared (IR) distance sensor (FC-51), which is positioned to the right on the frame (see Fig. 3).

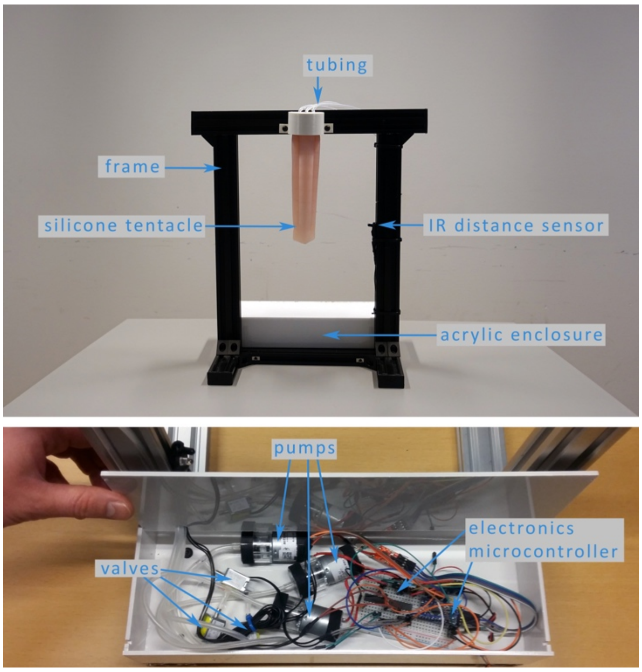

Fig. 3 The platform with the tentacle in its initial position (top). The electronics and pneumatic systems are located inside an acrylic enclosure (bottom)

We built two versions of the soft robotic platform for the experiment (see Fig. 1 and Fig. 4). The first (hereafter “red robot”) incorporates an open source tentacle design [32]. It was cast in uncolored Ecoflex 0030 by using a lost wax casting technique to create the inner compartments. Red jeweler's wax was used for the inner mold parts, which gave the tentacle a pale red hue.

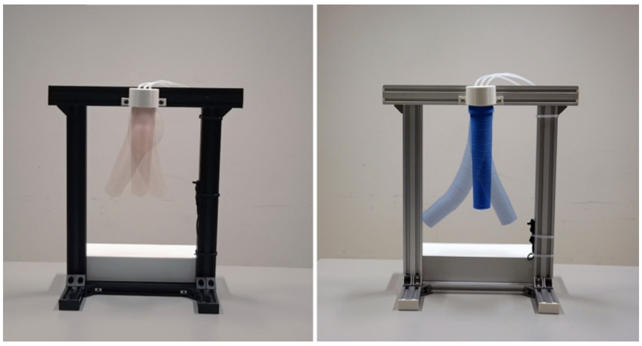

Fig. 4 Overlaid photos showing the movements of the two versions of the soft robotic platform

The second version (hereafter "blue robot") is equipped with a custom-designed, three-chambered tentacle constructed from Ecoflex 0050. It was wrapped with internal fiber reinforcements (braided fishing line 0.6mm 50kg) before a final layer of silicone was applied. The fiber reinforcements inhibit radial expansion, which constricts the movement so that the tentacle only expands and elongates along its central axis (see Fig. 4). Following fabrication, both tentacles were coated with talc powder to prevent lint and dirt from sticking to the surfaces. Fiber reinforcements and the blue color both give the blue robot a different appearance than the red robot. Taken together, the two soft robots cover different parts of the design space of soft robotics technology.

2.3.2 Rigid robot platform

To establish a baseline for investigating whether soft robots are perceived differently than rigid robots, and whether they elicit different interactions, we constructed a version of the platform where the soft robotic element was replaced with rigid components (hereafter "rigid robot"). We deemed it important to use a rigid morphology of approximately the same size and shape as the two soft robots and one that was able to realize similar movements.

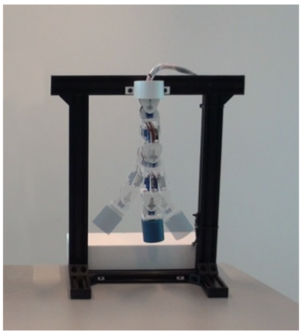

Fig. 5 The rigid version of the platform

We chose a morphology assembled from five servo motors (TowerPro SG90) and brackets from the Open Source mechanical modular system REPY-2.0 [33] that were 3D printed in white PLA (Fig. 5). Two of the servo motors were rotated 90 degrees around the central axis, giving the structure a three-dimensional range of motion similar to that of the soft robots. Many existing rigid robotic platforms have soft end effectors designed for tactile manipulation, therefore a silicone cylinder in a blue color was cast onto the final bracket at the end effector using Ecoflex 0030. The rigid robot is controlled by an Arduino Uno microcontroller equipped with a sensor shield (Sensor Shield V5.0 Upgrade) supplied with external power (4.8V, 2A).

2.3.3 Soft robot behavior

The microcontrollers were programmed from within the Arduino IDE with a code that facilitates two main interaction modes:

Mode 1: The user can observe the tentacle move on its own

Mode 2: The user can make the robot move towards their hand by positioning it in front of the IR sensor

Mode 1 is programmed to be triggered whenever the IR distance sensor does not detect an obstacle within a range of approximately 4 cm. The robot then shifts between six pre-programmed movement sequences – three "breath-like" sequences, where the tentacle inflates and deflates rhythmically, and three "exploration" sequences, where the tentacle inflates to assume different positions within its range of motion. The breathing motion is meant to indicate to the participant that the robot is active but not currently engaged in a specific task, hence open to interaction. A similar type of rhythmic signaling is already used for this purpose in laptop computers and other equipment with LED lights, and is a nonverbal cue that is both familiar and recognizable to many people. The exploration sequences are designed to showcase the robots' movement dynamics and appearance when they are inflated into different shapes.

Mode 2 occurs when the IR sensor is triggered by the hand of the participant. The tentacle then deflates and starts moving towards the hand. It moves for approximately 6 seconds before reaching the hand, and after this, it gently presses against the hand for approximately 6 seconds, before returning to its initial starting position.

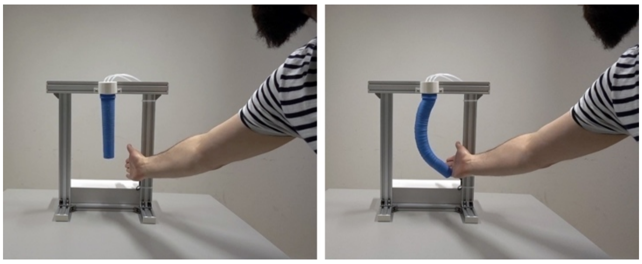

Fig. 6 Activation of the platform with the hand

The two interaction modes approximate semi-autonomous robot behavior that might be useful in a real-life use scenario. In such a situation, the robot would likely perform some tasks autonomously, but the user would also be able to guide or control its behavior.

The three robots are presented and their behaviors are demonstrated in the video Online Resource 1 under supplementary materials.

2.3.4 Rigid robot behavior

The rigid version of the platform was programmed with the intent to approximate the movement of the blue soft robot as closely as possible. The Arduino code used for controlling the soft robots was revised so that the preprogrammed movements were accomplished by incrementing the angles of the five servo motors, rather than switching the pumps and valves on and off. This was done by implementing a function that takes the final five servo angles and the duration of the movement to be performed as its input. It then interpolates linearly between the current positions of the servo motors and their destined values. We observed the preprogrammed movements of the blue robot and wrote down all the different positions the tentacle assumes during each 'exploration' sequence (e.g. "to the left right in front of the frame", "towards the user, then to the right, ends up near the sensor"). We then experimented with sending different servo values to the rigid robot until we obtained identical positions that were implemented into the code. The movements of the rigid robot were then compared with the movements of the blue robot, and final adjustments were made. As the 'breathing' motion could not be replicated given the rigid morphology, they were replaced with small rocking movements where the string of servo motors moves slightly towards the user and then back to its resting position rhythmically. The same timing was used for all the movements of the rigid robot so that each movement for a given 'exploration' sequence, 'breathing' movement, and the movement to touch the hand had the same duration as for the two soft robots. We validated the replication of movements by switching the blue robot and the rigid robot on at the same time, and noticed that they performed very similar movements in almost perfect unison (see Fig. 7 and the video under supplementary materials (Online Resource 2)). Furthermore, we ensured that the force delivered from the rigid robot to the hand was as close to that of the blue soft robot by comparing the two and adjusting the rigid robot's programming.

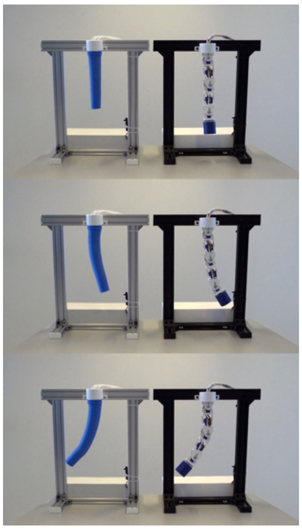

Fig. 7 Still images from video recording of the blue robot and the servo robot switched on simultaneously showing their similar movements. Video available under Supplementary Materials (Online Resource 1)

2.4 Setting

The interaction trials were carried out inside the library of the IT University of Copenhagen. Fig. 8 depicts the setup.

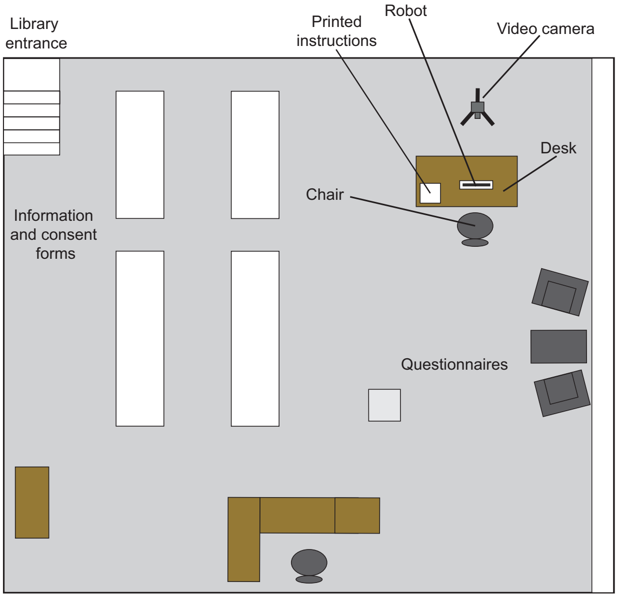

Fig. 8 Diagram of the setting based on the plan drawing of the building and measurements taken of the furnishings in the room

The trials with the red and blue robots took place outside of the normal business hours during a public event. The rigid robot trial occurred during regular business hours of the library, and the library was frequented by a few non-participant passersby.

