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SYMBIONT

SOFT-ROBOTIC OBJECTS FOR TACTILE COMMUNICATION

MASTER OF DESIGN - DIGITAL FUTURES

Symbiont: Soft-Robotic Objects for Tactile Communication

by
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Abstract

Sense is an intriguing facet through which we communicate with one another and our environment. However, due to our reliance on verbal communication, sensory mediums such as haptics remain relatively underexplored. "Symbionts" are a pair of soft robotic objects that facilitate non-verbal, tactile communication between individuals. These objects employ "bend and pressure sensors with actuators that pulse, vibrate and curl" to create a silent, tactile form of communication, allowing users to communicate through touch. Symbionts are designed to intrigue and engage by bridging physical distances and exploring the nuances of tactile sensation to create different layers of interpersonal communication. The design of these objects is informed by literature, contextual, and theoretical reviews in the areas of soft robotics, haptics, sensory design, tactile interaction, and Biomorphism. A mixed methods approach is used, drawing upon methodologies including Human-Computer Interaction (HCI), the Double Diamond Framework (DD), and Bio-Inspired Design. Additionally, the methods employed include an Annotated Portfolio, Reflective Practice, and Design by Metaphor. This leads to the creation of Symbionts based on material-driven design and tactile communication.

Acknowledgements

I would like to express my deepest gratitude to my incredible advisors, Kate Hartman and Nicholas Puckett. Your invaluable support and trust in me throughout this journey have been immense. The insightful discussions we had not only made me comfortable but also instilled in me the confidence to push further. Thank you for paying attention to all the tiniest details so elegantly!

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Over the past two years, working as a Research and Teaching Assistant has allowed me to collaborate with some truly amazing minds. A sincere thank you to Kate, Greg, Alexis Morris, and Fidelia Lam. Your wisdom has greatly enriched my professional and personal development.

In closing, and most preciously, I owe my deepest gratitude to my family—my loving parents, my amazing brothers, and my crazy diamond, Amir. You all have been my rock, supporting me through every moment. Amir, you stood by me through all the highs and lows, every challenge, day and night. Your presence in my life brings peace, beauty, and boundless support. With you, no mountain is too high to climb!

I am forever grateful for living this life with such a lovely family. Without your kindness and unwavering support shining through every tide I have faced, I doubt I could have come this far. You have made my life a truly wonderful journey!

Dedication

To the insatiable curiosity that fuels our journey of exploration...

Mona | April 2024

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Chapter 1. Introduction

1.1. Designer's Background

Throughout the course of my master's study, I engaged in a variety of projects spanning the fields of Interactive Media, Brain-Computer Interaction (BCI), Human-Robot Collaboration (HRC), Game Design etc. (Appendix A - 6) These areas, combined with my background in Industrial Design and Visual Arts, catalyzed a deep reflection on my interests for my thesis and the domains I have been keen to explore further. This period of introspection revealed a consistent fascination with navigating the interstices of various disciplines, and at that time and even today, I know that I have always been interested in exploring the flaws[1] (Fridman, 2023, 01:42:55) between different disciplines, a concept I have always been reminding myself as to what Design means for me.

1.2. Thesis Objective and Designer's Questions

According to Thomas and Hodges, the research objective is "specific statements indicating the key issues to be focused on in a research project," (Thomas & Hodges, 2010) and research question is "an alternative to research objectives, where the key issues to be focused on in a research project are stated in the form of questions." (Thomas & Hodges, 2010) The statement below is the core idea or primary objective which is driving my thesis forward and pointing out the purpose, the questions, and the process of this creation through which it will be carried out:

Thesis Objective: How can I design a nature-inspired soft robot object to facilitate nonverbal interpersonal communication?

As follows, my thesis questions are not only reframing my objective in more detail, but they are also acting as more granular questions that can lead to the achievement of my objective in line with my specific desires and helping me guide my thesis with answering the appropriate types of questions which are:

Designer's Question I (thesis approach – building the foundation)

What approaches, methods and methodologies could be used to achieve the transdisciplinary objective of my thesis?

Designer's Question II (which senses)

Which human senses might best be extended through a soft robot for nonverbal interpersonal communication?

Designer's Question III (how to design)

How might a soft robot could serve as a sensory object for nonverbal interpersonal communication?

[1] The following is Neri Oxman's response to a question regarding Manifestation during Lex Fridman's podcast: And if you look deep enough and specialized enough and if you allow yourself to look at the cracks, at the flaws, at the cracks between disciplines and between skills, you find really, really interesting diamonds in the rough.

1.3. Symbiont: Soft-Robot Objects for Tactile Communication

The term symbiont refers to an organism living in a symbiotic relationship; (*Definition of SYMBIONT*, 2024) thus, it represents a unique coexistence between two entities, which is often found in natural environments. In a metaphorical sense, the interaction between the human and the Symbiont can be described as a commensalist symbiotic relationship[2]. This term is used to illustrate how the Symbionts facilitate human-to-human communication through tactile means without benefiting or being impacted by the interaction themselves, akin to how one organism benefits in commensalism without affecting the other. This name, therefore, reflects sense-based interconnected communication, reflecting Symbionts' aim to create a new way of interacting and communicating through touch.

Developed as my thesis, Symbionts are a pair of soft robot objects that facilitate tactile communication between individuals within or without a shared space. In addition to their unique design (form and texture), Symbionts are sensory objects that allow us to communicate nonverbally by using tactile signals, without the intention of sharing any specific (and/or standard) meanings. As a result of Symbiont's soft robot nature, silicone was chosen as the skin material, which impacts the design process through material-driven design in many ways such as form/function ideating and the use of technologies (including multiple sensors and actuators). Diagram below illustrates the interaction loop between two Symbionts:

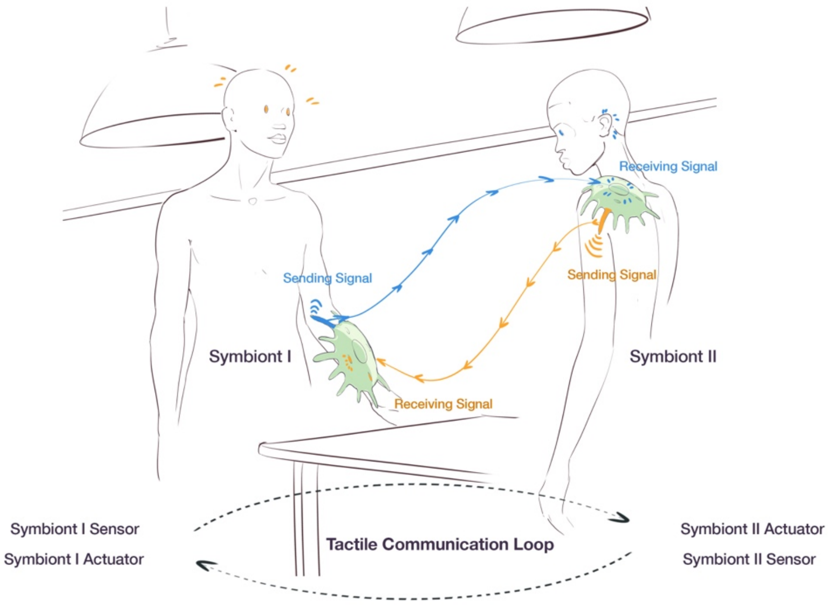

Figure 1 – Symbiont's Communication Loop - sketched by author

[2] According to Britannica, "Commensalism, in biology, a relationship between individuals of two species in which one species obtains food or other benefits from the other without either harming or benefiting the latter." (*Definition of Commensalism*, 2024)

Chapter 2. Approach, Methods and Methodologies

This thesis takes a mixed methods approach drawing together Human-Computer Interaction, Double Diamond and Biomorphic Design. The creation of my Symbionts is therefore an iterative process that requires combining these methodologies with the tools and methods they have developed. Throughout this chapter, and particularly in the approach section, I describe the many methodologies and methods I decided to combine to develop a mixed approach that empowers me to design symbionts.

2.1. Methodologies

2.1.1. Human-Computer Interaction

Human-Computer Interaction also known as HCI is ‘‘a discipline concerned with the design, evaluation and implementation of interactive computing systems for human use.’’(Hewett et al., 1992) The multifaceted nature of this field is widely recognized as interdisciplinary, due to the many traditional disciplines that contribute to its study. In the design process of any computer system, human-computer interaction (HCI) plays a pivotal (Kocsis, 2019), which not only contributes to the job itself, but also enables shared communication. (M. Jeon et al., 2019) In the context of Symbiont’s design, HCI becomes a crucial methodology, due to my intention to create interpersonal tactile communication through IoT technologies. In addition, the transdisciplinary nature of my design also contributes to this methodology.

Daniel Fall man in ‘Design-oriented human-computer interaction’, (Fallman, 2003) described the HCI development process used today as a research-oriented design process. (Section 2.3.) Accordingly, my thesis utilizes two Design Research methods, Research for Design (Rd.) and Research through Design (Rd.), which is due to the characteristics of my objective that required me to conduct research across multiple disciplines.

Furthermore, Zimmerman and Evenson, discussed the role of designers in HCI research, highlighting the importance of design thinking and the need for designers to make research contributions. (Zimmerman et al., 2007) According to them, designers are seen as integral participants who bring a unique perspective and approach to addressing under-constrained problems in the HCI research community. The authors also emphasized the concept of design research as a method to potentially transform the current state of the world into a preferred state which is also linked to my approach to using speculative design as a way of generating possible ideas and then leaning toward preferable futures in order to functionally make my design since preferable futures are not just about what is possible, but also about what is desired within the realm of those possibilities. (Section 2.3.)

2.1.2. Double Diamond Framework

In 2005, the British Design Council released the Double Diamond methodology which emphasizes divergent and convergent thinking throughout four phases: Discover, Define, Develop, and Deliver. "The two diamonds represent a process of exploring an issue more widely or deeply (divergent thinking) and then taking focused action (convergent thinking)." (Design Council UK, n.d.) The flexibility, iterative nature, and clarity of it enable design professionals to think creatively and solve problems effectively. Based on (Design Council UK, n.d.) and (Humble, 2024) below are the phases of the Double Diamond design process:

Discover: A key aspect of this phase is to gain a deeper understanding of the problem through expansive thinking by engaging with those affected by it.

Define: Through the Discover phase, insights gathered from the Discover phase help define the challenge in a more precise manner. This phase focuses on converging the information collected to identify the core problem to be addressed.

Develop: During this phase, different solutions to a clearly defined problem are developed in the solution space. In order to iterate and refine solutions, users and stakeholders participate in the design process.

Deliver: The final phase includes delivering the solution, testing it in the real world, gathering feedback, evaluating the effectiveness of the solution, and making necessary adjustments.

As part of the Double Diamond model, designers are encouraged to explore widely before narrowing down specific solutions, highlighting the importance of divergent and convergent thinking. The approach is versatile enough to be adaptable to a variety of design projects, making it a fundamental tool to innovate and solve problems in design.

2.1.3. Bio-Inspired Design

Definitions and Purpose

As a result of millions of years of evolution (Sciences (US), 1999)[3], nature has evolved certain forms to facilitate interaction and communication, which can be used to inspire the design of tactile interfaces. So, I decide to use Bio-Inspired Design methodology to guide the design and aesthetics of the soft robot, drawing inspiration from the forms and functions of nature. Soft robots are made of compliant materials with mechanical similarities to soft biological tissue, and their design is often anchored in biomimicry and bioinspiration, (Rus & Tolley, 2015) in which respectively the former mimics natural mechanisms for solving problems and tasks, (Bar-Cohen, 2006) while the latter seeks to abstract general principles from nature for technological purposes. (Kovač, 2014)

Thus, I decide to design the soft robot object in a way that mimics natural forms and textures named as biomorphic design, (More details about Biomorphic Design, section 3.2.4) and aims to appeal to human innate responses to natural stimuli, since “the presence of biomorphic forms and natural elements within a visual environment can serve to enrich human emotional experience.” (Joye & Van Locke, 2007) For instance, as illustrated by projects such as the Harvard Octobot, “Soft robotics could revolutionize how humans interact with machines.” (Burrows, 2016) (Appendix C - 2) Thus, I found this natural familiarity an essential element in shaping a natural (or, as I have sometimes referred to in my journey, *weird, ambiguous, and curious*) user engagement with my object. (Section 3.1.2.)

