Aesthetics in Soft Robotics

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ABSTRACT

The current explorative field of soft robotics shows exciting developments for a variety of novel application areas and a new found combination of system and embodied intelligence. It therefore gives space for redefining the robotics field by the potential to embrace the aesthetics within the design of these soft robotic systems.

This pictorial suggests an explorative approach to design and analyze aesthetic and intelligent qualities in soft robotic systems. By doing this, it sets a step towards addressing the broader goal of a discipline-shared framework embracing both engineering and aesthetic practices. A 'studio' methodology is employed together with reflections based on literature and expert input to document the journey towards the suggested approach. The explorative approach entails the design of a demonstrator which allows for modularity and decentralization of the soft robotic system. The discussion will reflect on the journey and the final proposed approach.

Authors Keywords

Soft Robotic Systems; Aesthetics; Intelligence; Studio Methodology

INTRODUCTION

Soft robotics is a relatively new subfield within robotics. In general, a robotic system is called "soft" when a significant and relevant part of the system is made out of one or multiple material(s) that can physically adapt to its environment due to their material qualities. These material qualities (or adaptability due to "softness") can take on various forms. Examples include rubber-like materials for the robotic actuators (one of the most commonly used material is silicon) [1]–[5], shape-changing materials with actuation and sensing abilities [6]–[8] and fully phase-changing materials [9] to name a few. This "softness" due to the adaptability of the material allows for safe interactions with both its environment as with its users and shows therefore potential in a variety of application areas.

Although application areas relating to health [10], manufacturing technologies [4], and disaster management are already being extensively developed, the field is still mainly in its explorative research phase. Seeing its beginnings in the 1960's, it has seen a big leap in development during the 2010's due to research done such as the 'Multigait' soft robot [1], the 'Octobot' [11] and more [12]. Many disciplines, ranging from Engineering to Design, from Chemistry to Computer Science, each (collaboratively) contribute to the knowledge development within the soft robotics field. The "language" used in these research papers remains mostly technical and highly focused on the practical, functional aspects of soft robotic systems.

Recently, the paper written by Jørgensen (2022) suggests a different approach, by incorporating the use of aesthetic theory to enrich the "language" and practices within research of soft robotic systems. The development of soft robotic systems often relies on intuitive and empirical ways of working due to complexity of the system, the properties of soft materials (of which some have some inherent material or embodied intelligence present due to both sensing and actuation abilities) and the computational difficulty of simulation these systems. Considering both engineering and aesthetic practices equally in the process would therefore support the valorization of "…such informal open-ended and experimental ways of working that are predicated on accumulated experience and embodied knowledge and to recognize them as valid means of invention." [13]. Hereby moving away from the perspective of traditional rigid robots who's applications mainly focus on their functionality due to their purpose of "serving" humans or replacing human labor.

This pictorial supports this notion of incorporating aesthetics within the research language relating to soft robotics. Furthermore, it wants to address the need for the overall development of a discipline-wide "common language" or shared framework to support interdisciplinary knowledge sharing and development within the soft robotics field. Concepts such as embodiment and emergent behavior are used both in engineering and design research [14]–[17], however there is a difference in the more functional and technology versus more experiential and aesthetic language use. A discipline-shared framework that would encourage the equal use of both and has, to my knowledge, not yet been explored discipline wide.

Before such a shared framework can be constructed, of which the formulation is out of the scope of this research project, there is relevance in further exploring the practice of designing soft robotic systems and how aesthetics can play a more prominent role. This pictorial shows the journey from this previously mentioned broad scope to a more refined research question by taking a 'studio approach' methodology together with reflections based on expert input. The final research question to be answered is "How can a soft robotic system be designed such that it allows for exploration of aesthetic and intelligent qualities to be present within the system?". This lead to the proposal of a demonstrator that allows for an explorative approach to the design of soft robot systems through its modularity and decentralized system.

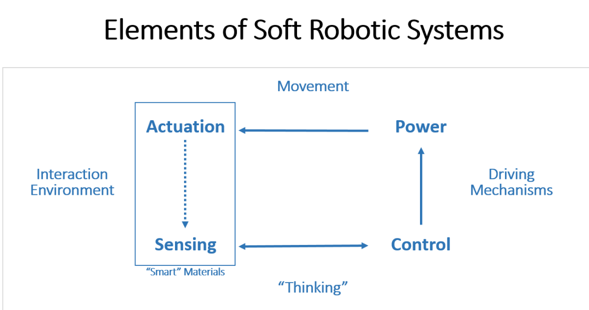


Figure 1: Elements of the Soft Robotic System

MORE ON SOFT ROBOTICS

The notion of 'soft' in soft robots has in other work been described as the use of materials within a range of elastic moduli that allows for a high level of compliance with its environment that is similar to that of soft biological materials [10], [18], [19]. The compliance of the material can be seen as a low-level intelligent quality called material or embodied intelligence [10], [12]. This technical description solely considers (part of) the body of the soft robot. Wehner et al. (2016) have developed a fully (autonomous) soft robotic system, but most soft robots are a hybrid between soft and rigid bodily parts.