The decision to use an 'in the wild' setting continues the recent interest within HRI research to conduct user studies outside of laboratories [29, 34–36]. We reasoned that a social setting would be more conducive to unstructured dialogue about the robots that would reveal unexpected and nuanced perceptions. Moreover, having participants engage in voluntary, non-purposeful interactions with the robot could lead to freer interactions, potentially revealing a larger variety of emergent interactions that soft robots might elicit in real-world scenarios.

2.5 Procedure

Participants received information about the study at the library entrance and were given the opportunity to ask questions. They signed a consent form agreeing to be video recorded and, if they chose, to fill out a questionnaire. The two main robot interaction modes (see 2.3.3) were described verbally or by means of printed instructions placed beside the robot. Participants were instructed to sit opposite the robot and to interact with it for as long as they chose. Participants interacted with only one robot individually or in pairs of two. The interactions were video recorded with a single HD video camera that was visible to the participants (see Figs. 8 and 9). Following the interaction, participants were asked to fill out the questionnaire inside the library on a computer or on paper. The entire study took approximately 15-20 minutes to complete.

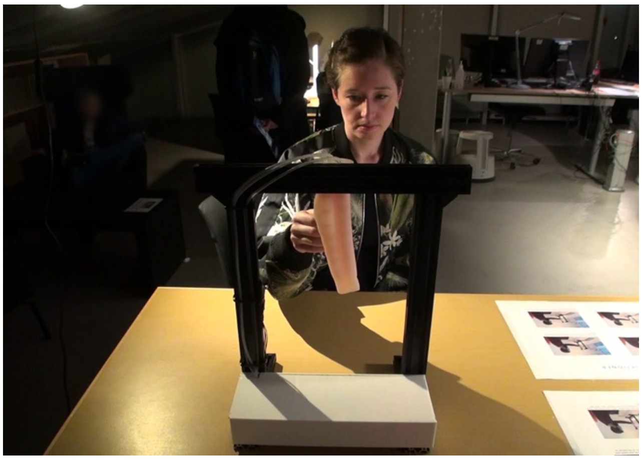

Fig. 9 Participant interacting with the red robot during the experiment

2.7 Data collection and analysis

There are several established questionnaires and evaluation tools for HRI [7, 37, 38]. Because they generally refer to conventional robots, we formulated a questionnaire that address our research questions concerning the perception of soft robots specifically. The questionnaire contained Likert scale questions (1=Strongly Agree, 5=Strongly Disagree) and open-ended questions where participants could provide short written answers. We asked participants to rate how “natural” and how “appealing” they found the appearance, movements and touch of the robot. We also asked participants to write down what they understood by the word “natural” and what they thought the robot resembled. For each respondent, the ratings for naturalness of appearance, movements and touch were added to yield an overall ‘perceived naturalness’ score. Similarly, appeal ratings for appearance, movements, and touch were added to yield an overall ‘appeal’ score.

2.7.1 Statistical Analysis

We used one-way between-groups analysis of variance (ANOVA), χ^2, or Fisher’s exact tests, as appropriate to assess whether age, gender, and mean values of each Likert scale rating differed for the three robots. The same method was used to assess differences between the three robots in quantitative data variables extracted from the video recordings. The assumption of homogeneity was tested with Levene’s test of homogeneity for variances that was fulfilled for all questionnaire questions except for question 1 ($p=0.042$) and age ($p=0.000$).

ANOVA was conducted to assess differences between the mean values for the primary outcomes for ‘appeal’ and ‘perceived naturalness’ (dependent variables) with ‘robot’ (the robots numbered as

0,1,2) as the independent grouping variable with the significance level set to $p<0.025$ (adjustment for two comparisons).

A regression model was used to test whether ‘appeal’ as a dependent variable was positively associated with ‘perceived naturalness’ and ‘robot’ as independent variables in the following model:

$$appeal = b_0 + b_1 \cdot perceived\ naturalness + b_2 \cdot robot + perceived\ naturalness \cdot robot$$

Adjustments for age, gender, and prior robot interaction experience were done in a secondary analysis.

2.7.2 Thematic Analysis

The video material was analyzed using *thematic analysis*, a qualitative method that is compatible with both essentialist and constructionist research paradigms. Thematic analysis is used to identify, analyze and report patterns (themes) within a given data set [39].Thematic analysis explicates the necessary steps to go from raw data to interpretation, and provides specific guidelines for moving through the different phases of a recursive hermeneutic process of analysis. We transcribed all audible verbal utterances in the video recordings verbatim with summaries of the physical actions between the participant and robot. If participants interacted with the robot in pairs, this was counted as two separate interactions. As the research questions were exploratory in nature (“What specific types of human-robot interaction behaviors do soft robots elicit?”, “Do these behaviors differ from those elicited by a comparable rigid robot?”), we coded the transcriptions using an inductive approach.

2.8 Hypotheses

Based on our experience discussing soft robots at public and academic events [21, 40–42], we formed the following hypotheses:

H1: The soft robots would be rated as having a more “natural” appearance than the rigid robot.

> We expected that the appearance of both soft robots would be rated as more “natural” than the rigid robot, as their smooth, continuous surfaces and gradual expansion are reminiscent of living organisms. We also expected that the blue robot, due to its color (rarely found in nature) and slightly more constricted motion would be considered less “natural” than the red robot.

H2: Perceived naturalness and appeal for a soft robot would not be correlated.

> We predicted that due to its ‘fleshy’ and ‘organic’ appearance, the red robot would probably be evaluated to have a more “natural” appearance than the blue robot, but would not be rated as appealing.

H3: Respondents would define the word “natural” with many different meanings.

H4: The soft robots would be said to resemble animals or animal body parts more often than the rigid robot.

> We hypothesized that the soft robots would be considered more “natural” in the sense that they would be said to resemble animals or animal body parts more often than the rigid robot.

3.Results

3.1 Quantitative results

Table 1. Mean rankings and standard deviations for the rating questions. Answers were given on a 5-point Likert scale (1=Strongly Agree, 5=Strongly Disagree). Questionnaires from four participants that interacted with the red robot were incomplete. Answers from these have been included and missing answers for specific questions is indicated in the N column that gives the total number of replies for each question.

Question	**Red soft robot (N=47)**	**Blue soft robot (N=23)**	**Rigid robot (N=24)**	**N**	**p-value (ANOVA / χ^2)**
1. *The robot has an appealing appearance*	M: 3.36 SD: 1.05	M: 3.45 SD: 0.74	M: 3.50 SD: 0.83	93	0.82
3. *The robot's movements are appealing*	M: 2.85 SD: 1.00	M: 3.00 SD: 1.04	M: 3.08 SD: 1.10	94	0.65
5. *It is appealing to touch and be touched by the robot*	M: 2.79 SD: 1.20	M: 2.86 SD: 1.11	M: 2.96 SD: 1.00	92	0.83
2. *The robot has a natural appearance*	M: 2.94 SD: 1.09	M: 3.32 SD: 1.00	M: 3.17 SD: 1.24	93	0.38
4. *The robot's movements are natural*	M: 2.89 SD: 1.24	M: 2.41 SD: 0.91	M: 2.88 SD: 1.04	93	0.22
6. *The robot feels natural when I touch it and it touches me*	M: 2.72 SD: 1.08	M: 3.05 SD: 0.81	M: 3.29 SD: 1.08	92	0.08
7. *Appeal* (= 1.+3.+5.)	M: 9.00 SD: 2.70	M: 9.35 SD: 2.58	M: 9.54 SD: 2.36	91	0.68
8. *Perceived naturalness* (= 2.+ 4.+6.)	M: 8.55 SD: 2.69	M: 8.76 SD: 1.92	M: 9.33 SD: 2.63	92	0.47
Age	M: 37.3 SD: 13.2	M: 29.8 SD: 10.4	M: 26.0 SD: 5.09	94	0.00
Gender (female/male)	(22/25)	(10/13)	(13/11)	94	0.75
Prior robot interaction experience (no/yes)	(32/15)	(8/15)	(11/13)	94	0.02

Table 1 summarizes mean values from the questionnaire, demographics data and statistics. The group of participants that interacted with the red robot was significantly older than the groups that interacted with the blue robot and the rigid robot. The groups that interacted with the blue robot and the rigid robot were not significantly different from each other with regards to age. Moreover, there were significantly more participants who had no prior robot interaction experience in the red robot group compared with the blue and rigid robot group.

3.1.1 Are soft robots perceived as more natural and more appealing than rigid robots?

Participants did not find the soft robots more natural nor more appealing than the rigid robots: there were no statistically significant differences in scores for *perceived naturalness* and *appeal* for the three robots ($p > 0.05$). Neither were any significant differences found between the three robots on any of the Likert scale questions ($p > 0.05$).

3.1.2 Is there a correlation between how natural and how appealing a robot is perceived to be?

Data were normally distributed. Preliminary analyses were conducted to ensure no violation of the assumptions of normality and linearity. The regression model revealed a significant main effect of *perceived naturalness* due to a positive association between *appeal* and *perceived naturalness* for all three robots ($F_{2,84}=48.33$, $b=0.62$, $p<0.0001$). The *perceived naturalness*robot* interaction was insignificant ($p=0.60$) indicating that this association did not differ between the three robots. The main effect of *perceived naturalness* remained significant after adjustment for *age*, *gender*, and *prior robot interaction experience* ($p<0.0001$).

3.2 Analysis of written responses

3.2.1 What do participants understand by “natural”?

To categorize and explore the 90 responses obtained to the question “What do you understand by “natural”?” (4 participants did not reply to this question), we compared the responses with the six main meanings of the adjective “natural” listed in Oxford Dictionaries (OD) [43]. Of these, only two were applicable to any of the answers provided. The first of these was ‘*Existing in or derived from nature; not made or caused by humankind*’. Apart from replies that paraphrased this definition or parts of it, we included responses that defined natural as being similar to natural organisms, as well as those using ‘organic’ and ‘biological’ as synonyms for natural within this category. The second definition from OD was ‘*In accordance with the nature of, or circumstances surrounding, someone or something*’. In this category, we included responses referring to natural as something intuitive, well-known, conventional, or habitual. The remaining entries that did not fit within these two definitions were categorized into three additional categories that were established inductively (see Table 2). 26 entries were not categorized as they were ambiguous. We observed no difference in the distributions within the different definitions of natural based on which robot the participant had interacted with.