[3] Along path leads from the origins of primitive "life," which existed at least 3.5 billion years ago, to the profusion and diversity of life that exists today. This path is best understood as a product of evolution. (Sciences (US), 1999)

According to (Sanchez et al., 2005), Bioinspiration is the development of novel materials, devices, and structures inspired by solutions found in biological evolution and refinement which has occurred over millions of years. This approach aims to "mimic or imitate characteristics of biological systems in non-living systems, rather than replicating or analysing the biological entity itself, in molecular detail." (Whitesides, 2015) In other words, the goal is to improve models and simulations of the biological system to better understand its structural features and then to translate that understanding into research and design.

As (Ng et al., 2021) mentioned, "nature provides an abundance of inspiration to draw upon," which in the context of Bioinspiration or Bio-Inspired Design, it could be a framework integrates solutions that nature has optimized for millions of years into design. In this approach, biological knowledge can be applied to architecture, engineering, and design to produce innovative products and processes. Additionally, this approach strengthens the bond between humans and nature, reminding us of its intricate and complex solutions.

Bio-Inspired Design Characteristics

In my research (Ng et al., 2021), (Whitesides, 2015), (Kaneko, 2006), (Labonte & Federle, 2015) and (Naylor & Higham, 2019), I found these characteristics to be particularly beneficial to my design process, which also affected the methods and approaches I developed for my thesis:

1. **Functionality:** Structures in nature are evolved for survival, without wasting energy on non-essential functions.
2. **Simplicity and Integration:** Complex mechanisms are elegantly integrated into seemingly simple functions in biological systems.
3. **Soft Matter:** In biology, most systems are 'soft', which means they are flexible and easily deformed, including bone at some level. New, soft, science can be stimulated by understanding how organisms use soft matter, such as muscle, tendons, connective tissue, membranes, and nerves.
4. **Drawing from Diversity:** Different species offer different or convergent solutions to life's challenges in the natural world. A broader range of biological strategies can be tapped into by designers by focusing on specific features rather than individual species.

Using the Bio-Inspired methodology and its characteristics in my design process allows me to make a meaningful contribution to the field as well as establish a mixed methods approach that directly addresses my research questions and objectives. As an example, by prioritizing the use of soft materials as part of the integration of soft robotics into my designs, I can create a synergy between the characteristics of bio-inspired design and the objectives of my project, which gives me a variety of options for creating and designing creatively and aligning with my objectives.

2.2. Methods

2.2.1. Discover

It was my intention at the beginning of my thesis journey to conduct a meandering exploration driven by curiosity and an openness to new ideas rather than a linear path. During this stage, my goal was to cast a broad net in search of a topic that not only intrigued me but also held the potential for innovative HCI research, and it is also something I have been exploring for the last few years as well as during my master's studies, which have always been rooted in sensory apparatus and nature. According to Buxton, "concern has been voiced on the failure of the design processes currently applied within the field of Human-Computer Interaction (HCI) to support breakthrough innovation."(Buxton, 2007) In particular, HCI design processes are held to lead mainly to incremental innovation and small changes." (Norman & Verganti, 2014)

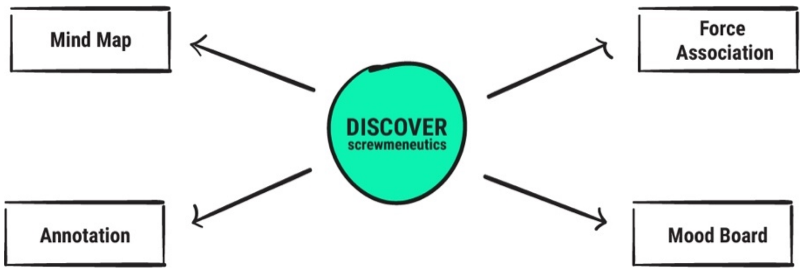

Figure 2 - Symbiont's 'Discover' phase (Screwmeneutics) - Methods used in thesis, created by author

I used the Model of Knowledge "Using Prototypes to Develop Research Questions" as a starting point for ideating about my thesis. It aims to bring together the diversity of practices across disciplines to create a common ground for interdisciplinary projects, as well as enable individuals of different skills to collectively find inspirations to begin. Using this approach was very beneficial to me since my intention was to find "the right kinds of questions."(Roberts-Smith et al., 2021) I used that as a way of divergent thinking integrated in the first diamond of symbiont's approach diagram where I can discover different ideas, inspirations and possible futures. The purpose of the first stage was modified to align with the priorities and objectives of my thesis. *"*Discover refers to exploring problems, gathering insights and understanding user needs, and forming ideas (divergent thinking)." (Wang et al., 2023)

My *prospective look* [4] at my process through Discover phase was not a linear progression, but rather an exploratory journey which led me to utilize a variety of methods and tools to explore and ideate to define my research objectives and questions such as Mood Boards which served as a visual brainstorming tool to capture inspirations and give them a tangible form, allowing me to visualize, synthesize, and connect diverse concepts that ultimately formed the thesis topic, as a practise of "visual thinking process which is the phenomenon of thinking through visual processing." (Deza & Deza, 2009) Within the same area and purpose, Annotated Portfolios was used not as static collections but as dynamic records that tracked my thinking process and provided a narrative of my findings and experiences during this stage.

As a brief overview, I will discuss Annotated Portfolios here, however, I will elaborate on this method in depth in the later phases, where I will address the design and prototyping aspects. "An

[4] According to Merriam-Webster: Prospective adjective is relating to or effective in the future. https://www.merriam-webster.com/dictionary/prospective

annotated portfolio, then, is a means for explicating design thinking that retains an intimate indexical connection with artifacts themselves while addressing broader concerns in the research community."(Gaver & Bowers, 2012)

In drawing upon Screwmeneutics (Roberts-Smith et al., 2021), the inspirations I gathered from various sources were not merely passive influences; they were active engagements that provided me with the opportunity to merge ideas until they took on a life of their own.

I used "Force Association" method to generate new ideas as a way of "lateral thinking technique."[5] (Interaction Design Foundation, 2016) "When using forced association for idea generation, we combine disparate concepts and try to come up with ideas based around them." (Tomitsch et al., 2020, p. 66) "The method can also be carried out by using an existing min map about topic and randomly selecting keywords from it." (Kokotovich, 2004) This involves identifying objects and themes related to the problem or brief that the designer intends to address. Keywords that might be appropriate for solving the problem or brief include user goals, possible activities, target user types, or possible technologies. The next step is to identify two or more keywords at random and generate an idea for a solution that contains all the characteristics described by the keywords.

> "Sometimes this might feel difficult or illogical. which is why we call these associations 'forced". By forcing difficult or illogical associations, it is possible to generate ideas that are different from those you would produce using brainstorming or other idea generation techniques."
> (Tomitsch et al., 2020, p. 66)

I will define questions and the methods I will use to answer them in next phase. The questions and objectives I develop will be based on the inspirations, research, and ideation I did in 'Discover' phase.

2.2.2. Define

During this stage, I integrate both methodical and practical elements to create, converge, and advance my ideas and solutions to create my object. Based on the results of the previous stage, I begin this phase by articulating my research questions. The Literature and Theoretical Review involves engaging in the academic discourse to ensure that my intention to design a biomorphic object for haptic communication is based on academic research. As a result of this foundational work, I can refine my knowledge and develop my design against a backdrop that guides the rest of the phase.

The Annotated Portfolio serves as a crucial tool during this stage or as Gaver puts it "the fruits of design," [6] (Gaver & Bowers, 2012, p. 43) serving as a dynamic record of my iterative progress. It is a living document where I capture the process of my ideas and ensure that my designed object "can be seen as a kind of position statement from its designers, not only about what

[5] Designers often don't realize what their limitations are when considering problems – hence why lateral thinking is invaluable in (e.g.) the design thinking process. Rather than be trapped by logic and assumptions, you learn to stand back and use your imagination to see the big picture. (Interaction Design Foundation, 2016)

[6] "In particular, we suggest that annotated portfolios provide a way to present the fruits of design that simultaneously respect the particularity and multidimensionality of design work while meeting many of the demands of generalizable theory." (Gaver & Bowers, 2012, p. 43)

is important to consider in a given design situation, but also about how to best respond to those considerations." (Gaver & Bowers, 2012, p. 43)

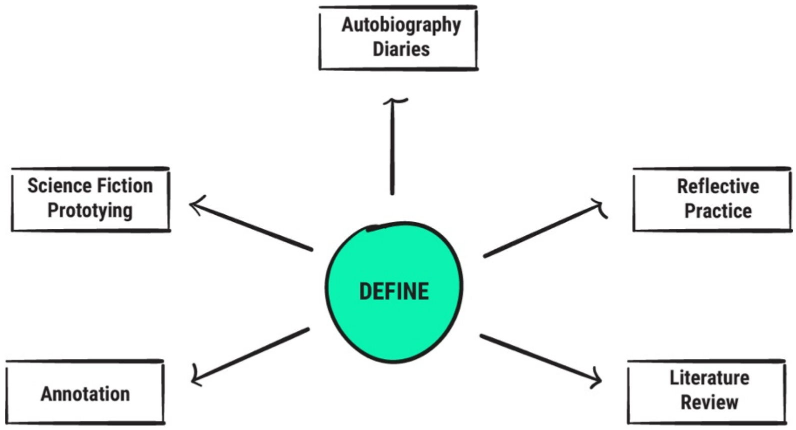

Figure 3 - Symbiont's 'Define' phase - Methods used in thesis, created by author

The idea of autobiographical design, according to (Neustaedter & Sengers, 2012b), is that people design a system for themselves, then use that experience as a guide to learn about the design space, and based on that experience, evaluate and iterate their design.

The concept of autobiographical design, as described earlier, involves individuals crafting systems for their personal use, which then inform their understanding of the design landscape, guiding the evaluation and iterative refinement of their creations. This method includes creating narrative and visual diaries that "capture the small experiences in everyday life that occupy most of our work time and majority of our conscious attention." (Reis & Wheeler, 1991) As (Reise, 1994) explained, this method allows the examination of events and experiences that arise naturally and spontaneously.

Using Generative Artificial Intelligence (AI) as a tool, I visualize other possibilities of my design using the Science Fiction Prototyping method. At the time of writing my thesis, I was unable to find any academic resources that utilized this method, but based on my previous experiences, I found this method to be a useful tool for exploring unconventional scenarios when thinking out of the box.