Although safety in interaction is mentioned mostly as a functional by-product of the soft body, this inherently indicates the presence of 'soft', aesthetic experiences such as 'gentleness', 'vulnerability' or 'empathy' [13], [19]. In this pictorial, I embrace the term 'softness' to describe the multilayered aesthetic and intelligent qualities that are present in these systems.

Figure 1 shows the internal and external relations of the elements or 'materials' of soft robotic systems that I will use as a basis for this pictorial . This division of system elements is based on a Guest Lecture by dr. Overvelde [20], yet other papers [12], [19], [21], [22] employ similar categorizations of the system elements. I will explain a bit more on what I consider to be the 'Power' and 'Control' elements, as my interpretations might defer slightly from that of the lecture and from other literature.

With 'Power' I refer to the 'driving mechanism' that is activated by the control element and in return activates the 'Actuation' (and 'Sensing') element(s). In the case of a tethered, pneumatic robot, this means the electronics such as the circuit board, air pump, solenoid valve etc. that are powered by an energy supply. In the case of the 'Octobot' [11] this means the chemical reactions that drive the actuation of the arms. In the case of the 'Soft Transporter Robot' [6] this means the external light emitted on the robot to drive actuation and sensing.

With 'Control' I refer to "memory" or "logic" of the system that gives and/or takes input to/from the 'Sensing' element and activates the 'Power' element. For a tethered, pneumatic robot, this means the programmed AI stored in the circuit board. In the case of the 'Octobot' this means the "microfluidic logic" present in the system. For the 'Soft Transporter Robot' this means the both the ordering of the material structure during fabrication and the "strategy" behind the light emission.

How each of the elements interact with each other highly differs per system, as can be seen from these examples. Trying to understand and explore the broad variety of relations between the system elements could tell us more on the potential of aesthetic and intelligent qualities in soft robotic systems.

MORE ON AESTHETICS

Aesthetic theory deals with "…reflective experiences of what things are, why they have come into being, and which experiences they encourage." [23]. Relating aesthetics to technology, it serves as "…a shift from efficient use to meaningful presence." [24]. In Folkmann's (2023) book 'Design Aesthetics: Theoretical Basics and Studies in Implications, he proposes a 3-dimensional design aesthetics framework in which he relates sensual, conceptual and contextual aesthetics to design. In relation to soft robotic systems (or even intelligent systems in general), I believe the conceptual dimension best describes the relevance of considering aesthetic qualities. It describes when objects are considered as so-called "aesthetic frames", they allow for "…new ways of relating to the world and conditioning the experience of the world." [23]. Exploring the relations of soft robotic system elements might serve as an aesthetic frame to discover novel qualities and meaning. However, as I am focusing more on exploring these system relations rather than solely the human-robot interaction (or as described as subject-object relation in the Folkmann's book), it feels fitting to additionally employ the fourth wave of aesthetics as a means to reflect on the explorations and final suggested approach.

This fourth wave of aesthetics is called 'Aesthetics of Intelligence' (AoI) as presented by prof. dr. Stephan Wensveen during the course 'Creativity & Aesthetics of data & AI' and the workshop 'Beauty and ugliness of AI' at Eindhoven University of Technology [25] (one can find more information on the subject from the TU/e 'Aesthetics by Algorithm' Symposium which was partly presented by prof. dr. Wensveen [26]). AoI sees intelligence as a system where intelligent qualities can take on multiple forms. These intelligent qualities are related to designer concepts, which I like refer to here as aesthetic qualities, to provide a framework that support a critical and reflective assessment of these systems and the relations that occur within.

In this pictorial, a 'studio' methodology is employed that allows for looking at these fundamental elements of soft robotic systems in an explorative way without being restricted to a pre-determined context. The elements can be seen as the 'materials' within the system that can be designed to develop novel relations and qualities. In the next chapter, I will give a short introduction on the 'studio' methodology. Furthermore, an annotated documentation of the journey towards the final suggested approach is presented.