Table 2. Categorization of the answers provided to the question ’What do you understand by ’natural’?’

Understanding of ’natural’	**Examples**	**N**
’existing in or derived from nature; not made or caused by humankind’ (Oxford Dictionaries)’	’Something that is made in a natural process’, ’Appears natural, not man-made’, ’Something that is reminiscent of what nature has created’, ’like a living being (animal)’	28
human-like	’human-like’, ’something that is human’, ’If a human did it / was it’, ’That the movements happen in a natural and ’human’ flow.’	14
’in accordance with the nature of, or circumstances surrounding, someone or something’ (Oxford Dictionaries)’	’something that is not too different’, ’Fits into surrounding context of the setting’, ’happens without thinking about it’, ’Things that are recognizable from everyday life and you can relate to’	12
opposes ’natural’ with ’mechanical’, ’robotic’, ’artificial’, or ’fake’	’Having non-machine or non-mechanical properties. Having non-linear motion’ ’Not robotic/artificial’, ’Non-artificial’ ’That it does not appear mechanical’ ’real, not fake’	8
defines ’natural’ in relation to appearance, movement, and touch in a robot and answers tautologically	’something that appears natural in relation to movements, sound, shape etc.’, ’resembling natural or coordinated movements’	2

3.2.2 What do the robots resemble?

To explore the replies to the question “What does the robot resemble?” we collected the responses in a single document. As several participants mentioned more than one object in their reply, we chose to treat each individual item mentioned as a distinct data item and to categorize them separately when measuring prevalence. This yielded a total of 131 items within replies obtained from 94 participants.

We searched the items for potential categories that could contain the most commonly mentioned types. As many entries mentioned specific animals or animal body parts, the category “animal/animal body part” was established. A few items specifically referenced human body parts, and so a category called “human/human body part” was added. Moreover, a high number of body parts were mentioned without any specification of animal or human. The category “organism/part of an organism” was thus created to encompass these responses. Most of the remaining items could be categorized as synthetic materials and man-made objects. The remaining 4 items were classified as “other”. The items thus categorized were distributed as shown in Fig. 10.

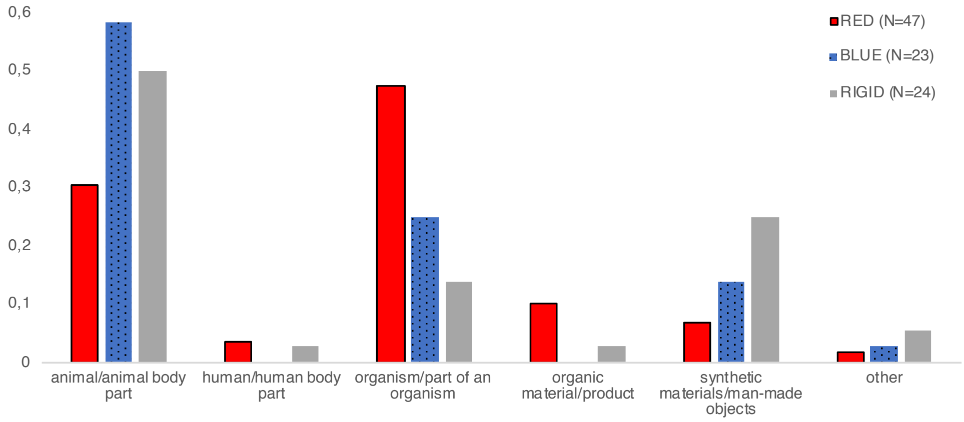

Fig. 10 All items categorized into six categories (replies to the question “What does the robot resemble?”). For ease of comparison, the bar graph shows relative values, the number of items for each robot within each category has been divided by the total number of items for that robot

To further study the entries of the two categories where the three robots had the highest number of items (Column 1: “animal/animal body part” and Column 3: “organism/part of an organism”), we subdivided these two categories into four subcategories – “animal”, “animal body part”, “organism”, and “part of an organism” (Fig. 11). The items contained within these four subcategories together account for 75% percent of the total items (99 out of 131).

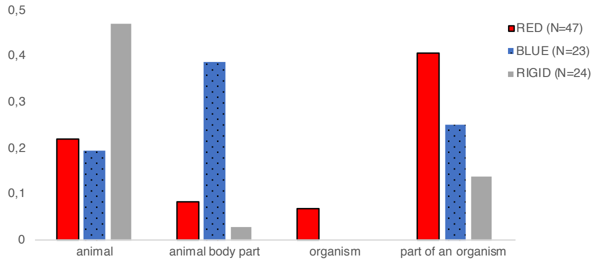

Fig. 11 Categories for living beings subdivided (replies to the question “What does the robot resemble?”)

The bar graph (Fig. 11) shows that the red robot is most often (52% percent of all entries for this robot) said to resemble a part of an organism, without any specification pertaining to human or animal. The blue robot is most often said to resemble an animal body part (39% percent of all entries for the robot), two body parts are mentioned more than once – an elephant’s trunk (N=10) and a tentacle (N=3). The servo robot is most often said to resemble a whole animal (47% percent of entries for the robot), the three most frequently mentioned are snake (N=7), larva (N=4), and worm (N=4).

3.3 Analysis of video recordings

We video recorded 25 interactions with the rigid robot that were all transcribed. For time reasons, we chose to only transcribe 44 and 25 of the recorded interactions with the red and the blue robot, respectively. Four transcribed interactions with the red robot were excluded from analysis as it was apparent from the video that the robot was not functioning properly during these interactions (the robot had a ruptured chamber, which was fixed before the remaining interactions).

Table 3. Quantitative data extracted from video recordings and statistics

	Red soft robot (N=40)	**Blue soft robot (N=25)**	**Rigid robot (N=25)**	**p-value (ANOVA / χ^2 / Fisher's test)**
Interaction type (alone/in pair)	(36/4)	(19/6)	(17/8)	0.08
Interaction time (mins.)	M: 1.22 SD: 1.06	M: 1.28 SD: 0.94	M: 3.54 SD: 1.88	0.00
Participant touched by the robot (no/yes)	(25/15)	(2/23)	(3/22)	0.00
Participant touching the robot (no/yes)	(12/28)	(7/18)	(9/16)	0.65
Participant sitting during interaction (no/yes)	(7/33)	(2/23)	(1/24)	0.28

The interaction times for the rigid robot were statistically significantly longer than for the soft robots (p=0.00 in post hoc tests). We ascribe this in part to a change in the social context of the experiment: there were markedly fewer people present in the library than at the previous event, and only rarely would a line form behind a participant to prompt them to conclude the interaction. Moreover, we speculate that at the first public event, participants were eager to leave the experiment and move on to other exhibits on display; hence participants interacted with the soft robots for a shorter period. We coded the transcribed interactions and inductively discovered five main themes in the interaction and discourse: function/application, touch, attribution of mental states, speaking to the robots, and safety. Below we describe these themes and discuss their interrelations and some possible interpretations. We illustrate the themes with selected excerpts from the transcriptions. Below, participants are denoted "red-", "blue-" and "rigid-", with a number that gives the order in which they interacted with the robot.

3.3.1. Function/application

Despite deliberately choosing a non-task driven, open-ended interaction, a number of participants mentioned potential applications for the robot they interacted with. Some people expressed a preference for having a specific function or specified action for the robot:

> *It is also like, when you don't know what it can do right?* (red-19)
>
> *What is it supposed to be used for?* (rigid-4) *That I don't know either* (rigid-3)
>
> *What do you think it is supposed to do?* [pause] *I just don't see what function it has* [pause] *I think it would be nice to know what function it fulfils before one has to interact with it* (rigid-9). [rigid-8 interrupts] *You talk about that a lot* (rigid-8). *Yes, but that is what one is thinking right? What it can do?* (rigid-9)

The lack of a specific task or goal in the experiment might also have contributed to the perception of the robot as more autonomous or subject-like, rather than it being perceived as a tool (see sections 3.3.3 and 3.3.4).

3.3.2 Touch

In all cases, a majority of participants touched the robot, and many were also touched by the robot (see Table 3). For clarity, we treat these two behaviors separately. When the participant actively moves her hand towards the robot up until the point where contact occurs, the behavior is classified as the participant touching the robot. When the hand is held in a fixed position and touch is accomplished by the robot's movement, this is classified as the participant being touched by the robot.

There were statistically significant fewer instances of participants that successfully got the red robot to touch their hand (Table 3). We attribute this to the robot's slower and less visible movement towards the hand. This prevented many participants from noticing the robot's movement, and they retracted their hand from the sensor before the robot could reach it.

Touching the robot

A few participants were uncertain about whether they were also allowed to touch the robot. Yet the majority of participants did so for all three robots. For the red robot, bystanders would sometimes even touch the robot for a short while, while someone else was interacting with it, which suggests an eagerness to do so:

> *I really want to touch that thingy!* (red-26 (young girl))

Some participants were intrigued to touch the robot, but also expressed ambivalence:

> *Oh, so I can touch it or?* [pause] *Actually, I don't really know if I want to* [smiles and then laughs] (red-21)

We observed a great variety in how people touched the soft robots. The types of touches ranged from gentle careful caressing, stroking, poking or squeezing to cupping, holding, bending, twisting, blocking, pulling, pushing or slapping the tentacles. Participants varyingly used everything from a single finger to both hands to touch the tentacle. Touches would occur almost anywhere on the surface of the tentacle. The forcefulness with which some participants touched the soft robots caused the red robot to rupture. A substantial portion of the participants (N_{red}=9) also placed their fingers on the bulge at the top of the red robot's tentacle that would form upon inflation. This often occurred while the bulge was starting to inflate with air, or when air was suddenly released.

For the rigid robot, people predominantly touched the soft end effector, only 3 participants (out of the 16 that touched the robot) touched the rigid robot anywhere else. Despite a longer interaction time, we observed far less variety in the touches for the rigid robot – there was no bending, holding, pulling, twisting, or slapping, and only two interactants obstructed its path. Participants used one finger to five fingers, but only one hand. As can be seen in Fig. 12, the soft tentacles were also initially touched at many different points, whereas the rigid robot was primarily touched on the soft end effector.