Another method is Autobiography which is using to recount the personal narrative of my intellectual journey, which facilitates a continuous dialogue between my evolving understanding in an attempt to answer my questions and the unfolding design process. As such, autobiographical diaries [7]complement research methods that aim to obtain a comprehensive view of users' needs rather than serve as a standalone method for gathering data. (Tomitsch et al., 2020) In many situations, autobiographical design also described as "the process of self-documentation" can assist with “a deeper understanding of one's own practices – design thinking”, (Tomitsch et al., 2020) also can give detailed, nuanced, and experiential understanding of a design space. (Neustaedter & Sengers, 2012a)

For example, Gaver referred the use of autobiographical design for, “where [researchers’] motivation for doing it doesn’t depend on the fact that they might get research points for it. In other

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[7] "an autobiographical design" stands for "design research drawing on extensive, genuine usage[7] by those creating or building the system."(Neustaedter & Sengers, 2012, p. 514)

words, where there's a... genuine... interest in the content of the thing." (Neustaedter & Sengers, 2012a)

> "Autobiographical design in HCI research: designing and learning through use-it-yourself", the term "genuine need" refers to a true and authentic requirement for a system or design, as opposed to simulated or artificial requirements that do not align with the actual requirements of the designers/researchers themselves." (Neustaedter & Sengers, 2012a)

The initial stage and thesis approach helped me determine my genuine needs and I framed them into my research questions, so using this method has been extremely helpful in terms of my iterative thesis as well as relevant to my approach and practice in general. "Documenting this process of self-experience can, in fact, be an opportunity for further reflection," (Tomitsch et al., 2020) This is why I decided to incorporate Reflective Practise into my autobiographical diary, which serves both as a self-evaluation tool and makes me aware of my knowledge and practice.

"Researchers describe and study the design process from one of two primary perspectives: design as rational problem solving, and design as a reflective practice. These perspectives are exemplified by Simon and Schön respectively." (Dorst & Dijkhuis, 1995) And according to Finlay, reflection "aims to make you more aware of your own professional knowledge and action by 'challenging assumptions of everyday practice and critically evaluating practitioners' own responses to practice situations."(Finlay, 2008)

Throughout my thesis project, I have been planning my approach and process as iterative phases, during which I need to continuously engage with my research questions and practice to design my object. As an example of this engagement and reflecting practices, during the summer of 2023, I took an independent study in Soft Robotics (under my thesis supervisor advised) to deepen my engagement with my thesis topic. It is through the Define stage that I distill my research objectives into clear objectives by combining these academic, creative, and reflective elements. As a result of the methods and tools provided during the Develop phase, my design concepts will be applied and realized on a practical basis.

2.2.3. Develop

This phase acts as a second opportunity for me to diverge my thinking process again, but this time more towards the result as I know by the time I write this section which technologies I intend to utilize and what theories I intend to explore. It is part of my design process to identify and explore the types of components, including sensors, actuators, materials, fabrication methods, and prototyping approaches, that I will choose to incorporate further.

This part forms a foundation for my thesis, since I must assess the making aspects and ensure their viability within my design considerations. By examining various components, I am able to select and integrate the most appropriate components (technologies and fabrication techniques) that match the functional requirements of the object I aim to design. As mentioned in the previous section, Autobiography, Annotated Portfolio and Reflective Practice are some of the methods that will remain throughout the entire design process. However, other methods and tools need to be defined in greater detail based on the purpose of my thesis.

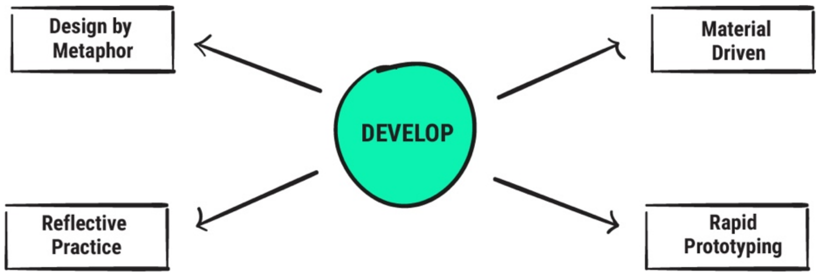

Figure 4 - Symbiont's 'Develop' phase - Methods used in thesis, created by author

I am using rapid prototyping [8]in this phase according to the nature of my thinking and design process. I need to test and experiment with different components to create the desired result. "Rapid Prototyping mainly covers techniques of additive manufacturing,"(Kruth, 1991) and for that I am using digital fabrication to produce precise and scalable prototypes. It is a critical component of my iterative design process. The practice enables me to quickly put ideas into tangible forms, which makes them easier to evaluate and iterate upon. It is also a method I am using both for fabrication and circuitry design where I need to create iterative circuits using different or the same components and conducting many tests on programming my circuit to achieve my desired results.

As part of this rapid prototyping method, different combinations of components can also be prototyped individually and in conjunction with one another in a circuit. Regarding my choice of material, which is silicone, they have all different reactions and collaborations. Additionally, each of them has different characteristics and capabilities that allow for the creation of different interactions between them and myself as first-person designer, which is why I am utilizing my reflective practice, in order to analyze, document, reflect, and plan for future prototypes and iterations. Within the context of my thesis, this keyword came from HCI researchers, "a first-person perspective means that designers are personally involved since they are part of and actors in the system object of study." (Desjardins et al., 2021)

"'Material' has been a central point of research and practice agendas for decades in product design," (Ashby et al., 2012) and that is the reason I choose to imply Material Driven Design (MDD), which is "a new type of design process is emerging, in which the material is present from the outset and can be seen as the driver of the process." (Bak-Andersen, 2018) This method enables me to ensure that the design of an object is harmonious with the material I choose, so that the material not only fulfills its purpose, but also contributes to its aesthetic and interaction quality. "Designing with a material entails a thorough understanding of the material in order to discover its unique qualities and constraints in comparison to other materials."(Karana et al., 2015)

As defined in "Material Driven Design (MDD): A Method to Design for Material Experiences," which coined the MDD method, it consists of three scenarios[9]: a relatively well-known material, a relatively unknown material, and a material proposal, of which I am a part of the first category as I intend to work with Skin Safe Silicone. At this stage, and through multiple prototypes and reflection on my practice, I intend to determine what silicone offers me in terms of aesthetics, its

[8] (Chua et al., 2003) described prototype "as an intermediate representation format (model) of a design, that is used to validate specific features or aspects of the final product."

[9] Learning from these projects, reviewing advantages and disadvantages of steps in the design process, and drawing upon theoretical foundations introduced in this paper, we developed the Material Driven Design (MDD) Method to facilitate design processes in which materials are the main driver. We envisage three scenarios where designers can apply the MDD Method. (Karana et al., 2015)

reactions with other scenarios, and its effects on my sensory experience. "This requires qualifying the material not only for what it is, but also for what it does, what it expresses to us, what it elicits from us, and what it makes us do."(Karana, 2022)

In the last two phases of my thesis, which I am focusing on making, a method called 'Design by Metaphor' is one of the most influential methods. As a conceptual tool, this method links two unrelated things symbolically, suggesting similarity or analogy between them, thereby shaping, and informing design projects. By connecting design elements to familiar experiences or concepts, metaphors make products, interfaces, or spaces more intuitive and relatable to users. (Section 2.3.3.)

2.2.4. Deliver

A major purpose of this phase is to design the aesthetics, fabricate and build the polished circuit after many prototypes from the previous phase. For the purpose of ideating and designing my biomorphic object's aesthetics, I decided to use two creative methods, the first of which was the creation of a mood board, which I used initially during my Discover phase, and the second was idea generating through Design by Metaphor and Morphological Analysis.

Biomorphic Design is part of my process with the intention of creating an object that has harmony with humans to enhance the experience and interaction between soft robot and human. (Sections 3.1.2. and 3.2.4.) Therefore, based on these practices, experiences, and diaries, I realize that I must create a new Mood Board with fresh reflection and ideas, but still grounded in the same roots.

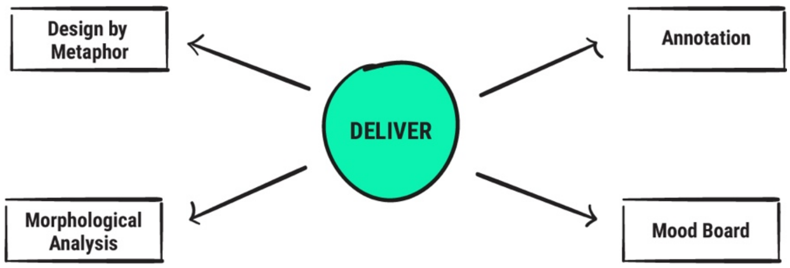

Figure 5 - Symbiont's 'Deliver' phase - Methods used in thesis, created by author

Another method in this phase is Morphological Analysis which "is a systematic approach for generating varieties of design."(Evbuomwan, 1995) A morphology is a solution that can be generated using this approach and can be large in number, and some of them may be absurd, familiar, or novel. According to (Ostertagová et al., 2012), "it is the methodological tool for the induction of associative procedure for searching the ideas for a new concept of solution." To deduce new combinations from the number of solutions, we need to break down the problems into several levels and list all known and possible solutions for each level. According to (Evan Green, n.d.), methodology of morphological analysis is based on the following steps. (Section 4.4.5.)

1. **Define the Problem:** Clearly articulate the issue that the design seeks to address.
2. **Identify Parameters:** Enumerate all potential parameters involved in the solution, including functions and sub-functions.
3. **Develop a Morphological Box:** Construct a morphological box or chart, using the identified parameters as columns.

4. **Populate the Matrix:** For each parameter, list possible components that could fulfill its function. These components are identified through analysis of existing solutions.
5. **Implement Evaluation Strategies:** Apply strategies to evaluate and reduce the number of feasible solutions.
6. **Generate Solution Concepts:** Formulate conceptual solutions by selecting at least one component from each column of the matrix to create a coherent whole.
7. **Analyze and Select Solutions:** Assess each conceptual solution against the set criteria or design requirements to determine their viability. Narrow down to a select few (recommend at least three) that show the most promise.
8. **Detail Selected Solutions:** Further develop the chosen conceptual solutions. This may include detailed design, prototyping, and testing, which form the latter stages of the design process.

The four phases of my design thinking and design process were described here, and in the next section, I will outline my thesis approach, which is a culmination and synthesis of all the methods, methodologies and approaches I am using to describe the lens through which I am examining my process.

2.3. Designer's Approach

To develop my thesis, I included Screwmeneutics as the first phase also called 'Discover'. This approach helped me identify the most promising ideas and subsequently, the best research questions. As I am transitioning to defining my research questions, the ability to think divergently was imperative. I sought an approach that not only rested on design thinking principles but also fostered creativity and pushing the conventional thinking [10] by reflects on potential futures. Due to its ability to engage with complex future scenarios, I found the speculative design approach valuable, not only for discovering potential ideas for my thesis, but also for defining my research objective during idea generation.

As part of the Symbiont's approach diagram I designed, I depicted divergent and speculative ways of thinking and ideating as a means of generating ideas for possible futures[11]. Since I wanted to make the symbiont with today's technologies and tools, I leaned towards the probable ideas[12] as soon as I began thinking about functional making.

As I progress through my thesis, my research process evolves from Research for Design[13] to Research through Design. I engaged in literature research, different studies and activities, reflective practice over my previous experiences through projects, and research for the appropriate components, materials, and methods of making during Research for Design, since "the research

[10] According to Merriam Webster, Conventional Wisdom means: "the generally accepted belief, opinion, judgment, or prediction about a particular matter." (*Definition of CONVENTIONAL WISDOM*, 2024)

[11] "Possible – these are those futures that we think 'might' happen, based on some future knowledge we do not yet possess, but which we might possess someday (e.g., warp drive). " (Voros, 2017)

[12] "Probable – those we think are 'likely to' happen, usually based on (in many cases, quantitative) current trends." (Voros, 2017)

[13] "Notably, research for design is the category of research that most practitioners and many academics associate with the term "Design Research," perhaps because it has the most potential to contribute to successful design outcomes."(Frankel & Racine, 2010, p. 5)

activity related to design is exploratory, and is both a way of inquiring and a way of producing new knowledge." (Frankel & Racine, 2010, p. 3)

These elements, along with other methods and tools used, contributed significantly to my understanding of the subject matter of my questions, along with how I could address them through design. My object was directly impacted by the way they functioned, what they looked like, what materials they were made of, their limitations and behavior, and how they would interact with the human body.