Aesthetics of *Intelligence*

Aesthetics of *Uncertainty*
Caring for *Instability*
Harmonizing *Agency*
Expressing *Intentionalities*
Anticipating *Emergence*

Figure 2: Aesthetics of Intelligence [25]

THE PROCESS

Studio Methodology

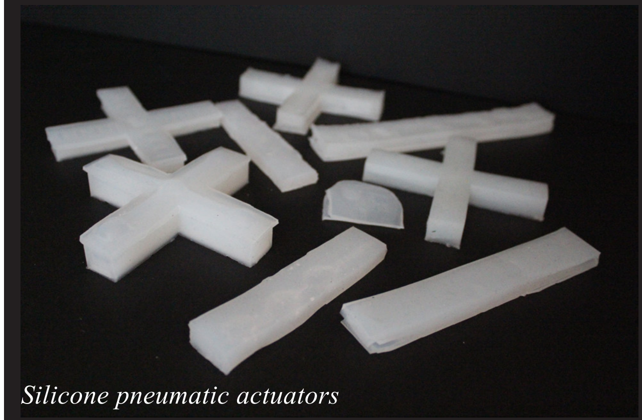
The 'studio' methodology allows for an auto-ethnographic and practice-based design research approach through documentation of the design research journey. Although there is no documentation on how to exactly conduct a 'studio' methodology, inspiration has been drawn from papers such as those of Da Rocha et al. [2022], Jarvis et al. [2012], Karana et al. [2015] and Restrepo-Villamizar et al. [2021]. Within this pictorial I embrace the explorative, open-ended creation of multiple samples and drawing from experience through a 1st-person perspective as done by the previously mentioned papers. The 'materials' used here, as described above, for soft robotics is very complex. As I am at the start of my soft robotics (explorative) journey, the main focus lies within exploration within the elements 'Actuation' and 'Power'. In the discussion I will reflect on the use of combining this with 'Sensing' and 'Control'. A sample library of different actuators and a variation of power inputs are explored and elaborated on below through the use of annotations. These annotations help to understand what potential scientific and aesthetic value might be present in the explorations or reflections [31].

Becoming Familiar

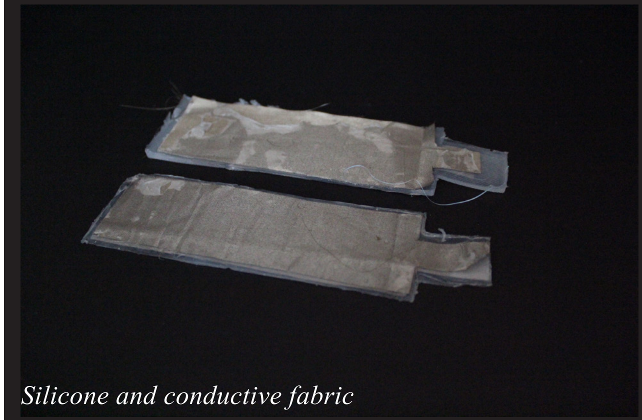
At the start of the journey, I needed to become familiar with the fabrication of soft robots. Compared to taking research papers as a starting point, Youtube tutorials and the website 'Soft Robotics Toolkit' [32] appeared to be less intimidating and accessible ways of obtaining information on maker-skills. The main fabrication is related to the actuator / body of the soft robot, therefore is seemed like a good place to start exploring. The initial explorations are mostly inspired by examples given on the website.

The main reflection on this part of the journey applies to the practical part of fabrication. It appeared to be quite a challenge to get good quality actuators. Even though the pneumatic actuators are the most documented soft robotic actuator, 'leakage' and therefore non-functional actuating was a common occurrence.