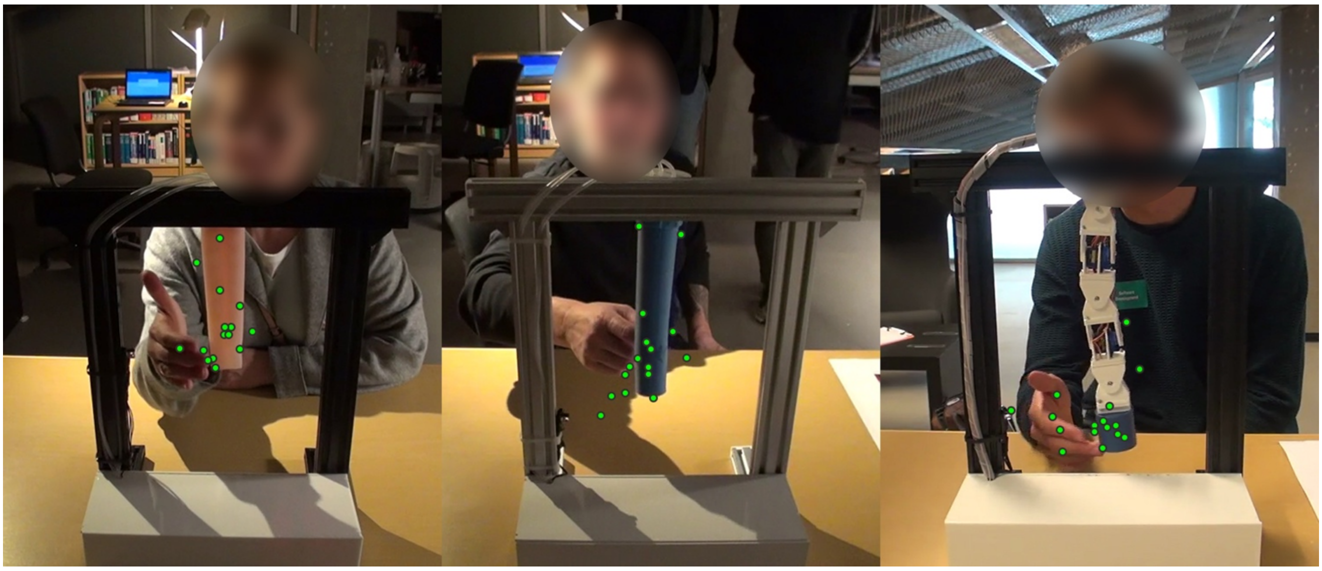

Fig. 12 The point where first touch occurs has been marked with a green dot for the first 16 participants that touched each robot. Dots placed beside the morphology are due to the robot bending while the touch is taking place

A video showing the range of touches from participants to the robots is available under supplementary materials (Online Resource 3).

Being touched by the robot

Several participants interpreted the movement where the robot initiated touch as socially communicative:

> *Then it actually, sort of, touched* [pause] *I wonder if* [pause] *or if it, kind of, wants you to* (rigid-3)
> *It wants you to shake its hand* (rigid-4)
> *Yes, or like – high five!* (rigid-3)

The experience of waiting for the robot's touch was often a moment of anticipation, and some participants verbalized their emotions by making a sound during the robot's approach. Participants frequently smiled immediately after being touched by the robot. For most participants, being touched by the robot seemed a somewhat transgressive yet simultaneously enjoyable experience:

> [The robot is nearing his hand] *It's groping me honey!* [he smiles] [while the robot is moving towards his hand in a high-pitch voice:] *Urghh!* (red-40) [he and bystanders all laugh]
>
> [red-40 jokingly slaps red-41 at the moment when the robot touches her hand; she exclaims:] *Don't!!* (red-41) [they all smile and laugh]
>
> [The robot touches her hand] *Hey, go away!* (blue-12) [blue-12 and blue-11 laughing]
> *Yes, it is like – urrrgh!* [while stretching her arm forward and shaking her body as if experiencing the chills] *– you know?* (blue-11)
>
> [The robot starts moving towards the hand] *Eeeewww!* [Looks at bystander] *It's creepy honey* [in a high-pitch voice] (blue-15)
>
> [The robot approaches her hand and touches it] *Whew!* [smiles] (rigid-11)

> [The robot touches her hand] *Wow, that is weird. Hmm.* [smiles] (rigid-12) [The robot touches her hand while she is looking away, she looks shocked and exclaims:] *Oh!* [then laughs] (rigid-12)

3.3.3 Attribution of mental states

It appears that participants perceived both the soft robots and the rigid robot as social actors. This is evidenced by *perspective-taking*, a term from psychology that describes the process by which people try to both perceive and understand a situation from another person's point of view [11]. Evidence of perspective-taking is seen in the quoted conversations above, for instance where participants attribute to the robot a desire to "shake hands" or when the word "groping" is used (albeit jokingly) to describe the robot's actions. This suggests that, at least to some extent, people attributed mental states and intentionality to these simple robots, and confirms previous work on perception [44] and conventional robots [45]. Perspective taking, even for non-anthropomorphic robots, emphasizes the human tendency to interpret movement as intentional. Further evidence for the perception of the robots as social actors is found in the verbal utterances, where participants imagine the sensory perspective of the robot (perceptual perspective-taking):

> *Isn't it* [the robot] *cold?* (red-35 (young boy))

There are also instances of cognitive perspective-taking, where participants reason about the robot's possible cognitive states, for example what the robot "wants". The inability to cause the robot to touch a person's hand, for instance, would cause participants to speculate on the robot's social preferences:

> *It doesn't want to touch you* (red-9).
> *Maybe I am gross* [jokingly] (red-8).
> *It thinks you are gross* [while smiling] (red-9)
>
> [The robot approaches blue-15's hand instead of blue-16's hand:] *It doesn't like you* (blue-15).
> *No, it doesn't like me. Oh wait, here it is* [the robot is moving towards his hand]. *It likes me a lot* (blue-16).

Cognitive perspective-taking also occurred in relation to an emergent interaction behavior, where the robot continued touching the interactant's hand, which was interpreted as a desire of the robot to prolong the touch:

> [The robot touches her hand. It is pressing on the hand and she pulls the hand slowly away, due to friction the tentacle sticks to the hand and bends as she removes the hand]
> *Oh god!* (blue-23) [both laughing]
> *Very clingy!* (blue-24)

Moreover, the personality trait "curious" was attributed to the blue robot in one interaction:

> *It is kind of trying to go down and touch things* […] *It is kind of a curious, little elephant's trunk in a way* [inaudible], *it tries to find things and it does so on its own* (blue-2)

The word "curious" was also used by 5 (out of 23) respondents to describe the blue robot in the comments section of the questionnaire, where participants were asked to describe the robot using 5 adjectives.

The attribution of mental states also included empathetic responses such as:

> [In a joking tone:] *We are just sitting here, torturing a poor little robot animal* (rigid-15)

That non-anthropomorphic and non-zoomorphic robots evoke significant perceptual and cognitive perspective-taking underscores the human propensity for intuitively responding to machines and other artificial systems as social entities [46, 47].

3.3.4 Speaking to the robots

The video data shows a high frequency of people speaking to the robots. Speaking confers on the robots a type of discursive subjectivity: when participants speak directly to the robots it suggests they are relating to the robots as social actors:

> [she accidentally bumps her hand into the tentacle, which results in a slap-like gesture:] *Whoops!* [looks at the tentacle:] *I am sorry!* [starts laughing out loud] (red-21)
>
> [while the tentacle pushes on his hand:] *You might as well stop! I am going to stay here!* (red-29)
>
> [looks at the tentacle] *Are you coming over here?* (blue-9)
>
> *Aaaahh…Come oonn..* (blue-26) [she moves her hand to different positions near the tentacle, the tentacle then starts moving to the side] *Wow, how did you do that?* (blue-25 (small girl) *This is almost like being a snake charmer* (blue-26)
>
> *Cooome on…* [rubs the fingers on his one hand together and holds it in front of the robot while smacking his lips, speaks in a high-pitched encouraging voice:] *…Come on…Come on…* [the robot approaches his hand] *Ah, good booy!* (rigid-2)
>
> *Now you are just teasing it* [laughs] (rigid-14).
> [rigid-15 looks at the robot:] *Do something! Roll around! Play dead!* (rigid-15)

The above dialogues show the various ways participants addressed the different robots: they address the rigid robot in a manner similar to how one might speak to a companion animal or pet (e.g. a dog), whereas this is not the case for the red and the blue robot. This observation aligns with the observed tendency for participants to compare the rigid robot to an animal (see Fig. 12).

3.3.5 Safety

We observed a difference in perceived safety for interactions with the red robot and the rigid robot. For the red robot, several participants expressed concern for the safety of the robot, whereas for the rigid robot, participants only expressed concern for their own safety.

> *Try to touch it* (red-12 (boy)) [red-13 (boy) touches the tentacle with one finger and then wraps his hand around it near the middle] *No* [red-13's name]*!* (bystander (adult woman))
>
> *Be careful to not over-inflate it – boom!* [laughs] (bystander to red-25))
>
> *You should burst it!* (bystander (girl) to (red-26 (girl)) *Oooh…it does inflate a lot.* (red-26)

In the quote below, the participant compares the rigid robot to a snake that could potentially strike (and thus harm) the human:

> *It is kind of like a snake that comes to you* (rigid-1)
> *Uh-huh...The way it just rolls in* (rigid-2)
> [The robot moves toward rigid-1's hand:] *Then it just comes and it is just like – chu!* [while assembling the fingers of his one hand together and making a gesture with his arm suggesting a snake that attacks] *Then it just strikes – krrr!* (rigid-2) [both smile]

In another instance, the same participant comments on the likelihood that the rigid robot might trap his hand:

> *Then it just pushes…hehe.* (rigid-1)
> *Then your hand is just stuck* [smiles] (rigid-2)

Similarly, while the blue robot and the rigid robot were calibrated to apply approximately the same force to the hand, only the rigid robot caused a participant suddenly withdraw her hand:

> [When the robot touches her hand:] *Oh, it is kind of pushing me a little* [pulls her hand back and holds it close to her body] (rigid-8) […] [When the robot touches her hand again:] *Now it is actually pushing me a little* [pulls her hand back and holds it close to her body again]

By contrast, a participant feeling the red robot's touch speculates that the robot is not capable of significant physical force:

> *I don't think it has much force, it bulges out instead* (red-30)

Most participants appeared to experience being touched by the robot as enjoyable, but the different reactions to perceived safety for the red robot and the rigid robot is an interesting finding as it suggests different perceptions for different morphologies.