According to an article titled “The Complex Field of Research” (Frankel & Racine, 2010), the focus of this approach "is on the research objective of creating design knowledge, not the project solution. This may also be called project-grounded research and/or research-oriented design." (Frankel & Racine, 2010) “Design is both a making discipline and an integrated frame of reflection and inquiry. This means, that design inquiry seeks explanations as well as immediate results.”(Friedman, 2000) In this context, also as depicted in the diagram, these foundations were transformed into practice, in which design itself becomes a method of inquiry.[14] Due to this transition, the boundaries between the defining through Research for Design and developing through Research Through Design phases overlap and are influenced by each other.

Appendix B - 1 contains a table adapted from ‘Design as a Mode of Inquiry in Design Pedagogy and Design Thinking’ that shows how each mode of inquiry can be implemented productively. Different modes are characterized by different possibilities and consequences. To better position myself in my track, I used this table before and after each phase.

Following is a diagram illustrating my thesis approach based on the research questions and objectives I have set forth. The reason for drawing these elements together primarily is about the transdisciplinary nature of my thesis which sometimes causes me to face gaps and limitations within a standard way, so I decided to create my approach as it was also one of my research questions because of its crucial role in my thesis. As detailed in this section and illustrated below, each has played a significant role in shaping my approach and each need to develop through many iterations, evolving thoughts, and reflections, as Wynn and Eckert said, "iteration has positive effects, such as enabling progressive generation of knowledge, enabling concurrency, and integrating necessary changes."(Wynn & Eckert, 2017)

[14] “a method of inquiry”, inspired by the title of this article "Design as a Mode of Inquiry in Design Pedagogy and Design Thinking." (Ejsing-Duun & Skovbjerg, 2019)

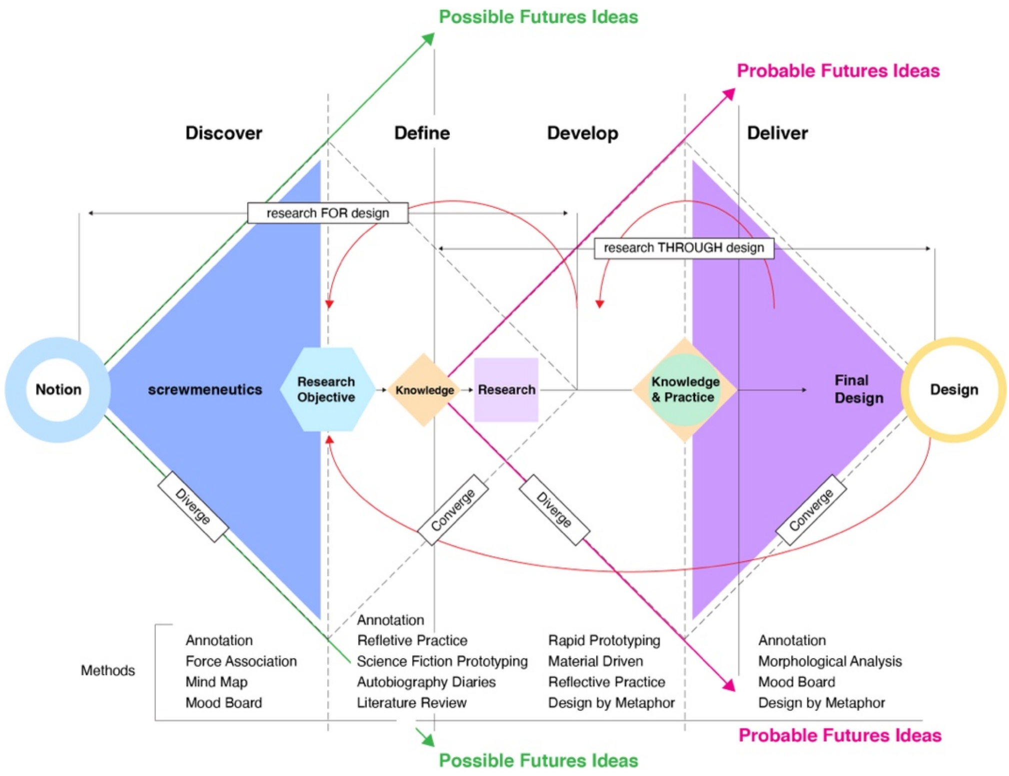

Figure 6 - Symbiont's Approach in Design and Research, diagram designed and created by author

2.3.1. Screwmeneutics as an Approach

I used "Using Prototypes to Develop Research Questions"[15] (Roberts-Smith et al., 2021) as an transdisciplinary approach that fueled my curiosity before and during the thesis research process. This approach shifts the traditional research focus from immediately deciding on methods and data collection to a more fluid and explorative process that prioritizes the development of relevant and impactful research questions through iterative learning.

Because, the inventive nature of the research means that any given step can branch to several possible next steps, there is a similar pattern of iterative divergence and convergence with these kind of prototypes that can be seen in many other kinds of prototyping. (Roberts-Smith et al., 2021, p. 252)

This approach begins with the identification of an area of interest, followed by the definition of research objectives and the formulation of research questions. When I began my thesis, I was clear that I had already explored and prototyped to get "interested rather than how to get to the question."(Roberts-Smith et al., 2021, p. 245) According to Robert-Smith et al, (2021) These are the stages involved in this model:

[15] The book "looks at the use of prototyping in design research across a range of disciplines." (Jennifer Roberts-Smith, n.d.)

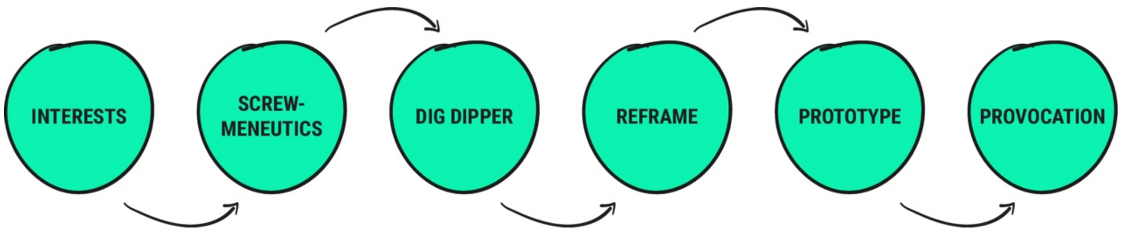

Figure 7 - "Using Prototypes to Develop Research Questions" - graphic by author, adapted from R. Smith et al. (2021)

1. **What is interested to you?**

Begins with a topic that is intriguing. This could be anything that captures the curiosity and prompts further investigation.

2. **Screwmeneutics (Ramsay, 2014)**[16]

Engaging in an initial exploration of the topic through an environmental scan and literature review. This step involves a casual and broad search related to the topic to identify potential challenges and areas for further inquiry.

3. **Dig Deeper**

Conducting a more focused review of the literature to understand what has already been done in the area and identify gaps that the research could fill.

4. **Reframe the Topic**

Based on the information gathered, refining, and expanding the topic into a more specific area of study that implies broader issues or questions.

2. **Start Prototyping**

Create prototypes to explore potential solutions or further refine the research questions. This can be an iterative process where the prototype's reactions and feedback lead to more precise questions or adjustments in the research direction.

3. **Provocation**

These prototypes, or "provotypes," [17] are designed to challenge conventional thinking, opening new perspectives on the research topic and gather data. It serves as a tool for both product development and the formulation of research questions and supports an iterative process of exploration and refinement that can lead to more targeted and meaningful research inquiries.

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[16] Screwmeneutics definition according to Robert-Smith et al, (2021): The next step was to start an environmental scan and literature review, or, as the digital humanities philosopher Steve Ramsay puts it, the hermeneutics of screwing around with the topic. (Ramsay, 2014)

[17] "A provocative prototype (or "provotype") is one intended to elicit an emotional response from the user, as a way of suggesting an alternative perspective on a topic of interest." (Roberts-Smith et al., 2021, p. 251)

2.3.2. Speculative Design as an Approach

While speculative design is derived from Critical Design[18] practice, Anti-design, and Italian Radical Design [19] could be considered as its ancestors. Rather than creating commercially viable products, this approach is intended to ignite debate and reflection on potential futures and the role of design in them, to explore future possibilities. According to Dune and Raby, who coined this term, speculative design is “an activity where conjecture is as good as knowledge, where futuristic and alternative scenarios convey ideas, and where the goal is to emphasize the implications of ‘mindless’ decisions for mankind.” (Dunne & Raby, 2013) Speculative design is distinguished by its focus on proposing alternatives to current design practices and models. It serves as a catalyst[20] for imagining different futures, encouraging designers to engage in a form of speculative thinking that combines emerging technologies with alternative plans or ideologies.

I incorporated speculative design into my thesis because it extends beyond problem-solving by addressing issues and not just designing for consumption or as Paolo Antonello said, designing for possible futures[21]. As a result, my design work is not a means of solving problems, but rather a method of inquiry—a way of imagining the future of interpersonal communication through tactile experiences and asking, "what if" (Dunne & Raby, 2013),[22] which is relevant to my research question regarding the creation of soft robotic objects that support tactile communication through metaphor and Sensory Design.

According to (Swanson, 2021) it can be overwhelming to explore the possibilities of the future as there are many ways in which it might unfold, and the 'Future Cone' can be helpful in guiding that exploration. Josep Voros who created the latest iteration of the future cone also said, "futurists have often spoken and continue to speak of *three* main classes of futures: possible, probable, and preferable. It is convenient to depict this expanded taxonomy of alternative futures as a ‘cone’ diagram."(Voros, 2017) Using this framework, potential futures can be identified and discussed as they are arranged into a cone-shaped diagram that shows how possibilities expand as we move from the present to the future.

2.3.3. Design by Metaphor as an Approach

According to (Darke, 1979), designers narrow down the search space, where a design solution can be found, by using basic ideas, organizing principles, and heuristics during design

[18] "Critical Design uses speculative design proposals to challenge narrow assumptions, preconceptions and givens about the role products play in everyday life. It is more of an attitude than anything else, a position rather than a method."(Dunne & Raby, n.d.)

[19] “Anti-design and Italian radical design could be considered as ancestors of speculative design." (Streitz & Konomi, 2022, p. 357)

[20] “Design speculations can act as a catalyst for collectively redefining our relationship to reality.” (Dunne & Raby, 2013)

[21] "Speculative design, the discipline that imagines possible futures through design at all scales, is very important." (Antonelli, n.d.)

[22] The design proposals in What If... probe our beliefs and values, challenge our assumptions, and encourage us to imagine how things could be different — that how things are, is only one possibility, and probably not the best one. (Dunne & Raby, 2013).

problem solving. In addition to providing them with 'primary generators' or starting points for tackling ill-defined designs, they enhance their understanding of the problem as well.

In essence, the use of metaphors facilitates structuring design problems, which are by definition non-routine[23] in nature. Thus, when solving non-routine design problems, it is difficult to predict what a solution will look like. According to (Casakin, 2007) not only can metaphors assist in problem reflection but also help to break away from the limitations imposed by initial problem constraints (Snodgrass & Coyne, 1992), explore unfamiliar design alternatives, and establish novel associations with the design problem. (Coyne, 1995) As a result, metaphors are thought to stimulate design creativity in themselves.

Erickson described metaphor as a "valuable design method in interactive interfaces, enabling us to use familiar knowledge to comprehend new and abstract concepts. For instance, in computer interfaces, the metaphor of a folder is used to help users grasp the concept of data storage." (Erickson, 1995) According to him, the purpose of an interface metaphor is to provide users with a useful model of the system, which I found this concept quite related to my exploration, because I need to make familiarity between my soft robot object and its user, thus I decided to use these steps to understand and explore my design objective better and to imply metaphors into my design process.