Pneumatic actuators

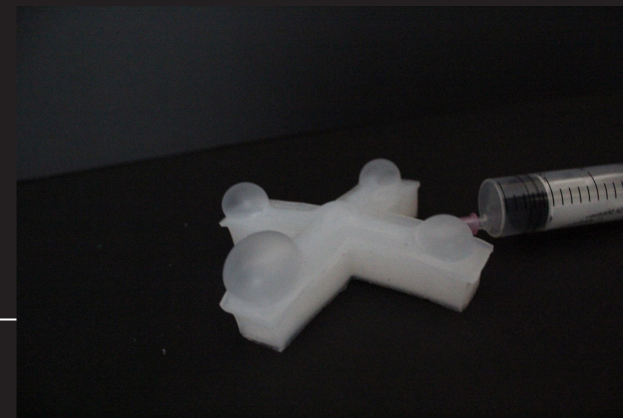


Silicone pneumatic actuators

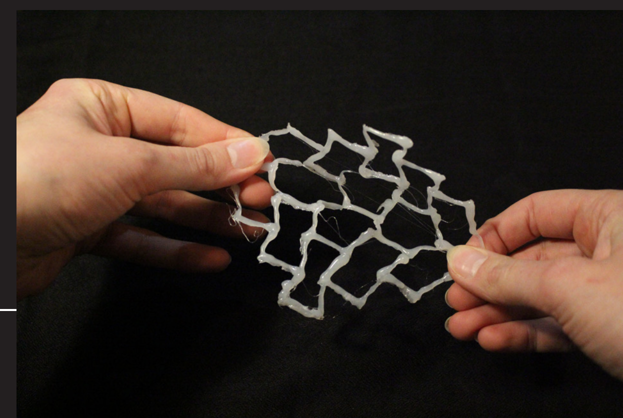


Silicone and conductive fabric

Inspired actuator form research on variety in flexibility due to vacuum versus inflated actuation [33]. Quite some leakage occured here, but allowed for experimentation with combining materials. In this case plastic foil and paper.



"Failed" gripper actuator, but showed some interesting instabilities in actuation of bubbles.



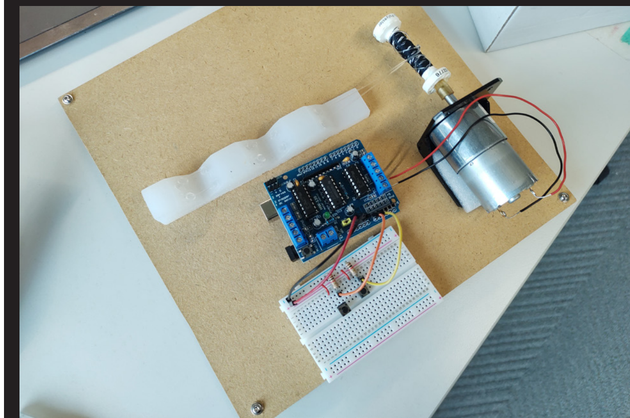
Experimentation with auxetic patterned material.

Inspired actuator from research on instabilities within actuation [2].

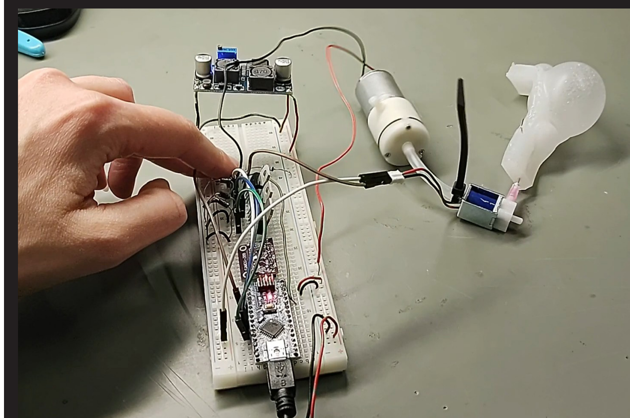
Combining Actuation and Power

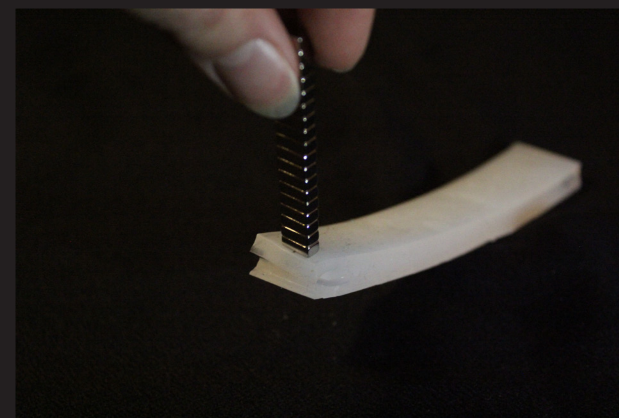
An almost logical next step into the journey of building a soft robotic system was to look at the 'Power' elements as to move away from manual actuation. The 'Soft Robotic Toolkit' website provided circuits for pneumatic and kinematic actuation and were replicated and explored with different actuators. Furthermore, an electromagnetic driven system was considered inspired by the solenoid valves used for the pneumatic circuit and related research [34]. However, due to time limitations, this was not further explored in following steps.