4.Discussion

The two main goals of this study were:

1. To initiate critical discussion of the claim that soft robots are more "natural" than conventional robots
2. To gain insights into people's perceptions of silicone-based soft robots and the spontaneous interaction behaviors that soft robots elicit

Below we discuss how our research findings can be seen to contribute to these ends.

4.1 Moving beyond "natural"

The empirical findings of this study question how applicable or useful the word "natural" is for differentiating soft robots from traditional robots. Firstly, there was no statistically significant difference in scores for overall perceived naturalness for the three robots. There were also no statistically significant differences in how natural the appearance, movement and touch were rated. For this reason, we conclude that the quantitative analysis does not support the hypothesis that soft robots are perceived as more natural than traditional rigid robots. This result challenges prevailing assumptions about people's perceptions of soft robots as compared with conventional robots.

Secondly, analysis of written responses concerning what the robots resemble revealed that the categories which contained the most data items for the three robots were "animal", "animal body part", and "part of an organism" respectively. These three categories are all traditionally associated with the natural world; hence, this result further challenges the foregone assumption that soft robots are perceived as more natural than conventional robots. Finally, we observed a wide range of responses when participants were asked to define the word "natural". This finding further suggests that language and discourse surrounding robot embodiments should be more carefully considered.

With regards to the specific hypotheses, H1 hypothesized that the soft robots would be rated as having a more natural appearance than the rigid robot, which proved not to be the case. To our surprise, the rigid robot was on average rated as having a more natural appearance than the blue robot. Moreover, the rigid robot's movements were also on average perceived as marginally more natural than the red robot's movements. These results might be explained if participants responded with the meaning of natural as conventional or habitual in mind. For example, the blue robot might have been considered to have an "unnatural" appearance, as the color is rarely observed in natural organisms, while its softness simultaneously diverges from typical expectations about robots. Similarly, the rigid robot might have been perceived as moving naturally because it moves according to the principles of its mechanical design, which are evident from its machinic appearance.

H2 conjectured that perceived naturalness and appeal would not be correlated, but our results demonstrate a significant relationship between perceived overall naturalness and overall appeal for all three robots. Given that a correlation exists between perceived naturalness and appeal, this could indicate that natural is used both as a descriptive term and as a term of positive valuation, as has previously been highlighted within discourse analysis [48, 49].

As anticipated by H3, we found that when asked to define "natural" in writing, participants used a number of different meanings to describe what they meant by the term. Somewhat surprisingly, "human-like" was a prominent descriptor, and it appeared even more frequently than one of the dictionary definitions. This result, however, echoes the tendency to interpret "natural" as meaning "human" when communication is discussed within social robotics research [50].

The two other most frequent meanings included natural as something existing in nature, or not man-made, and natural as familiar or habitual. The great variety in reported usages of the word "natural" further problematizes its use as a descriptor in technical literature that defines soft robots as "more natural". We interpret this result as evidence that the term "natural" is both ambiguous and imprecise, not just from a theoretical standpoint, but also empirically when it is used to describe a robot's qualities.

H4 hypothesized that the soft robots would be said to resemble animals/animal body parts more often than the rigid robot. This did not hold, as the rigid robot was more often said to resemble animals/animal body parts than the red robot. However, the rigid robot had considerably more entries in the "synthetic materials / man-made object" category compared with the soft robots (Fig. 10).

The word “natural” has dominated the discourse on human interaction with computer interfaces [51] social robots [50, 52], and now, soft robots. The results of our study make clear that the term natural is highly problematic, and we advocate that researchers be cautious when articulating claims about HRI. As argued by Hansen and Dalsgaard [51], words are not only descriptive but also formative: language shapes our perception and also our possibilities to act in the world. The words we use to describe robots and HRI matter because they ultimately help shape the interaction. It is therefore important to look more closely at the discourse surrounding emerging technologies, not least when considering a new class of robots that possess radically different appearances than their mechanical counterparts. The underexamined use of the term “natural” could potentially pre-empt a necessary, nuanced examination of people’s appraisal of soft robots and their interactions. Hence, we argue that researchers working with soft robots consider how and when they use the term “natural”, and consider adopting descriptive language that is less totalizing and ambiguous.

4.2 Key differences in perception and interactions

While participants did not show a clear preference for one robot, the different robots prompted considerably different interaction patterns and behaviors. From our analysis of the interaction behaviors, three main take-aways stand out that are especially relevant for future soft robot designs and further research, which we describe below.

4.2.1 Soft robots encourage touch

People were more bold when manipulating and physically exploring the soft robots than the rigid robot. Participants gripped and handled the entire surface area of the soft robots, even to the point of unintentionally damaging one robot. For the rigid robot, the touch that occurred was also almost exclusively (81% of participants) restricted to the soft end effector. We believe that these interaction patterns are important considerations for robot designers, as they connect directly to safety and reliability. Our observations suggest that soft silicone material invites touch in a way that rigid materials do not. From a design perspective, we suggest that only parts of a robot that can be touched should be made out of soft silicone: if the entire morphology is made of soft materials, as with the red and blue robots, people might feel safe (or perhaps even expected) to touch all parts of it.

That the soft robots were exposed to more forceful handling also suggests that for robots intended for close physical interaction with humans, durability is tantamount. Users are not familiar with soft robotics technology in the same way as with mechatronics and conventional robots. Based on our experiments, we found that some people are under the false impression that a soft morphology can withstand almost anything. The timidity or caution that people show for conventional robots does not seem to carry over to robots made of soft materials. For close interaction scenarios, this can potentially pose problems for both the robot and also the human.

There are different plausible explanations for why touching occurs more intensively in interactions with the soft robots than the rigid robot, and why some people even started to touch the robots while other participants were interacting with them. One reason could be that people are unfamiliar with the technology and the material; hence, there is a strong desire or need to explore it tactilely to gain experiential knowledge about it, whereas rigid mechatronics are more well-known and users are well-aware that they can break from a too forceful handling. Research in psychology also provides possible explanations for this divergence in physical interaction. Harlow’s historical experiments showed the innate preference of infant rhesus monkeys for soft, terry cloth-clad artificial mothers over bare mesh wire ones [53]. Moreover, the findings demonstrate the importance of soft body contact for subsequent psychological development, a finding that Harlow implied would most likely also apply to humans. Additionally, the psychological phenomenon known as *dimorphous* *expressions* [54] might also be relevant for soft robots: in the study researchers found that when presented with an image of something cute that produced positive emotions, people also experienced stronger aggressive expressions, such as wanting to pinch a baby's cheeks. Dimorphous expressions explain why people make both caring and aggressive gestures towards appealing stimuli: a soft body that is pleasing to touch could inadvertently also prompt aggressive touching or excessive force. This might explain why the soft robots prompted more brazen and rough interaction behaviors.

4.2.2 Soft robots might be perceived as more safe than rigid robots, but they are not inherently safer

That concern for human safety is only mentioned in interactions with the rigid robot suggests that soft robots could be perceived as more safe to interact with than similar shaped robots made of rigid materials, a finding that is consistent with a previous HRI experiment where rigid robots were covered with soft foam [55]. This might make it easier for users to accept soft robots than rigid robots as partners for collaborative tasks. On the other hand, as our experiment showed, a soft robot body prompted more excessive force and handling, even to the point of breaking one robot. One might say that the soft design did not adequately communicate its physical limitations, and some people grossly overestimated its durability. Soft materials make people feel comfortable taking bigger risks in their physical interactions, but this might not be advisable for all scenarios as it could lead to an overestimation of safety and underestimation of the risk of physical harm. Just as the design and materiality of conventional robots conveys important information about affordances, safety, and risk, so should the aesthetic design of soft robots accurately communicate these properties. Our findings suggest that soft, pliable robot bodies can appear more robust and durable than they actually are.

4.2.3 Embodiment suggests usage

We found evidence that all the robots used in the study were perceived as social actors, rather than simple technological tools (see *3.3 Analysis of video recordings*). The robots had no other capacity for communication besides movement, and were not designed with explicitly zoomorphic or anthropomorphic features. We find the aspects of perceived agency and perspective-taking very interesting and worthy of further study. Based on video data that showed people speaking to the robots and engaging with them as social actors, our findings suggest that even simple, soft robotic systems evoke social responses.

Studies repeatedly show that a robot's embodiment impacts task performance and the perception of robots as social agents. Our experiment illustrated how the specific material of a robot's embodiment can trigger specific attributions of social agency and intentionality, even for non-humanoid and non-anthropomorphic robots. Analysis of the written replies showed trends for how participants attributed different use cases for each robot. The red robot was most often said to resemble a part of an organism. Specific mentions included arm, lung, penis, a muscle, "a piece of lose skin", trachea, small intestine, vein, and "intestinal section". For the red robot, it was often internal body parts that were mentioned. By contrast, the blue robot was said to resemble external parts of an animal: an elephant's trunk and a tentacle were the two most frequently mentioned. This difference could be attributed to the difference in color, but can also have been influenced by the more constrained and firm movements of the blue robot, which might create a sense of purpose-driven movement reminiscent of that involved in manipulation tasks. Finally, the rigid robot was most often said to resemble an entire animal, possibly indicating that this morphology is, to some degree, perceived as being both autonomous and complete. This interpretation is further supported by the video analysis, wherein participants can be heard talking to this robot in ways people talk to animals. These three categories of resemblances could potentially serve as input for the design of robots to interact with humans: they imply specific behaviors and usages such as close or interior contact with the body, manipulation of objects, and, in the case of the rigid robot, independent behavior. One could choose to align a robot's design with the corresponding behavior to make it easier to intuit the robot's purpose or function, and how to interact with it.

5. Limitations and further work

This study problematizes the notion that soft robots are more "natural" than traditional robots and identified differences in how participants interact with soft and traditional robots. The study, however, also has some limitations. One weakness is that participants were only asked to rate the robots in an open-ended, non-specific context. In order for the ratings to be transferable to specific applications/use-cases, the study would ideally account for the fact that specific embodiments and a specific aesthetic might be preferential for specific purposes. That is, a robot that is associated with safety and precision might be preferred for e.g. a health care context, but this consideration need not apply for e.g. an educational robot. Another limitation is that the data reflects first impressions and interaction behaviors that might change or fade over time, as people learn to adapt to the robots. The findings are important indications of how people perceive and interact with silicone-based soft robots upon the initial encounter, which is important to understanding acceptance and adoption of novel technologies [56].