For doing this the first step is to understand how the system really works. Second, because no metaphor can capture every aspect of a system's functionality, the designer must determine what parts are likely to challenge users. Finally, once the designer has identified the type of model required, metaphors that support that model must be generated. For more detail about the steps involved in this process and how I plan to use them please refer to Appendix B - 2. The following table outlines my approach to creating metaphors, using three main activities and incorporating some recommendations described in (Cila, 2013):

Steps	Definition	Recommendations
Finding an Idea	Utilizing a metaphor to emphasize the obscured quality of the target.	• Highlight a hidden quality of the target. • Be mindful of the metaphor you intend to use.
Finding an Apt Source	Select a source whose primary meaning is in line with the message of the design.	• Choose a source that conveys the salient property you intend to convey. • Sources should be optimally related to targets. • Evaluate the source's applicability. • Find a source that is both novel and understandable. • Select a source that contributes to the product's functionality.
Applying the Metaphor	Subtly incorporating metaphors into the design, ensuring that they complement but do not overshadow the product.	• Reference the source in a subtle but recognizable way. • Match the inherent properties of the target. • Blend the source properties with the target properties. • Make sure to map a source's salient properties. • Transferring everything from one source is not necessary. • All modalities should be considered. • Metaphors can be applied in different ways.

Table 1 - Steps to create a good metaphor, created by author, based on 'The use of metaphor in product design' (Cila, 2013)

[23] […] "the first produces designs that are some minor variation of existing designs, called *routine designing*, and the second produces designs that are noticeably different to existing designs, called *non-routine designing."* (Gero, 2000)

Chapter 3. Thesis Framework

I explore the intricate frameworks that support my thesis journey in this chapter. A literature review is used explore communication with a particular emphasis on non-verbal communication and interpersonal communication. In the following sections, I focus on tactile senses, how soft robotics can be integrated into tangible experiences, actuation mechanisms, and how they contribute to the development of tactile communication devices.

As I progress, the thesis unfolds the sensory design paradigm and examines how this field can be applied to other elements in the thesis through studying literature review and theoretical review. Further exploration of biomorphic design principles is undertaken, whose applications include but are not limited to creating nature-inspired, functional, resonant, and engaging interfaces. I conclude this chapter with a map of the contexts within my thesis that are being studied and examined as essential pillars.

3.1. Literature Review

3.1.1. Non-Verbal Communication Through Tactile Medium

Communication: Definitions and Types

“The term Communication generally designates the transmission of a message of concepts, feelings or needs from a speaker to a receiver by means of verbal or no verbal language.” (Russo, 2010) Communication also as an activity, is “a complex multidimensional process of establishing and developing contacts and connections between people, generated by the needs of joint activities and including the exchange of information, perception, understanding of another person and the development of a single interaction strategy.” The three types of communication, according to (Prabavathi & Nagasubramani, 2018), include verbal, non-verbal, and written. Verbal communication refers to the use of spoken words, whereas nonverbal communication (NVC) refers to body language, facial expressions, and gestures, and written communication refers to the use of written words, such as emails, letters, and reports.

Nonverbal Interpersonal Communication

Nonverbal communication (NVC), "is conveying of emotions, feelings, and messages through actions and expressions rather than words." (Hans & Hans, 2015) Such communication is, “sometimes mistakenly referred to as body language (kinesics), but nonverbal communication encompasses much more, such as use of touch (haptic) and distance (proxemics).” (Hans & Hans, 2015) Haptics, which is the focus of my thesis, "is the term derived from the Greek word, *haptesthai*, which means sense of touch," (Yadav & Krishnaiah, 2013) and “touch is the earliest sense to develop, providing us with means of contact with the external world."(Gottlieb, 1971)

According to (Abed et al., 2023), "Interpersonal refers to relationships and communication, and to the processes therein that shape social interactions," and "Interpersonal communication refers to the transmission of information between at least two individuals." Based on these definitions, the object I am designing is for this form of interpersonal communication, in which individuals can communicate through the exchange of haptic cues.

Touch as Communication

Touch, which is also one of the first means of communication between a newborn and its parents, is "to a large extent non-verbal and one of the primary purposes of non-verbal behavior is to communicate emotional states," (Van Erp & Toet, 2015) and "as touch implies direct physical interaction and co-location, it inherently has the potential to elicit feelings of social presence." (Van Erp & Toet, 2015) Touch plays an essential role in social communication due to the fact that the human skin has specific receptors for processing affective touch[24], or, as Morrison titled her article, "the skin as a social organ."(Morrison et al., 2010) "We use touch to share our feelings with others, and to enhance the meaning of other forms of verbal and nonverbal communication." (Gallace & Spence, 2010) For instance, whether we touch someone when we make eye contact indicates a different meaning.

Hertenstein et al. (Hertenstein, Keltner, et al., 2006; Hertenstein et al., 2009) demonstrated that touch can effectively convey distinct emotions such as disgust, anger, and fear. Furthermore, "results showed that touching typically conveyed more composure, immediacy, receptivity/trust, affection, similarity/depth/equality, dominance, and informality than its absence."(Burgoon, 1991) Also it has been shown that, "touch is the preferred nonverbal communication channel for conveying intimate emotions like love and sympathy." (Debrot et al., 2013)

"While many efforts have been applied to establish haptic experience design in Human-Computer Interaction (HCI), they are mostly restricted to market or academic research with expert hapticians." (Schneider et al., 2017) However, based on my research, most of the currently available technologies are lacking in the tactile aspects of interpersonal communication, whereas according to (Erk et al., 2015), it "plays a crucial role in establishing a sense of togetherness." Considering that, the sense of *touch* plays a vital role in haptics-based communication, as it allows for the transmission of tactile information. As Field points out "Touch is ten times stronger than verbal or emotional contact, and it affects damned near everything we do. No other sense can arouse you like touch... We forget that touch is not only basic to our species, but the key to it." (Field, 2014, p. 57)

3.1.2. Soft Robotics: Tangible Senses

Definition and Background

"In recent years, soft robotics has become one of the fastest-growing topics within robotics research." (Bao et al., 2018) It 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) "where the behavior can be determined by

[24] "It is worth highlighting that affective haptics refers to the computational aspects of mediating affective touch. Affective touch studies how participants emotionally react to haptic stimuli and explores the quality of experience measuring methods." (M. A. Eid & Al Osman, 2016) – For more information refer to Theoretical Review Chapter.

the robot materials, morphology, control and the interactions with the environment." (Stella & Hughes, 2023)

"Soft robots can be defined as systems that are capable of autonomous behavior and primarily composed of materials with elastic moduli in the range of that of soft biological materials." (Rus & Tolley, 2015) "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 & Cianchetti, 2014)

Jessica Riskin has suggested that some of these devices, referred to as "eighteenth century wetware" (Riskin, 2003), might be considered as precursors to artificial life (Alif) research. "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." (Jørgensen, 2019) Riskin said, "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, p. 112)

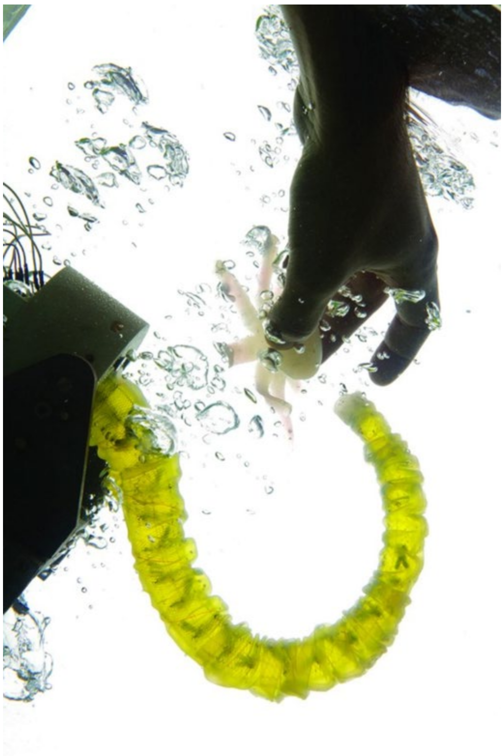

Figure 8 - 'The Lighthouse', prototype of an artificial bio-inspired arm - photographed by Massimo Brega

Control and Actuation

A soft robot's inherent flexibility is captured by (Coyle et al., 2018), who note, "Soft robots have distributed deformations over their soft components allowing for theoretically infinite degrees of freedom." Soft robots are uniquely adaptable to a wide range of tasks and environments, but the field is still confronted with practical challenges, as (Yasa et al., 2023) note: "Actuation technology is one of the core challenges for soft robotic research," a statement that underscores the pivotal role of actuation in advancing soft robotics capabilities. The theoretical versatility of soft robots is linked to their practical application through these mechanisms. As a result, (Hegde et al., 2023) provide a taxonomy of these crucial components, stating that there are six mechanisms of actuation, including:

- *Fluid*
- *Magnetic*
- *Die-electric elastomer-based*
- *Contact-Driven*
- *Tendon-driven deformation*
- *Shape memory materials-base*

I am considering using three of the six mechanisms mentioned above for my prototypes to determine which mechanism would be most appropriate and achievable for my object, which are fluid (inflatable chamber using air flow), magnetic, and shape memory alloy (SMA).

Fluid Actuation

Through fluidic actuation, soft robots can be controlled by controlling the fluidic pressure and frequency of the actuation medium (air or liquid). (Hegde et al., 2023)

Magnetic Actuation

It is possible to control or preprogramme the magnetic domain orientation of the soft robot either by printing or microfabrication locally. As soon as the magnetized soft robot is placed in a magnetic field, it can be moved and actuated by magnetic forces and torques, and its movement mode can also be controlled by controlling the external field. (Hegde et al., 2023)

Shape Memory Alloy Actuation

“Shape memory alloys are a unique class of alloys that have ability to ‘remember’ their shape and are able to return to that shape even after being bent.” (Sekhar & Uwizeye, 2012) Robotics can be made smaller, lighter, and more complex with SMAs due to their large force-weight ratio, long life cycles, small volume, sensing capabilities, and noise-free operation. (Cianchetti, 2013)

Material and Fabrication

A key difference between soft robots and rigid robots is the use of materials that are highly stretchable, flexible. "The most common materials used in soft robotics are silicone, elastomers, and hydrogels." (Bo et al., 2024) Elastomer robots have a viscoelastic material that can stretch and compress, silicone robots have a flexible silicone material, and hydrogel robots are composed of a water-based gel that can be easily molded and shaped. My thesis led me to select silicone as my material of choice, since it allows me to do as many rapid prototypes as necessary to achieve my desired form and function.

According to Marchese et al, "the vast majority of soft elastomer robots rely on the processes of soft lithography and/or shape deposition manufacturing,” (Marchese et al., 2015) and for soft fluidic elastomer robots, this fabrication process generally involves three steps:

1. Using pourable silicone rubber, two elastomer layers are molded through a casting process. When casting, the outer layer contains a negative image of the channel structure. The outer layer contains a model of the channel structure. During the elastomer pouring process, fiber, paper, or plastic film are incorporated into the constraint layer, thereby creating the inextensibility required for actuation.

2. A thin layer of uncured elastomer is applied to the joining faces of the two layers after they are cured and removed from their molds.
3. After the two layers have been joined, they are cured together.

Related Works: Human-Soft Robot Interaction Through Haptics

"Wearable robotic systems interface with the skin, which is a major component of the human haptic system, associated with the sense of touch." (Zhu et al., 2022) "Touch technology can mediate social touch in situations when people cannot be physically close," (Weda et al., 2022) and "arm is one of the most comfortable and socially acceptable areas for receiving touch." (Suvilehto et al., 2015) This study (Weda et al., 2022) delves into the sensory and emotional dimensions of haptic feedback and underscores the critical role of parameters such as peak force, rate of force change, and surface area in crafting haptic experiences that resonate on a sensory and emotional level.