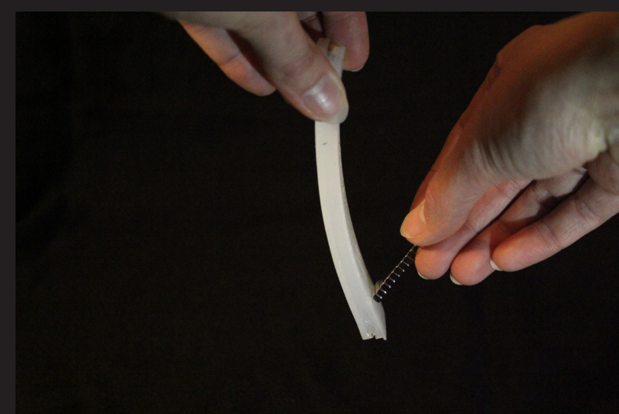
Reflecting on the process so far, indeed fabricating the softness in actuation is an accessible and arguably necessary route to take in the soft robot design journey. However, reflecting this to the discussions with experts, softness should be considered system wide. As long as it is meaningful and logical. Hereby opening the question if indeed a fully soft system is desired compared to hybrid systems when it comes to aesthetic and intelligent qualities to be present within the system. Opinions on this differ per expert. Of course, context plays a role in this, but what of finding these qualities outside of a context? Experts mention 'expressivity' and 'temporality' as meaningful aesthetic qualities of these soft actuators. Drawing from their own experiences, this can be used for data visualization purposes or for intuitive ways of understanding complex systems and processes. However, discussion arises relating to intelligent qualities in these systems. Adaptability and dynamic materials (materials that incorporate both actuation and sensing abilities) show a low-level of intelligence. But the general consensus is that for high(er)-level intelligent qualities to be present, some form of 'memory' in the (as I call) 'Control'element, should be employed. The use of 'Control' will be elaborated more in the Discussion chapter. However, having done this reflection, I wondered whether the exploration of other levels of intelligent qualities, even with the absence of or a very low level of 'Control', could be obtained. I will elaborate more on this below.

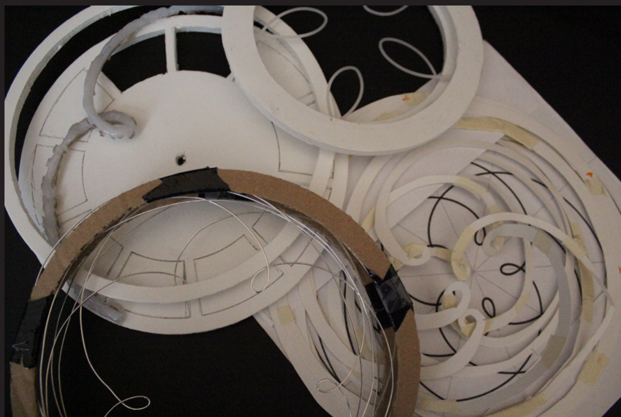


Exploring kinematic, pneumatic and electromagnetic driven circuits. Although all driven by electricity, the variety of rigid electronics require different considerations on attachement/incorporation to the soft actuator.



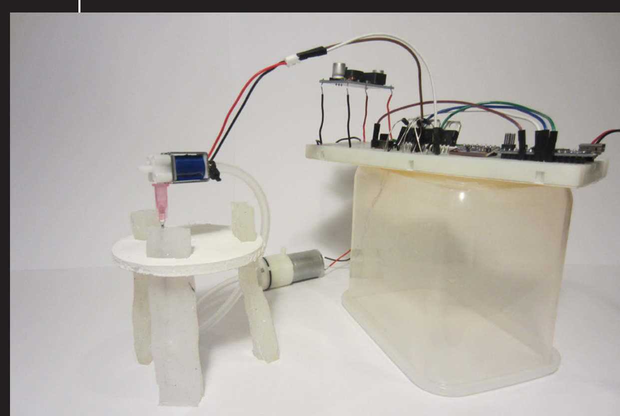






The ‘Rose of Venus’ design, combining both pneumatic and kinematic actuation. Fabrication of this seemed rather complex due to the overlapping orbs. Also the restriction of the degrees of freedom left little possibilties of exploration.

Rapid prototyping of soft robot. Testing if the material, which in this case is silicone, would hold the rigid top part potentially needing to contain some electronics.