Context is also an issue to take into account in relation to the recruitment procedure and the execution of the two experiments. Participants were recruited at public events on a university campus at an educational institution that focuses on information technology, and this might have biased the results. However, from the age range of participants (19-70 years) as well as the high proportion of human-robot interaction naïve participants (54%), it seems reasonable to assume that many participants were neither students nor faculty. The two trials were also conducted over two days: the trial with the soft robots took place in the evening as a part of a citywide event, while the trial with the rigid robot was conducted during the day at a matchmaking event for college and university students.

Another limitation of the study is the questionnaire, which we constructed in order to be able to address the specific research questions that motivated this study. Further work is needed to ensure the validity and reliability of this subjective self-reporting tool.

Based on statistical analysis, we concluded that our data could not support that soft robots are perceived as more natural than rigid robots. We did, however, observe lower mean scores, indicating a higher level of agreement, for the overall naturalness rating of the soft robots compared with the rigid robot. Hence, the inability of the results to support the hypothesis could be due to the study being statistically underpowered and hence unable to detect marginal differences.

Finally, this study is only a single case study where we used one specific type of soft robot. In order to determine differences in people's perception of and intuitive interactions with soft robots and traditional robots, further studies are needed. Moreover, the differences should be replicated in studies with a higher number of participants and quantitative analysis to strengthen their generalizability.

6. Conclusions

Using a mixed-methods approach, this study highlights the problematic character of the term "natural" when evaluating soft robotics technology. Within the emerging field of soft robotics, it has been a foregone assumption that soft bodies are more "natural" and therefore more appealing. Our experiments did not support this claim: we found no statistically significant differences in appeal and naturalness ratings overall nor for the appearance, movements, and haptic qualities of the three robots. We did, however, find a correlation between overall perceived naturalness and overall appeal ratings for all three robots. From both written questionnaires and video recordings of interactions, we found that the term "natural" is unnuanced and does not sufficiently capture the experiential qualities of interactions with robots. Our findings suggest that "natural" is an imprecise, and possibly even unproductive, term for evaluating HRI. While soft robots might be inspired by natural organisms and biology, the evaluation frameworks used to identify and describe the human perception of robots, we argue, would do well to leave out questions of "natural." Based on our results, we recommend that evaluation research within the field of HRI and social robots leave aside the discussion of "natural" and rather focus on developing more precise language that adequately captures and reflects the experiences of the participants and the interactions emergent in practice.

Our positive findings represent preliminary but important first steps in researching how soft robots and traditional robots might be said to differ with respect to HRI. The results indicate that touch and perceived safety are potential aspects that might differentiate interaction with soft robots from interaction with traditional robots.

Supplementary materials

Online Resource 1: Video showing the three robots
(Also available at: https://youtu.be/K_Pxjw6IUGY)

Online Resource 2: Video of the blue and the rigid robots' similar movement
(Also available at: https://youtu.be/qacuhyn4P8M)

Online Resource 3: Video showing examples of how the robots were touched
(Also available at: https://youtu.be/c4_I7zh53-I)

Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

Informed consent Informed consent was obtained from the study participants.

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Enacting the Soft Automaton: Empirical Ontologies of Two Soft Robots from Technical Research and Media Art

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This paper examines two soft robots from technical research and media art respectively and the practices through which they come into being. Departing from a juxtaposition of video presentations of the two robots, the empirical ontologies of a soft robot enacted in practice are analysed. The paper argues that two different versions of softness are being done and that the two sets of practices concomitantly respecify "knowledge" and "autonomy" as concepts, with different ethical and political implications.

Soft robotics. Soft material robots. Media art. Robotic art. Empirical ontology.

1. INTRODUCTION

In the course of the past ten years, soft robotics has become a thriving subfield of technical robotics research. Despite an observable tendency towards convergence, a number of different definitions of soft robotics and what a soft robot is still exist within the technical literature. Wang and colleagues (2017), for instance, remark that soft robotics "encompasses solutions that interact with [the] environment relying on inherent or structural compliance". Whereas Rus and Tolley (2015) define soft robots as "systems that are capable of autonomous behavio[u]r, and that are primarily composed of materials with [elastic] moduli in the range of that of soft biological materials".

Constructing robots from soft and elastic materials yields a number of technical benefits that include safe interaction through passive compliance, the possibility for shape-shifting and bodily adaptation, ease of control through *morphological computation*, and the potential to reuse stored elastic energy. But soft robots are equally endowed with a specific expressivity and a different aesthetic than their rigid precursors. These latter aspects have recently begun to be explored in a number of appropriations of soft robotics technology by artists, designers and architects. Examples of soft robots featured in artworks that were produced prior to soft robotics' emergence as a field, however, also exist.

This paper seeks to unpack the notion of a soft robot through an ontological mode of analysis inspired by *Actor-Network Theory* (*ANT*). Departing from the assumption that ontology, understood not as "that which is" but as "how things exist", is entwined with ethics and politics, the paper explores the practices of designing, constructing, interacting with and thinking about soft robots within two projects of technical robotics research and media art respectively. How are soft robots "being done" and by which means are different versions of soft materiality enacted? What tendencies and capacities of soft matter do these different soft robots actualise? In what sense is softness rendered active or agential?

1.1 Approach

As mentioned, the approach taken is inspired by ANT and the so-called *ontological turn* within Science and Technology Studies (*STS*). It is grounded in the argument put forth here that reality, as we inhabit it, is performed within different practices. Reality itself is thus multiple, not in a social constructivist sense, but in a deeper ontological sense (Mol 1999). And an object, such as a soft robot, can come in various versions, that despite sharing physical similarities, or even being physically identical, might diverge ontologically. In their studies of Atlantic salmon, John Law and Marianne Lien (2012) put this in relational terms as "different salmon are done in different practices" and "different salmon are being enacted". And Annemarie Mol (2014) has similarly articulated this notion in her argument that each version of practicing stages, performs, does, and enacts a different version of "the" object, which must therefore be considered "an object multiple" (Mol 2014). Within the ANT tradition this assumption of ontological multiplicity is operationalised in interpretive strategies that foreground and study practical ontologies empirically by paying close attention to the practices and networks of relations through which a specific version of an object is brought forth.

In the case of soft robotics as an emerging technology, the indeterminacy and multiplicity of the object in question, is perhaps even more readily apparent, as the technical object, a soft robot, is currently still being invented and articulated. But what a soft robot is and does, is also already gradually becoming more specified and stabilised through the contingent processes, actions, and discourses that make up practices. At this juncture, it is therefore relevant to consider how different enactments of "a soft robot" diverge, and that, given the choice between these different versions, to reflect on what politics and ethics that are enacted in conjunction with their differences.

The main interest of this paper is therefore to explore how soft robots get put together within two different contexts and associated sets of practices. Consequently, its focus lies on analysing the practices and the soft robot ontologies they enact – how specific versions of "a soft robot" emerge and how these might differ. Furthermore, the paper seeks to engage with the merits and drawbacks of these two different ways of assembling "a soft robot". It aims to extend the specific risks and potentials "that singulari[s]e each position", to use a formulation of Isabelle Stengers (2005a).

1.2 Analysis of video / analysis of practices

A few further methodological remarks are needed before continuing, about how this paper extends the analytical practices of ANT and STS. Unlike most work anchored in the STS tradition, this paper is not based on ethnographic fieldwork. Instead it utilises two videos as its most immediate empirical materials. Even if ANT as a theoretical formation is critical towards the notion that there is ever such a thing as an unmediated access to the field, or reality as such, the kind of access to practices provided by a video obviously differs from the one obtained by being present at a physical site and associating with informants. Moreover, a framing evidently occurs when practices are translated into the video medium. Consequently, when analysing video, one obviously runs the risk of mistaking an edited representation for "the thing itself". In my analyses, I aim to stay aware of the limited and mediated access to practices the two videos offer. Both videos are clearly censored and staged accounts influenced by specific agendas and aspirations as well as the affordances of video as a medium. But analysing the practices as they are depicted in these videos rather than doing field ethnography, I argue, holds a different potential. Precisely because the videos are self-representations emerging from the practices they depict, what is included or excluded betrays assumptions about what is important and unimportant within these practices. Comparative analysis can thus function as a means to become aware of the blind spots of each video and potentially reconstruct some of what is left out in each of them. A further resource, that forms a backdrop for this work, yet remains a tacit voice in the text, is my own involvement with soft robotics, that have unfolded as both academic research and artistic practice, over the course of the past two years.

Embracing the situatedness of my own account, I have chosen to let the paper reflect its process of coming into being by starting the analysis with excerpts from notes that I originally jotted down while watching the videos on my computer as a prerequisite for writing this paper. Unless otherwise specified, quotations come from these notes.

2. TWO VIDEOS

> An upbeat yet restrained music played on acoustic instruments is heard (it is similar to the kind of music that is featured in commercials for products). The first images we see is of the semi-transparent Octobot with its characteristic blue and red fuel chambers and channels. It is seen from above on a white background. The title of the video then emerges in the white space next to the robot along with the Harvard seal …

Figure 1: *Still image from the opening shot of the first video. Courtesy of Harvard SEAS.*

The first video (Harvard University 2016) disseminates research from an academic paper published as a letter in *Nature*, one of the most prestigious high impact science journals. The paper is authored by seven researchers from Harvard University and Weill Cornell Medicine. The video was produced by Leah Burrows, a Science and Technology Communications Officer at Harvard University. It was released on YouTube on 24 August 2016, the same day as the paper was published. The video is 1 minute and 34 seconds long and entitled “Introducing the Octobot”.

> The opening shot shows a woman sitting with a piece of paper reading aloud from it. Besides the voice only static noise and room noises can be heard. There is no professional lighting to improve the quality of the video images. The woman reads […] in Spanish. There are English subtitles displayed at the bottom of the video. She informs us that she has designed “an autonomous robotic agent, whose most relevant behaviour is its capacity of having a body ‘language’”.