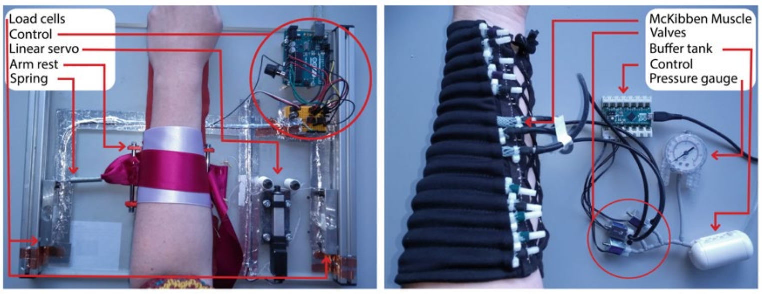

Figure 9 - Left image: the motorized ribbon, right image: McKibben sleeve by (Weda et al., 2022)

In another work, titled "Touch Me Gently" (Muthukumarana et al., 2020), they explored the potential of soft robotics in simulating gentle and naturalistic touch interactions but using different methods. "In HCI, tactile sensation has been extensively explored, such as to provide feedback to compliment auditory and visual channels, as well as for sensory substitution." (Muthukumarana et al., 2020) They explored the use of shape-memory alloy (SMA) plasters to recreate tactile sensations through shear forces on the skin, since the research aimed to enrich virtual and augmented reality experiences by mimicking natural touch interactions.

Figure 10 - User is experiencing the touch of another's hand in 'Touch Me Gently' by (Muthukumarana et al., 2020)

"Psychology findings show humans can communicate distinct emotions solely through touch."(Zhou et al., 2022) Various nonverbal cues are used to communicate between people. “Transferring these cues into the design of robots and other artificial agents that interact with people may foster more natural, inviting, and accessible experiences.” (Urakami & Seaborn, 2023) They discuss the exploration of emotional robotic touch through the involvement of designers in the design process. In their work, they examine how designers explore emotional robotic touch in a designedly manner.

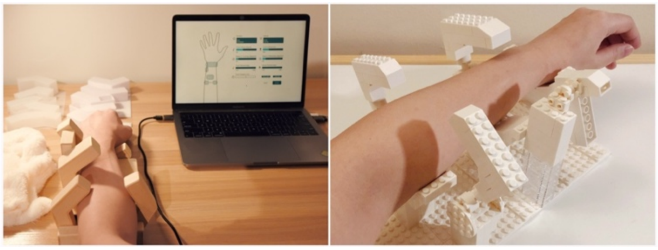

Figure 11 - 'EmotiTactor' by (Zhou et al., 2022) - left image: Elicitation study setup, right image: LEGO prototype

In the context of soft robotics close connection with human body, ‘ambienBeat,’ (Choi & Ishii, 2020) serves as an example of emotional communication through biofeedback. Choi and Ishii explore the use of tactile biofeedback combined with auditory and visual stimuli for regulating heart rate and task engagement levels. It discussed the importance of interoceptive interaction and ambient media in promoting wellness. The research delves into the physiological synchronization achieved through touch and the impact of mindfulness on stress reduction. “Inducing a change in the timing of a repetitive, regular behavior like breathing could potentially have various health benefits, like helping people to calm down in a stressful task or facilitating deeper breathing in meditative exercises, such as yoga.”

Figure 12 - 'ambienBeat' can be worn in various circumstances by (Choi & Ishii, 2020)

While touch plays a crucial role in how we feel and interact with our environment as well as our emotional well-being, most haptic technologies emphasize its functional aspects, such as improving task completion time, distinguishing between shapes and textures, and grasping virtual objects, but (Asadi et al., 2022) in their work, highlighted the significant role of haptics in enhancing emotional and sensory experiences beyond traditional functional aspects, setting the stage for further research and development in contactless haptic technologies for affective touch applications. In ‘Inducing Changes in Breathing Patterns Using Soft Robots,’ they focused on the effectiveness of soft robots in affecting humans' emotional states and behavior through designing a pneumatic-haptic feedback device for breathing guidance and to illustrate how haptic technology can induce emotional states, suggesting a new dimension in non-verbal emotional communication.

Figure 13 - Left image: 'Breathing robot', right image: 'Experimental setting with participant' by (Asadi et al., 2022)

In another research titled ‘it brings the good vibe,’ (Christiansen et al., 2023) a paradigm of Soft Biomorphism was designed in soft robotics by researchers. They explored enhancing organic qualities without resembling specific organisms in soft robot designs. To understand soft biomorphic applications and human-robot interactions, two empirical studies were conducted on various soft biomorphic prototypes.

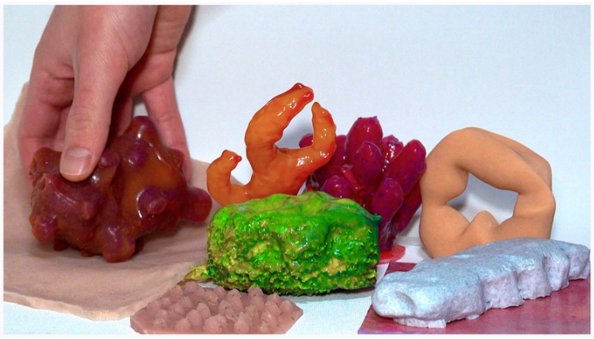

Figure 14 - Soft Biomorphism prototypes by (Christiansen et al., 2023)

Using biomorphic soft robots, study 1 examined human-robot interactions elicited by personal robot applications and revealed that participants were drawn to soft robots' aesthetics intended to improve physical and emotional health.

Figure 15 - Study 1, design evaluation workshop by (Christiansen et al., 2023)

In study 2, participants evaluated prototypes with enhanced biomorphic qualities as more appealing and appropriate for well-being support through physical interaction, but the results were mixed.

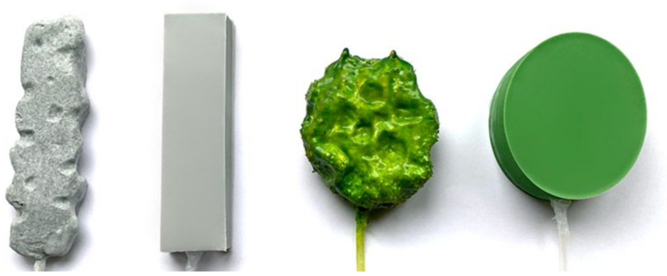

Figure 16 - Study 2, four soft robot prototypes by (Christiansen et al., 2023)

Researchers found that soft robot designs negotiate between organic and geometric aesthetics, with biomorphic designs perceived to be more appealing and organic, while geometric designs were viewed as angular and clinical in design. According to the study, soft robot designs should balance biomorphic and geometric traits and align formal attributes to ensure that they are appropriate for specific applications.

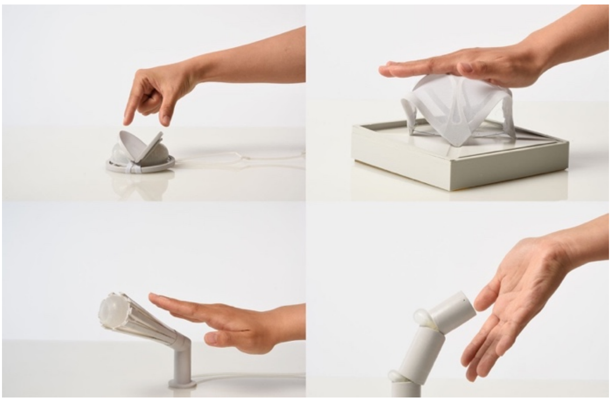

Figure 17 - Interaction between user and 'Info-Motion' by (Yao, 2024)

Taking a different perspective across this field, 'Info-Motion,' (Yao, 2024) introduces a method called the Metaphor Ring, which proposes the use of metaphor to define the types of information that can be conveyed through shape-changing interfaces (SCI) inspired by plant motion. Using soft robotics technology, Yao et al. outlined five possible use cases for applying plant motion to shape-changing interfaces to improve the user experience and convey information in a more intuitive manner. With three types of dynamic feedback provided by each physical object, computers and home appliances can be used to display status and data.

Inspirational Works: Aesthetic Use of Silicone

Materials affect emotions. According to some studies, they "perform a role that is in a sense invisible. No longer do we use objects to perform essential functions in our lives: their role are based more on an emotional level." (Lefteri, 2021) For instance, "different textures may have the potential to elicit either positive or negative emotions in us through their physical and sensorial properties." (Karana & Kesteren, 2013) This fundamental understanding of human sensory perception underpins the significance of material choice in design, particularly in the context of soft robotics. The tactile interaction with materials not only mediates our immediate experience but also has the power to shape our emotional responses and connections with objects. (Sections 3.2.2., 3.2.3. and 3.2.4.)

In my thesis, I find the material and aesthetic properties of the object to be influential, as they affect both the interaction between a human and the soft robot object, as well as the quality of communication between the two people. This consideration of materiality extends beyond mere functionality; it involves a deliberate engagement with the aesthetic qualities that influence human experience. "With a robot's physical appearance drastically influencing our perceptions of trust, a greater awareness of how design elements and their aesthetic effect may trigger what affective processes are imperative." (Pinney et al., 2022)

> "The aesthetic engagement with the materials and components of soft robotics can function as a foundation for technical invention, given that a central premise of soft robotics has been to focus less on the software side of robotics and more on its material design and ways of embedding programmed intelligent behavior into designed structures." (Jørgensen, 2023)

In the context of my thesis, by exploring the potential of materials to evoke emotional responses along with using biomorphic design style as a way of bringing nature's forms and patterns into my design, I aim to design a soft robot object that connects with users on a sensory and emotional level. The relationship between materials and our senses is complex and multifaceted. Different aesthetics can evoke unique sensory experiences, triggering specific emotional responses and influencing our perception. "Experimenting with new and familiar materials, customizing products, and embracing the differing needs and experiences of users, contemporary designers are realizing newfound sensations and capitalizing on our extraordinary powers of perception to enrich and improve daily life." (Lupton & Lipps, 2018) This exploration of material aesthetics represents a broader trend in design towards creating products that engage all the senses, offering users a richer, more immersive experience.

In relation to the material affect in product and therefore the relationship and interaction created, there is a term called Aesthetic Interaction, but it is not "about conveying meaning and direction through uniform models; it is about triggering imagination, it is thought-provoking and encourages people to think differently about interactive systems, what they do and how they might be used differently to serve differentiated goal,"(Petersen et al., 2004) which for my object, such an approach not only enhances functionality but also elevates the robot from a mere tool to a partner capable of enriching human life through sensory engagement. "The aesthetic interaction can promote a relationship between the user and the computer (*i.e.,* robot) that encapsulates a person's full relationship—sensory, emotional, and intellectual." (Pinney et al., 2022) "In doing so, it can entice an 'engaged interaction' which can change the user's perceptions and interpretations." (Carroll, 2010) Following the impact of aesthetics in this context, 'Hydrophytes' has been one of the most inspiring projects for me because of its delicate and intricate design and biomorphic approach.