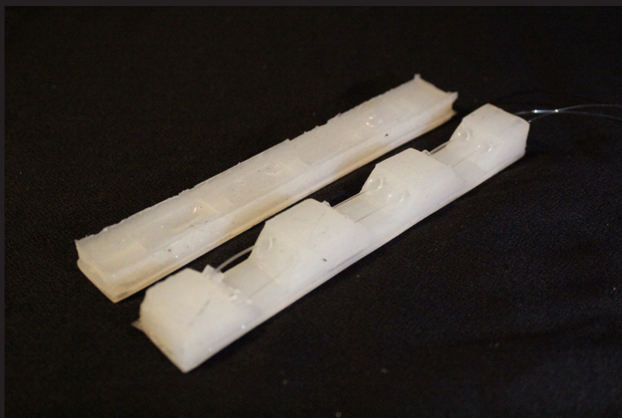


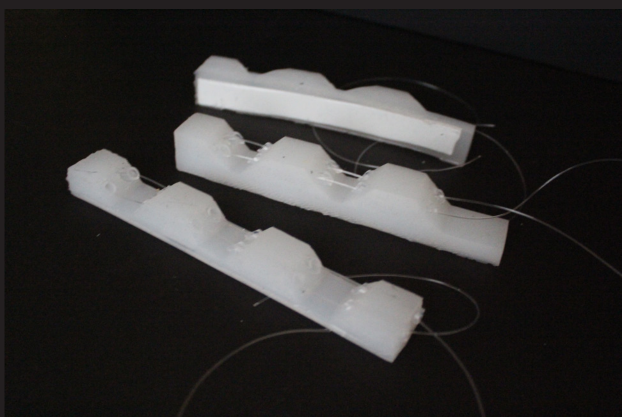
Decentralization and Modularity

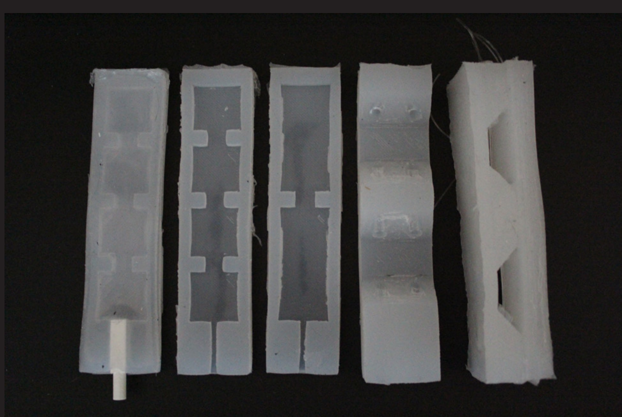
The next stage in the journey towards an approach for exploring aesthetic and intelligent qualities, I drew inspiration from decentralization of the soft robotic system such as done by Oliveri et al. [2021], system modularity [35]–[37] and one of my own past group projects. The idea came about to create a soft robotic system that combines the decentralization and modularity. The reason for this combination is due to the previously mentioned research showing potential in intentionalities in behavior, emergence and uncertainty to occur in these soft robotic systems. This can be related back to the AoI framework, where these are considered to be intelligent qualities. Combining this with an explorative and intuitive making approach, it might open up possibilities for aesthetic qualities to prevail as well.

The initial idea was to apply this to an old group project from the course ‘Creative Mechanical Engineering’ at Eindhoven University of Technology. The design consisted out of an inner structure that was a part of the ‘Rose of Venus’, whilst the outer rings would allow for turning the inner structure as one would with an iris of a camera lens. The idea was to make the inner structure out of tubes to allow for pneumatic actuation which could be interchanged. The outer structure would allow for kinematic actuation. Apart from this connection in actuation, the systems would be operate completely separately.

When ideating further on this idea, it seemed to restricted towards solely aesthetic qualities in interaction due to the limitations in degrees of freedom. A new design came about of a robot with 3-4 legs. The pneumatic and kinematic circuits are connected via the legs, allowing for both types of actuation. Modularity would now also be possible for both principles. Practical implications regarding leakages of the pneumatic actuators were resolved due to input from experts and information obtained from the ‘Soft Mod Bot’ Recitation given by Katrien van Riet [38]. This lead to the design of the final demonstrator and suggestion to an explorative approach.





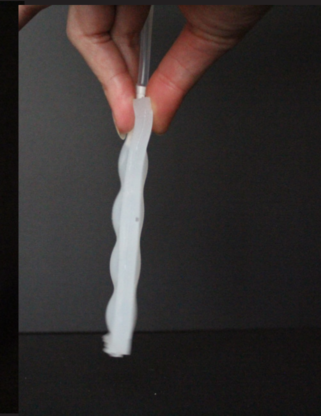


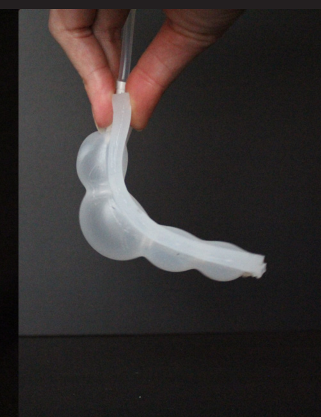
Iterations on the seperate actuating elements. The top images shows first proper fabrication of the soft robot legs. The dimensions were adjusted to be able to support a heavier top structure.