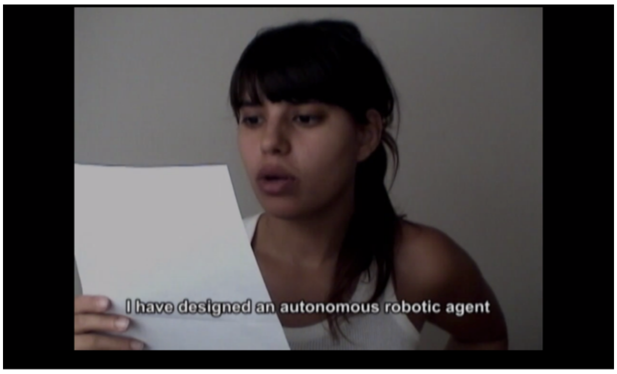

Figure 2: *Still image from the beginning of the second video. Courtesy of Paula Gaetano Adi.*

The second video (Gaetano Adi 2006) is stored on the Vimeo platform and embedded on the webpage of media artist Paula Gaetano Adi. It documents her robotic artwork *Alexitimia* (2006/2007). It was produced by the artist in 2006 and is 9 minutes and 43 seconds long[1].

2.1 Fabrication

What defines a soft robot and through which methods and procedures might we know about and construct soft robots? Proceeding from an interest in empirical ontology, these are some of the questions we can ask of practices. For both videos, the answers given seem to hinge on revealing and making visible an origin and function but also on something more. Both videos share a similar symmetrical narrative structure: first there is footage of the robot, then its fabrication and functioning are explained and lastly the finished robot is shown again.

Consider the midsection of the Octobot video:

> We see footage of the manufacturing of the robot, which occurs on a multimaterial embed 3D printer that uses a syringe to pierce through the uncured liquid silicone in a mould. Materials with the right mechanical properties are deposited into [what]… will later become the body of the robot. The [rigid] robot constructing the soft robot moves fast and precisely … The uncured silicone lights up in a bright fluorescent bluish hue, and the printed inner channels appear in red. … The [soft] robot is then seen from above, as in the beginning, and we are told that it is controlled with a microfluid[ic] logic circuit … “The logic circuit acts just like a circuit board, autonomously directing fuel”

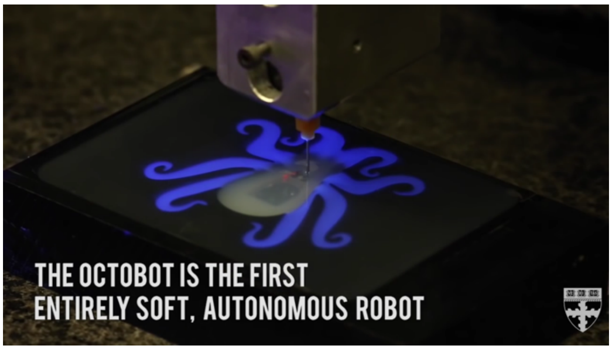

Figure 3: *Still image from the video showing the Octobot’s fabrication. Courtesy of Harvard SEAS.*

Compare this with how the fabrication is depicted in Gaetano Adi’s video:

> 4:40: A spherical shape is shown occupying most of the frame. She gradually adds pieces of clay to cover its surface, making sure to even them out using both of her hands … A gloved hand is distributing a white layer of liquid material (latex) across the surface. Footage where hoses are seen being attached. This occurs with the use of a brush that gently adds latex on top of a white fabric mesh that looks like gauze … Flexible piezo film sensors are added, painted over with latex meticulously (… [she] handles and controls the brush skilfully) to sense the touch. 6:23: Using what looks like a soldering iron she very carefully punches holes [in the tubing], wearing glasses to better see … The gestures and setup look like an operation being performed on a human body that is partially covered, but the tool that is used is usually used to repair or assemble electronics. It is at once a technical operation (repairing a machine) and a surgery…

Figure 4: *Still image from the video: Holes are made. Courtesy of Paula Gaetano Adi.*

> 6.47: The semi-sphere is seen lying on a plinth(?) it is lifted over to reveal wires, which the woman is seen twisting together (the sensors were "connected in parallel…"). The microcontroller is placed in a small plastic suitcase-like enclosure that looks to be fixed atop a baking tin. It activates four pumps, hidden inside [the] pedestal in [a] reservoir with distilled water.

Juxtaposing the two different versions of soft robot fabrication in the two videos, it becomes clear that soft robots are enmeshed in dissimilar practices characterised by markedly different procedures and aspirations. In the Octobot video, there are no humans present. We are in a sort of ideal decontextualised flat space of modern science, devoid of subjects and subjectivities. The only actors present are precise machines that manipulate and combine materials with full reproducibility. In great contrast to this, *Alexitimia* is always depicted in the presence of its human creator, the artist, whose physical labour is portrayed as bringing it into existence through careful and caring attention.

2.2 Production as knowledge

How to make sense of these differences? Scale obviously has a bearing on some of them – the Octobot is driven by chemical reactions and microfluidic circuits whereas *Alexitimia* has a size comparable to that of the human body and is powered by a traditional microcontroller, electrical sensors and water pumps that can be assembled by hand. The two videos thus attest to what soft elastomers are capable of becoming when entering into composition with computing technologies on different scales. But the actions and practices depicted also reverberate with ideals from their respective cultural domains – the artwork as a materialization of the artist's embodied mastery of her physical medium and the scientific object as founded on pure objectivity, unsoiled by human desire. The two fabrication processes can, moreover, be seen to echo different historical modes of technical practice – automated industrial mass production in the case of the Octobot and traditional crafts in the case of *Alexitimia*. This observation that the Octobot fabrication takes mass production as its ideal might also lead one to take note of the word "Veritas" that is included in the diagram of the Octobot's microfluidic logic circuit in the video (Figure 6) and printed on the physical circuit, just as a brand name often is on mass produced commodities.

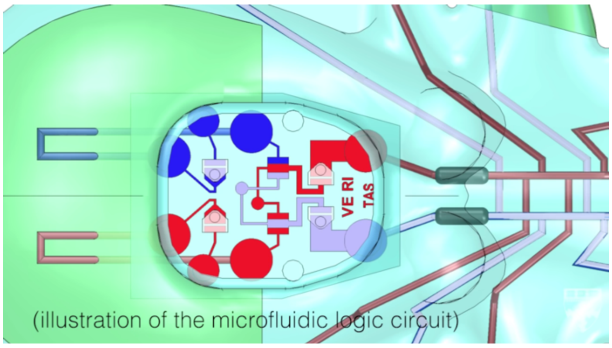

Figure 5: *Still image from the video: Diagram of the logic circuit. Courtesy of Harvard SEAS.*

"Veritas", truth, is the motto of Harvard, its brand. As a sign, "Veritas" branded on the robot performs several functions. On the one hand, it is an authoritative sign of truth, that is – a symbol referring to Harvard and the Ivy League system and its institutionalised politics of knowledge. But it also denotes the robot as a physical instance of *the* truth, a research insight. But how exactly does a *thing* become *truth*? And if this *thing* is the truth, then has this truth been produced, and not discovered? And how exactly did that occur?

If one looks elsewhere than the video, it becomes clear that this process was indeed a production, and one of a considerable volume. More specifically, 300 not-quite Octobots were produced before arriving at a functional Octobot (Sklar 2016). That this iterative material process was needed to produce the truth of the Octobot, points to that soft materials are hard to simulate accurately in a computer. While roboticists routinely simulate rigid morphologies to determine their most optimal designs, this is not easily done with complex soft morphologies with existing techniques such as the *finite element method* (*FEM*). In this respect, the dynamics of soft materials can be said to resist or escape numerical representation and computation as a force of knowledge production. This unknowability of the physicality of soft materials exemplifies what Andrew Pickering (1994) has termed the "resistance" of matter: When we probe and prod it, that is, when we push, it also pushes back in its own specific, and sometimes unpredictable, ways (see also Hayles 2014 on this). The right design parameters of a functioning Octobot could not be predicted beforehand by combining existing models from soft matter physics and chemistry. It had to emerge from complex dynamics and adjustments that were negotiated through material practice.

2.3 Unknowing softness

The way Gaetano Adi stages and addresses her robot also points to something that is unknowable in the abstract. But here the notion that some insights about soft robots and soft materiality can only be experimented, or intuited, is embraced as an explicit and integral part of practice and the resulting artwork, and not merely seen as an obstacle to overcome. Overall, *Alexitimia* is concerned with trying to find a "body language of robots", Gaetano Adi tells us in the video, and with establishing "a dialog between two kinds of bodies: a corporal dialog" (Gaetano Adi 2006):

> the interface of the work is the skin, the sense of touch is what enables the interaction, and between them [the human and the robot] it is the sweating of the robot's body [t]hat creates the dialog. (Gaetano Adi 2006)

Despite the fact that the haptic exchange, described above, serves as the locus of the artwork, no attempt is, however, made to explain or interpret its content in the video. The technical functioning of *Alexitimia* is demonstrated in great detail, but the practices depicted before and after this propose that this is not all that there is to know about the robot. Presented in its partially assembled or unfinished state, the robot is rendered comprehensible to causal thinking and reasoning. But in the depiction of the interaction between the finished robot and the human, the emergence of a knowledge or even a *not knowing* (see Borgdorff 2012), that cannot be subsumed under the concept, appears to lie at the heart of the practices through which the robot's "functioning" is proposed to unfurl. In the video, we thus encounter multiple, yet specific, ways of interacting with *Alexitimia* through touch:

> 8:39: A hand is seen gently massaging the blob, which secretes liquid. Zoom out: The hand belongs to the creator. She is kneeling beside the robot

And different choreographies of touching unfold: a slow gentle caress, a surface smear, a mechanical folding of layers, an assembling of the skin-like material. The robot responds by sweating but also with a distinct vocabulary of bodily gestures afforded by its elasticity and structural configuration: bending in, popping back out immediately or slowly, folding inwards, lying in wait of what's next. The robot's response to the touch engenders the next touch, which engenders another response from the robot – and so on, it seems. A sense of reciprocity emerges.

Figure 6: *Still images from the video: Touching unfolding between the artist and the robot. Courtesy of Paula Gaetano Adi.*

From the perspective of intentionality, touch might be considered the primary gesture through which softness becomes active or known. Yet Erin Manning has also articulated touch as a movement towards the not yet known (Blackman 2009). Specific gestures of touch, however, also entail an anticipation of a specific sensation and sometimes also an intent of use. Thus the repertoire of human gestures performed onto the robot can equally be considered embodied techniques that are informal ways of knowing softness. They each subtly index classes of activities that unfold within different contexts of human activity. Some are appropriate and fit for touching a material, others a machine, others still for engaging with a living being. Yet they all unfold slowly and exude a certain calmness and gentleness.