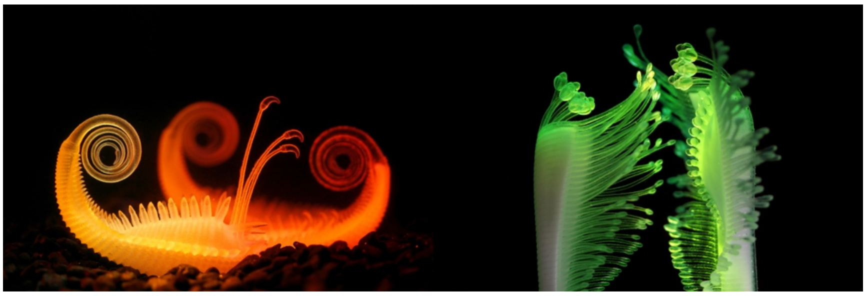

Figure 18 - 'Feather Nurse' by (Hone, 2018)

Nicole Hone, in her thesis, titled 'Tangible Animation' (Hone, 2018) explores the intersection between multi-material 3D/4D printing technologies and organic performance design to produce dynamic and interactive objects. A key motivation for Hone's research is the ability of multi-material 3D printing to incorporate both rigid and flexible materials, enabling the creation of objects that can change shape or appearance over time, known as Tangible Animation. According to Hone's thesis, these technologies can be applied to create aesthetically appealing and functionally diverse objects that mimic organic movements, contributing to the fields of design innovation and interactive art through these applications. Her "diminutive creatures are each imagined serving 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." (Jørgensen, 2019)

3.1.3. Sensory Design

Definition and Position

> "One might well wonder—is there a category under which *everything* falls? Offering an informative account of such a category is no easy task. For nothing would distinguish things that fall under it from those that don't—there being, after all, none of the latter. Nonetheless there are candidates for such a fully general office, including *thing*, *being, entity*, *item*, *existent*, and—especially—*object*." (Rettler & Bailey, 2017)

As I design the soft robot object for tactile communication, I have found that the concept of the "object" is crucial to understanding how these devices can serve human needs. According to Strawson's definition of objects, my soft robots are not just tools or devices, but objects in the fullest sense—tangible, perceptible entities that facilitate another kind of sensory exchange.

It is Strawson's interpretation of an object [25] that its essence lies in its perceptibility, a distinction that resonates deeply with my work. According to Strawson (Strawson, 2000, p. 235), objects are entities that can be perceived directly through our senses: smell, sight, hearing,

[25] "There is, for example, the suggestion that general, unlike particular things cannot be perceived by means of the senses… It is not with the eyes that one is said to see hope. But one can quite literally smell blood or bacon, watch cricket, hear music or thunder." (Strawson, 2000, p. 235)

and touch. This perceptual accessibility distinguishes them from abstract properties or concepts, "so properties (like hope) are the things that cannot be perceived, and objects (like bacon) are the things can be perceived." (Rettler & Bailey, 2017)

Therefore, my soft robots are objects in this sense: they are designed to be touched, held, and interacted with, allowing people to communicate through tactile sensations. Understanding why I refer to these creations as objects requires an understanding of how perceptible they are. Their tactile sensations are not abstract concepts, but real, perceivable experiences shared by individuals.

Additionally, Strawson's discussion of the perception of objects, which focused on colour and shape, reveals the complexity of perception - how we interpret physical characteristics and understand them. In the context of my thesis, this perspective underscores the importance of design and the sensory experiences my objects provide. Therefore, how these soft robot objects are perceived and the way they mediate communication between users is influenced by their shape, texture, and movement. In the same way that bacon is perceived as rectangular through the act of seeing it, the tactile feedback and form of my design inform the user's perception, resulting in rich, non-verbal communication. I aim to design other possibilities for communication by embedding communication within the tangible, perceptible realm of my objects. Through the tangible, the felt, and the intimately sensed, I envision a future where the space between us is softened, not by words alone, but through the meaning of human touch and communication.

Inspirational Works: Design for Tactility Through Sensory Design

"Vision reveals what the touch already knows. We could think of the sense of touch as the unconscious of vision. Our eyes stroke distant surfaces, contours and edges, and the unconscious tactile sensation determines the agreeableness or unpleasantness of the experience." (Pallasmaa, 2007, p. 42)

This section includes a few interesting and inspiring projects regarding the use of tactile experience in various mediums, from 2D graphical pages to 3D spatial objects, to create different meanings. All these tend to reveal to us hidden aspects of our sensory capabilities, especially in touch, and encourage us to communicate with the world around us, including objects, through our tactile experience. Patterns and textures we normally and even unconsciously touch throughout the day have a specific knowledge of our surroundings since "the sense of touch is of major importance for the perception of three-dimensional shapes." (Kappers, 2011)

More generally, we know that our senses[26] are what allow us to perceive the world around, since "senses move us through space," (Lupton & Lipps, 2018, p. 10) and they are "unique to every person."(Lupton & Lipps, 2018, p. 11) Touch, in particular, is one of those senses we are often unaware of its impact, since "we have allowed two of our sensory domains-sight and sound-to dominate our design imagination. In fact, when it comes to the culture of architecture and design, we create and produce almost exclusively for one sense-the visual." (Lupton & Lipps, 2018, p. 20)

The SF-SO reimagines everyday radio through minimalism and tactile interaction. Among their three designs, the 'Tamed Digital Product Project' (Hahn, 2020) includes a Cone Bluetooth Speaker, a Wheel Digital Radio, and the Ball Internet Radio, which is controlled by three colorful magnetic balls. The radio's innovative interface allows users to physically interact with it by moving the balls to control it. The simplicity and intuitiveness of the tactile pleasure of childhood toys like marbles or similar objects is used not only to simplify the user experience but also to reintroduce tactile engagement. Through its playful, intuitive design, SF-SO offers a refreshing

[26] The various attributes of the body such as shape, proportion, posture, and movement can be both derived from the various sensory systems and can affect perception of the world (including the body itself). (Harris et al., 2015)

departure from today's touchscreens and buttons that dominate gadgets, and aims to provide a more direct, enjoyable, and tactile user experience.

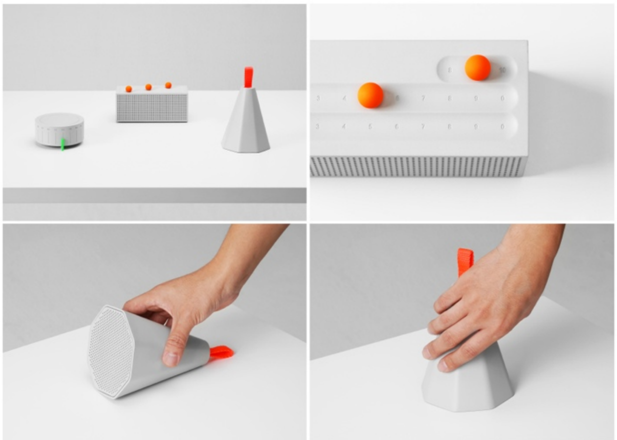

Figure 19 - 'Tamed Digital Devices,' SF-SO studio by (Hahn, 2020)

In another project, the designer made graphic touchable and used it to create meaning through the perception of different "tactile patterns to illustrate the emotions and associations for each story," (Sakdanaraseth, 2020) which we normally perceive visually. The 'Touch Project' combines tactile sensations with visual graphic design to create a universal language that can be used by both sighted and visually impaired individuals. Starting with a university module, Sakdanaraseth embarked on an experimental journey involving paper textures and printing techniques, evolving into a comprehensive exploration of tactile patterns that evoke emotions. By collaborating with the Thai Blind Association, this project explored the emotional impact of tactile patterns on visually impaired people[27]. To demonstrate the project's ability to bridge visual and tactile communication, a series of booklets were produced that depicted emotions and associations derived from Rainer Maria Rilke's Poems[28] using various techniques.

[27] "In the next stage of my project, I choose to work with one of the fully blind participants, a Fine Art student called Lookpla. I thought her artistic knowledge might help draw out and illuminate some of the links between emotions and tactile patterns. During this session, I handed her the textured pieces one at a time. As she touched each one, she told me if the piece held positive or negative associations, and which emotion it reminded her of. She gave me a different answer for each of the 35 pieces and was able to recall precisely all the pieces she had touched. It was interesting to observe some of the overlaps between myself as a visual 'user' making associations with the eyes and Lookpla as a visually-impaired 'user' making associations through the hand." (Sakdanaraseth, 2020)

[28] 'The Book of Images' by Rainer Maria Rilka. (Rilke & Rilke, 1994)

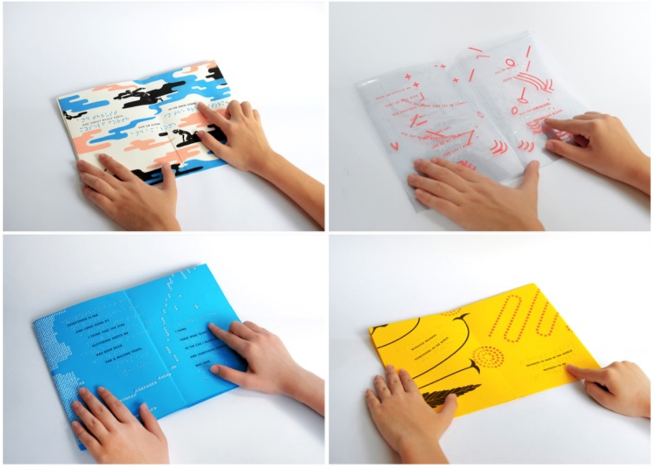

Figure 20 - 'Booklets' Collection by (Sakdanaraseth, 2020) - top left: 'Fate', top right: 'Love', bottom left: 'Hope', bottom right: 'Friend'

The Cooper Hewitt Museum in New York hosted "The Senses: Design Beyond Vision," which was an innovative exhibition that "featured direct sensory experiences and displayed practical, inventive and exploratory objects to touch, hear, see and smell through several interactive installations." This sensory experience included a furry wall with digital sensors that played music and smelts of winter, chairs that vibrated in response to audio cues, a scent-diffusing “clock” that signalled mealtimes for those who couldn’t see or hear, and color-changing lights that varied with the population density of the room.

Cooper Hewitt Director Caroline Baumann explained: “Across all industries and disciplines, designers are avidly seeking ways to stimulate our sensory responses to solve problems of access and enrich our interactions with the world,” (Hewitt, 2018) or as titled her article “the future of design is tactile, aromatic and euphonious.”(Budds, 2018)

Figure 21 - Left image: visitors interact with Tactile Orchestra, right image: 3D printed vessels smell like sugar - Photo by Matt Flynn © Smithsonian Institution. (Hewitt, 2018a)

Figure 22 - 'The Senses: Design Beyond Vision' - Photo by Matt Flynn © Smithsonian Institution. (Hewitt, 2018a)

Over 65 designers showcased their creations in the exhibition, demonstrating how multisensory design can enhance information reception and problem-solving, especially for people with sensory disabilities. Touchable objects, audio, and visual descriptions were included in the exhibition, demonstrating how design can enrich interactions with the world and ensure accessibility for all visitors through the activation of touch, sound, smell, taste, and sight.

Figure 23 - AEIOU Collection, Sensory Dessert Spoon by (J. Jeon, 2015b)

Jihyun Jeon through multiple projects including 'U-A III. Candy Volume n' (J. Jeon, 2018), 'Tableware as Sensorial Stimuli' (J. Jeon, 2012) and 'AEIOU VII, Inner Bumps 2.0' (J. Jeon, 2015a) ingeniously crafted a set of cutleries that challenges our conventional perceptions of taste. She delves into the intriguing phenomenon of synesthesia—a neurological condition where sensory stimuli intertwine, such as seeing colors when hearing certain sounds. "To find out whether this 'sensory cross-wiring' could be encouraged and used to enhance taste, Jeon created cutlery based on five sensory elements: colour, tactility, temperature, volume and weight, and form." (Chalcraft, 2012) For instance, she utilized various colored glazes on ceramic pieces to investigate color's effect on appetite, with warm colors like red and orange intended to increase it. Stainless steel, silver, or plastic materials were chosen for their unique textures and shapes to stimulate touch, while incongruous appearances, such as plastic that mimics glass, were designed to create a jarring sensation, challenging our expectations of sight and touch.

Figure 24 - AEIOU Collection by Jihyun Jeon - top left and right images: Sensory Cutlery Collection (2012), bottom left image: AEIOU VII Inner Bumps 2.0 (2015), bottom tight image: U-A III. Candy Volume n (2018)

Jeon's innovative approach extends beyond mere functionality; it challenges the traditional boundaries of tableware, transforming it into an extension of the body that engages multiple senses simultaneously. This concept of expanding the role of the objects we interact with daily resonates deeply with my own design aspirations.