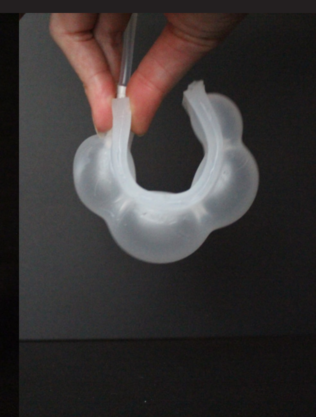
The bottom image shows the seperate actuation elements and an assembled prototype.

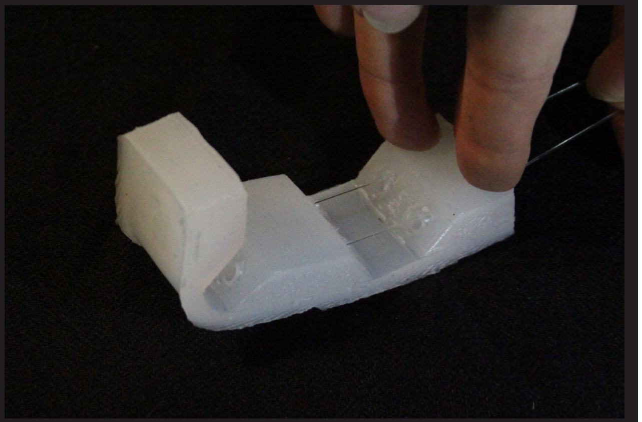
Design of rigid top structure. After some iterations, it was possible to only have stepper motors in the top structure to minimize the weight put on the legs. the lower part of the structure is 3D printed. The system is externally thetered, yet allows for a wide range of movement.

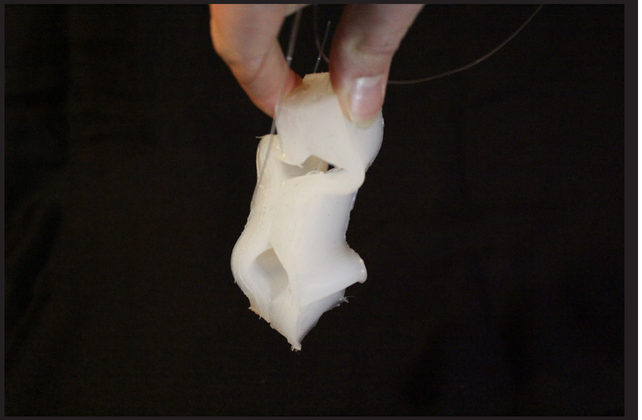
Testing pneumatic actuation abilities by exploring the chamber sizes.

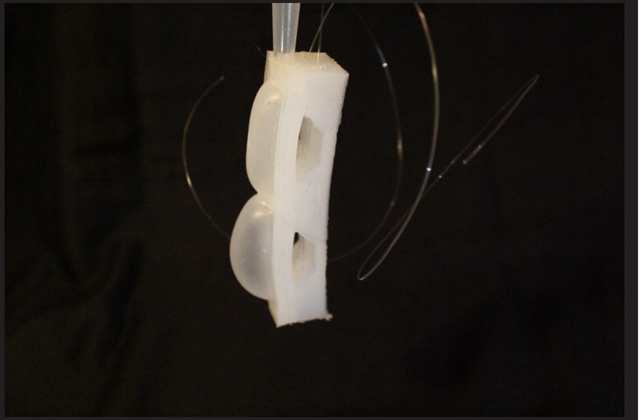












Testing actuation possibilities of the legs with both structures attached.

Final design and suggested approach

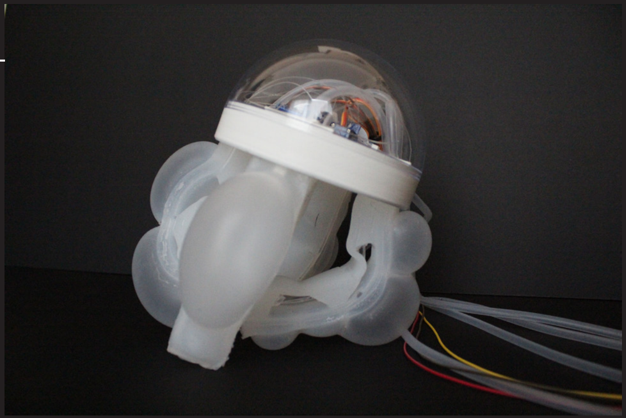
The final design suggests an approach towards exploring aesthetic and intelligent qualities within the soft robotic system by employing modularity and decentralization.