2.4 Autonomy

Given the videos' thorough dissection and demystification of the workings of both robots, it might seem curious that the discourse in both videos explicitly mention and emphasise "autonomy" – a concept that broadly refers to independent, self-conscious self-determination and not deterministic processes. *Alexitimia* is presented as "an autonomous robotic agent" (Gaetano Adi 2006) and the Octobot as "the first entirely soft, autonomous robot" (Harvard University 2016). Autonomy is of course a concept that in general figures prominently in robotics discourses. It relates to agency, or, one might say, the degree to which a robot is able to enact itself. But how and in what sense does softness afford autonomy for these two robots?

In *The Robotics Primer*, an introductory textbook on robotics, a robot is defined as: "an autonomous system which exists in the physical world, [that] can sense its environment, and can act on it to achieve some goals.” And autonomy is further specified in the following manner: “An autonomous robot acts on the basis of its own decisions, and is not controlled by a human” (Mataric´, 2007: 2). By this definition (which is of course itself rife with ambiguities) neither robot would obviously qualify as being autonomous – the Octobot does not have sensors and *Alexitimia* appears to be a simple reactive robot, only capable of one behaviour, namely to pump “sweat” when bending is detected by the piezo sensors above some threshold.

The Octobot is, however, also not conceived as autonomous by this broad textbook definition, but more narrowly by not being tethered to a pneumatic or electrical power source, as soft robots usually are. Hence, it is solely by virtue of breaking with the contingent assumption of contemporary soft robotics research that a soft robot must be tethered in order to function, that the researchers claim to have attained autonomy in the Octobot (Wehner et al. 2016). As mentioned already, the video emphasises this notion of autonomy-as-disconnection by depicting the robot separately from humans and any specific and identifiable environment. The manual human labour and handling involved in its production is also elided and its fabrication presented as fully automated – thus figuratively fulfilling the future vision to which the research project itself aims to contribute. Yet upon further inspection, it becomes evident that the humanless staging in the video, in fact conceals that the human sensorium and cognizing is deeply imbricated in the design and presentation of this “autonomous” robot. The footage of its manufacture and functioning, for instance, is played at ten, twelve and fifteen times the actual speeds at which they occur. And the colourful materials have been stained with pigments in order to better reveal the design and the functioning of the robot (Science Magazine 2016). Both the robot itself and its documentation have thus been adjusted and enhanced to lend themselves easily to the human eye and its temporalities and to be fully legible. Furthermore, as a research robot the Octobot is not intended to be a working robot that successfully fulfils some purpose “in the wild”, it is only a “proof of concept” (Burrows 2016). Paradoxically, its primary function is therefore not to operate autonomously on its own but to perform and communicate itself as a research finding to a human audience.

In stark contrast to the Octobot, *Alexitimia* enacts a version of autonomy that seems only actualisable in the close company of a human. Its autonomy is equally not predicated on an ability to physically influence its environment in order to attain some specific goal. Instead it seems to be relational in kind and to inhere in the robot’s proposed ability to sustain what Don Ihde (1990) refers to as an *alterity relation*, that is, to conjure up a sense of independent existence or *quasi-otherness* (whose nature and implications I will return to in the final subsection of this paper).

3. SOFTNESS AS A FORCE OF ROBOTICS

So what is at stake politically in the two different enactments of a soft robot? The analysis unfolded so far suggests that central categories of soft robotics can in themselves become pliable and malleable in practices: Softness and knowledge hereof can be constructed in more than one way, soft autonomy equally so. But this should not make us forget that how things exist, and whose reality is considered more accurate is indeed a political question. Domination could in fact be considered “a matter of holding the capacity to differ under control”, as anthropologists Martin Holbraad, Morten Axel Pedersen and Eduardo Viveiros de Castro have put it (Holbraad et al. 2014). As a first move in approaching the politics of these two robots, we might therefore start by taking note of the different positions of enunciation from which they are articulated. The Octobot was published in Nature and has been hailed widely as a seminal research accomplishment in soft robotics research. *Alexitimia* and other soft robotic artworks, however, are yet to be recognised as contributions to the production of knowledge about soft robots.

To go further in addressing this question, it is insightful to dwell on another way in which specific object ontologies enact an ontological politics, namely through their reality effects and concomitant modulations of other objects and concepts (Mol 1999). I have already noted how “softness”, “knowledge” and “autonomy” are *respecified* in different ways within the two sets of soft robotic practices. That is, these concepts are enacted with specific meanings that modulate their theoretical definitions (which in turn might lead us to reconsider these)[2]. A central contrast herein is that the practices that envelop the Octobot tend to emphasise a separation between humans and robots, while those of *Alexitimia* embrace the similarities and the zone of indiscernibility softness can produce. And through this, the two robots enact two different ways of distinguishing between a human and a robot, and with that two different ways of performing human subjectivity, different modes of subjectivation, that have purchase on politics and ethics. To be more precise, the Octobot research was driven by, so it appears, an instrumental desire for humans to gain control of soft matter. And this matter was to be mastered through practices that combined techniques of both modern science and cybernetics – measurements, numerical representation and abstraction (“Veritas”, tellingly, resided in the robot’s its “logic circuit” and not its limbs) and systematic technology-aided trial and error. A number of philosophies of technology and science have been critical of this set of epistemological operations, that have been considered “reductive” acts of epistemic violence towards situated experience and non-hegemonic ways of knowing. But seen from a post-critical perspective, the reduction they entail is not necessarily simply negative or lamentable. Concepts and abstractions, in general, function to reduce and manage the multitude of differences we encounter in the world. As such, they effectuate a reduction of complexity that is necessary for thinking and acting to occur. Hence in practice the reduction performed via natural science and technology is also productive. Furthermore, from a posthumanist perspective, *Alexitimia*’s enactment of softness in a robot can equally be considered both reductive and productive, albeit in a different manner: It is predominantly articulated from the point of view of a human body and does not acknowledge the equally (possibly) real myriad processes that unfold through other modalities than human sensation on different scales (the global circuits of latex manufacture and their ecological and social effects, the entropic grounds of soft polymer elasticity etc.).

In line with this view of reduction as productive, Isabelle Stengers (2005b) has argued that instead of seeing the successes of experimental science and technology as instances of matter’s submission to thought, we might also affirmatively view them as increases of what has now become possible: “[W]hat they [experimental science and technology] address becomes able to do what it could not do in the usual circumstances” (Stengers 2005b). Consequently, what we are witnessing in functioning technology, according to Stengers, is not submission but “a force which has been both unfolded and re-folded” (ibid.). So how is softness produced here, within these specific empirical ontologies of the two soft robots, how is softness actualised as a force and what does it become capable of?

By looking at soft matter and chemistry through concepts previously used to describe electronic circuits and aided by rapid prototyping technologies, it was possible to construct an oscillatory control circuit for the Octobot out of soft matter and chemical reactions. That is, coupled with these specific concepts and their associated practices and this equipment, softness can afford a robot untethered autonomy and allow for an integration of systems and components (actuation, control, computation) that are usually separate in a robot.

Alexitimia, on the other hand, evinced that assembled with a microcontroller and sensors as an interactive artwork, soft matter can equally engender what we might term “soft interactions” with humans. These exchanges were characterised by specific speeds and specific gestures that appear to be tied to soft matter in general (as previously described). The result was, that in this configuration, coupled with this set of practices, the physical softness of the material was translated into “soft” movements and also aided in manifesting other meanings that the word “soft” has as an adjective – “producing agreeable … sensations”, being “characterized by ease and quiet enjoyment” and being “of a calm or placid character” (Oxford English Dictionary).

3.1 Towards an affirmative soft robot ethics

That multiple meanings of softness were actualised in the “soft interactions” of *Alexitimia*, illustrates the need to go beyond the strictly technical definitions of softness, used within contemporary soft robotics research, when conceptualising the interactions that a soft robot might have with organisms or other elements in its environment. Furthermore, it points to the potential for artworks to help in inventing new ways of knowing and experiencing softness and a more adequate expanded vocabulary to address it.

Taken as a representation of an epistemic practice, the video on *Alexitimia* aligns with Andrew Pickering’s description of how some interactive artworks can be considered “implicit invitation[s] ... to adopt a non- or post-scientific worldview which sees humanity not in a position of cognitive control but rather as simply caught up in the weather of unpredictable becoming” as he puts it (Pickering, 2016). In that sense *Alexitimia*’s versioning of softness can be seen to point beyond a purely instrumental notion of technology, and towards a receptivity to not just the quasi-otherness of a soft artificial embodied agent, but also to the otherness that resides within the human, i.e. the non-human constituents of human subjectivity that elide conscious knowledge and control. Given the imperative of posthumanist theory to rid ourselves of the humanist fantasy of the Cartesian subject as autonomous and set above the world (see Braidotti 2013; Wolfe 2009), this is arguably a both relevant and timely experience. The work can, moreover, serve as a productive counter to the currently existing discourse on soft robot ethics. The only academic publication that currently deals with soft robots from the point of view of ethics namely worries that their soft tactility might have the effect of creating more deeply felt emotional attachments in interactions with humans. The authors therefore recommend soft roboticists who are involved in designing soft robots for interaction with humans to “balance tactile engagement against emotional manipulation” and to “model intimacy on the bonding with a tool not with a person” (Arnold and Scheutz 2017). This recommendation, formulated from a stance of morality (what people should do) rather than ethics (what people can become capable of), I posit, is problematic as it elides the growing body of work within STS and related disciplines that stress that advanced technological “tools” are rarely uncomplicated and straightforward to “bond with” let alone implement in societies. As I have tried to articulate through my treatment of the *Alexitimia* video, embracing, rather than repressing, the affective potentials of soft robots on the contrary has the potential to make us question the conception of robots as simple tools that we can expect to yield and fully control. Artworks and the onto-epistemic practices of art could potentially add this more modest way of engaging with and thinking about the world, that does not presuppose a fixed power relation between humans and world or humans and robots, to the current repertoire of methods within soft robotics research. If the proposed application of soft robots (outside the lab and the white cube) in so-called welfare and care technologies stands to happen, surely this would be no small feat, as this clearly raises other issues than functionality and safety, that one needs to attend to in a careful, experimental manner.

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NOTES

1. Paula Gaetano Adi, email to author, 29 May 2018.

2. On the concept of *respecification* see Sormani et al. 2017.