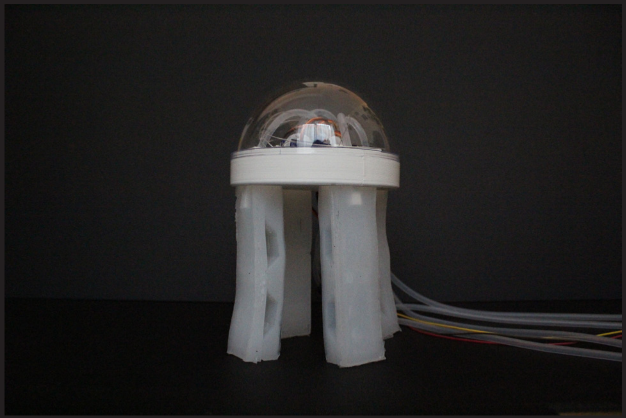
The modularity of the robotic legs allows for accessible explorations regarding actuation. Explorations in physicality regarding for example shape, materials, and in combination with sensing through the use of "smart" materials are possible by employing this modularity.

The decentralized system allows for exploration in the 'negotiation' of these systems. The decentralization together with the connectedness via actuation allows there to be a forced 'negotiation', 'conflict of interest' or potential 'collaboration' between the separate systems.

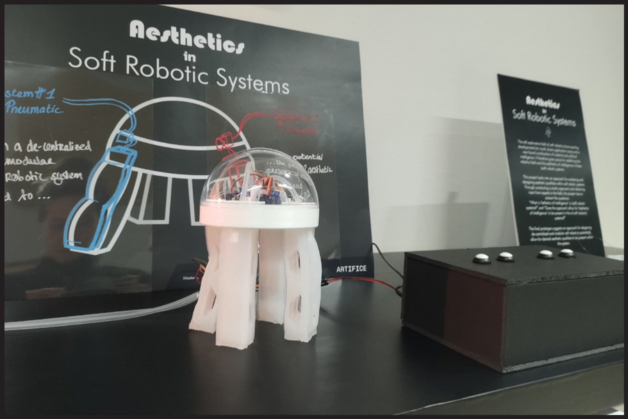
The combination of these two elements form my suggestion for an explorative approach towards designing soft robotic systems. It allows for intuitive making, embraces potential system complexities and allows for creating a diverse 'library' of explorations. This 'library' supports to understand how to design for the presence of aesthetic and intelligent qualities to prevail in these systems.

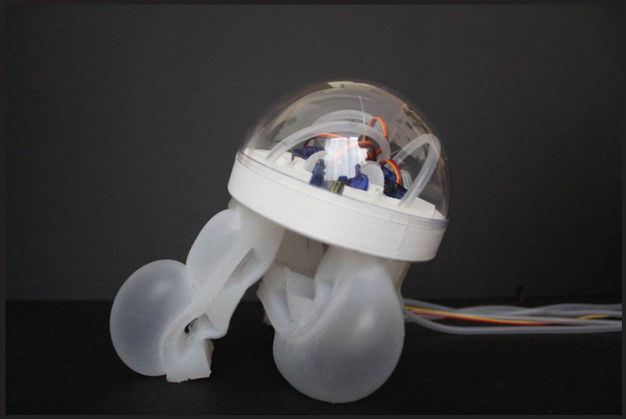
Top left images shows full pneumatic actuation. Middle and bottom left image show kinematic actuation. Rigth top to bottom images show unactuation to both pneumatic and kinematically actuated states.





The image below shows the demonstration during the Demoday of the Industrial Design department of Eindhoven University of Technology (December 15th 2023). The 'Sensing' and 'Control' elements are here inputs that come from passers. They can interact via the push buttons to activate the separate systems.





DISCUSSION

This pictorial documents a 'studio' methodology towards an explorative approach, supported with a demonstrator, for designing and analyzing aesthetic and intelligent qualities in soft robotic systems. Limitations in the approach prevail however, as the 'Sensing' and 'Control' elements are not or not yet fully explored. Further development of the approach should incorporate this, taking inspiration from previous research such as that of Audry et al. [2020] who take a design-oriented approach towards exploration of these system elements. Furthermore, from the discussions with experts, the approach would highly benefit from looking into the diversity of softness in soft systems and how these shape the relations of system elements.

As mentioned before, formulating a discipline-shared framework is out of the scope for this research project. However, future research should apply the approach to discover if indeed both the aesthetic and intelligent qualities occur. If the approach indeed shows the presence of these qualities as presented in the AoI framework, it would have the potential to elaborate on this framework by creating a framework tailored for the soft robotics field. One could speculate that potential new aesthetic categories could prevail that describe the aesthetics present within these systems and support the creation of a novel 'language' that supports interdisciplinary knowledge and innovation towards softness.

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