I started to think instead of confining sensory stimuli to the traditional contact points like the hands, forearm, etc., I can envision my soft robot objects in an experience to be perceived by any part of the body, since sensory perception[29] is unique to each individual[30] and so that designing these objects without a prescribed point of contact can offer a more inclusive and personal interaction. The process of refining soft robots through the design of sensory objects allows me to consider their "invisible aspects"[31] (Dal Palù et al., 2018) in order to create a unique experience through active, intra-active, and intrapersonal touch, which will be discussed in more detail in the next chapter.

[29] Sensation and perception are two separate processes that are very closely related. Sensation is input about the physical world obtained by our sensory receptors, and perception is the process by which the brain selects, organizes, and interprets these sensations. (“Sensation and Perception,” n.d.)

[30] “All humans get the same sensory information input. However, every human has a unique brain. Therefore, different humans perceive the same sensations in different ways. Sensations are the same, but perceptions differ.” (Schiffer, 2023)

[31] A designer’s ability to control and consider the “invisible aspects” of the project such as sound, primary, but also other invisible sensory aspects such as touch and scent, represents a real opportunity in product development and takes on an important role in user experience and product interaction. (Dal Palù et al., 2018)

3.2. Theoretical Review

3.2.1. Sensory Design

> "Humans possess powerful sensory capacities that allow us to sense the kaleidoscope of sights, sounds, smells, and tastes that surround us. The human perceptual system is wired for accuracy, and people are exceedingly good at making use of the wide variety of information available to them." (Stoffregen & Bardy, 2001)

In other words, we use this powerful sense not just to interact with the outside world, but also as a foundation for our understanding of it. Using multiple senses to perceive reality is crucial to a richer perception. This understanding forms the basis for how we experience and interpret our environment. As humans become increasingly engaged in sensory experiences, the field of design has begun evolving to accommodate these multisensory experiences better. "The more senses we engage, the more strongly we are tied to a moment, an object, a space. As a result, design is evolving to incorporate sensory experience into the places where we live and work." (O'Gara, 2019)

By integrating sensory experiences into design, we can forge deeper and more emotional connections between people and their environments, resulting in more immersive and emotional experiences. We can make everyday interactions more meaningful by integrating sensory experiences into design. Or as Abraira & Ginty said, "the sensory system receives and processes information that generates an individual's awareness of their environment (Abraira & Ginty, 2013)."

Based on the literature I am delving into; I have come to understand that taking a deeper look at sensory perception reveals that it plays an essential role in shaping our interactions with the world around us. Sensory systems are responsible for the reception and processing of environmental stimuli, and our perceptions can be used to enrich our engagement with the surrounding world through this dynamic interaction.

"Products designed with multisensory features can create emotional and meaningful interactions between people and the products they use. The more designers become familiar with the sensory aspects of design, the better they will apply sensory interactions in their products." (Frankel, 2023a) This emphasis on multisensory features in design highlights the importance of creating products that offer emotional and meaningful interactions. Such products do not merely serve functional purposes but also enrich our lives by appealing to our sensory experiences. As designers grow more adept at incorporating sensory aspects into their work, they unlock new dimensions of product interaction that resonate on a deeper emotional level with users.

Although this discussion is primarily centered on product design, as John Heskett described, "design is to design a design, to produce a design,"[32] (Heskett, 2005) and so the knowledge of multisensory definitions and purposes in product design is extremely beneficial to me in understanding this holistic view of sensory engagement in design, that our perception of the world is the result of a combination of our senses. "We perceive our surroundings and interactions as a

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[32] Consider, for example, the shifts of meaning when using the word 'design' in English, illustrated by a seemingly nonsensical sentence: 'Design is to design a design to produce a design.' Yet every use of the word is grammatically correct. (Heskett, 2005)

combination of sensory interactions," (Frankel, 2023a) however, "our sense of touch supports and sometimes confirms what our distal (far) sense of sight has already taken in, and together these two sensory experiences guide us in operating the product.” (Paterson, 2007) Through this lens, sensory design not only enhances functionality but also fosters a deeper, more intuitive connection between people and objects, thus it helps me to design my object not only visible but also feelable or as Thomas Fueller said, “seeing is believing, but feeling is the truth.”[33] (Ablart et al., 2017)

3.2.2. Design for Creating Haptic Experience

Haptics: Definition and Technologies for Communication

Haptics, derived from “the Greek verb *‘haptesthai’* meaning “to touch”, refers to the science of sensing and manipulating through touch." (M. Eid et al., 2007) “The term haptic was first proposed by German philosopher and psychologist Max Dessoir, as an attempt to encompass all different aspects of the sense of touch and its study.” (Grunwald, 2008) In the psychology and neuroscience literature, haptics is the study of human touch sensing, specifically via kinesthetic (force/position) and cutaneous (tactile) receptors, associated with perception and manipulation. Haptic communication relates to touch-based (nonverbal) forms of interaction between humans, and haptic technology as technology that interfaces with a user through the sense of touch. (Weda et al., 2022)

“The feeling of touch acts as self-specifying sensory information,” (Bermúdez, 2018) “since tactile stimuli necessarily provide information on one's own body,” (Choi & Ishii, 2020) thus the significance of touch in human perception and interaction cannot be overstated. According to (Chew et al., 2023), most haptic technologies have focused on the functional aspects of touch, despite the fact that touch is crucial for the way we feel and interact with our environment and is fundamental to our emotional well-being. Touch's non-functional aspects, on the other hand, are experiential and relate to feelings of agency, trust, and attachment. "Haptics allow humans to perform various exploration and manipulation tasks in the real world."(Lederman & Klatzky, 2009) "With the emergence of haptic technologies and increasing interest in affective computing, researchers may rely on the use of haptics to display emotion to users and also to detect their emotions to communicate what audio-visual modalities cannot accommodate." (Paterson, 2007)

"Most existing affective communication techniques use text, speech, gesture and facial expressions information transfer or a combination of these approaches, known as multimodal methods. These techniques exploit only two of the human senses: visual and auditory."(Meng, 2015) "Therefore, the next critical step is to bring the sense of touch to computer-mediated emotional communication."(M. A. Eid & Al Osman, 2016)

As a powerful tool for communicating emotions, touch often goes unnoticed to communicate feelings, whereas touch can convey a variety of emotions such as love, trust, anger, and sorrow. It can also be used to connect people emotionally, making it a vital communication method. "Despite the importance of touch in several key domains of social life, its role in the

[33] “Seeing is believing, but feeling is the truth”. This idiom from the seventieth century English clergyman Thomas Fuller gains new momentum in light of an increased proliferation of haptic technologies that allow people to have various kinds of ‘touch’ and ‘touchless’ interactions. (Ablart et al., 2017)

communication of emotion has received little attention compared with facial and vocal displays of emotion. " (Stack, 2004) In two studies, researcher investigated whether people could detect emotions from a stranger's touch without seeing the stimulation. They indicated that touch “possess the possibility of communicating distinct emotions even between strangers.” (Hertenstein et al., 2009, p. 572) Their studies provided “evidence that touch communicates distinct emotions and does so in a robust fashion. We documented that touch communicates at least eight emotions: anger, fear, happiness, sadness, disgust, love, gratitude, and sympathy.”(Hertenstein et al., 2009, p. 569)

Emotions Through Haptic Experience

"Research into vibrotactile (Xu, 2023)[34] feedback has traditionally focused on utility and usability, rather than experience." (Singhal & Schneider, 2021) However, some studies like ‘Affective Haptics: Current Research and Future Directions’ indicated that "haptic stimulation can be successfully used to achieve a higher level of emotional immersion during media consumption or emotional telepresence (Shen & Shirmohammadi, 2006)[35]," which is where I also intend to incorporate my thesis aims (even though it had not been included in my thesis objectives initially), by expanding this notion of designing objects for tactile communication, even though "the interpretation of the haptic stimulation by human beings is highly contextual." (M. A. Eid & Al Osman, 2016) In spite of the critical role touch plays in human communication, “research has paid very little attention to how touch is utilized to communicate affection." (Hertenstein, Verkamp, et al., 2006) According to (Smith & MacLean, 2007), a powerful tool to elicit and modulate human emotion is the sense of touch. Touch helps us communicate our feelings and enhances the meaning of other forms of communication such as visuals or verbalization. Different cues can easily evoke human emotions, and touch is one of the most emotional channels.

Haptic Experience Design Principles

Researchers in ‘Juicy Haptic Design’, (Singhal & Schneider, 2021) provided ten guidelines in order to assist novice haptic designers due to a lack of practical guidelines in the field. A literature review and iterative brainstorming process led to the development of these principles, which are based on Disney's twelve basic principles of visual animation, principles of haptic cinematography, Apple's WWDC 2019 presentation on creating audio-haptic experiences, and studies on the experiential dimensions of haptic experiences. As a result of the proposed principles, haptic feedback[36] can be created in a variety of applications, including video games and animations. “The principles are neither exhaustive nor prescriptive and need not be used all at once – one must still

[34] According to BuiltIn: “Vibrotactile feedback applies vibrations to stimulate a user’s skin and is one of the most common types of haptics. This feedback is often used for mobile phones, touchscreens, wearable electronics and video game controllers.” (Xu, 2023)

[35] Telepresence, also called virtual presence, is a technique to create a sense of physical presence at a remote location using necessary multimedia such as sound, vision, and touch.

[36] There are two types of haptics feedback, according to See et al. One is Cutaneous Feedback, which includes electrotactile feedback, skin stretch, skin indentation and vibrotactile stimulation. The second group is the kinesthetic feedback group, which includes the ground force feedback system and exoskeleton-based force system. (See et al., 2022)

iterate and exercise judgment. Finally, though we study them as vibrotactile feedback, their ideas should apply to other haptic modalities." (Singhal & Schneider, 2021)

Based on their definitions and purposes, the four principles listed below are most relevant to the creation of my thesis. They are presented in the article along with animation embellishments and audible haptic feedback frequency. Hence, I decided to present my selected principles with these supplemental materials to illustrate them not only with words but also with engaging other sense cues for a better understanding of their affect and characteristics. (Complete figure adopted from Singhal & Schneider: Appendix A – 1 and complete table adopted from Singhal & Schneider: Appendix B – 3)

Principle	Definition	Relation with Visuo-Haptic Figure	Example
Realism	Use of haptic parameters to mimic an object's physical qualities.	In animation, realism is achieved by matching visual cues with appropriate haptic feedback to enhance the perception of the material properties of objects.	*A squishy ball bouncing is paired with low frequency vibrations, while a marble ball bouncing comes with high frequency feedback.*
Slow In and Out	Implementing gradual acceleration and deceleration in haptic feedback.	Making movements more natural by adjusting the intensity of haptic feedback gradually, akin to the easing in and out in animation.	*Gradual increase in vibration intensity as a car starts moving, then a gradual decrease as it stops.*
Energy	Matching haptic feedback intensity with the visual energy of an object.	Haptic feedback reinforces the energy of a scene or object by matching or amplifying the perceived energy through the intensity and frequency of vibrations.	*Faster-paced, more intense vibrations paired with a visually pulsating object demanding attention.*
Expressivity	Distinct haptic feedback for different interactions or events.	Providing varied haptic responses to different actions or events, adding depth and a richer sensory experience, akin to how visual and auditory variations are employed in animation.	*Differentiated haptic feedback for a small pebble and a large boulder falling, reflecting their impact and aftermath.*

Table 2 - Principles of Haptic Embellishments for Symbiont, created by author, data extracted based on Symbiont's objective - Original Table Content by (Singhal & Schneider, 2021)

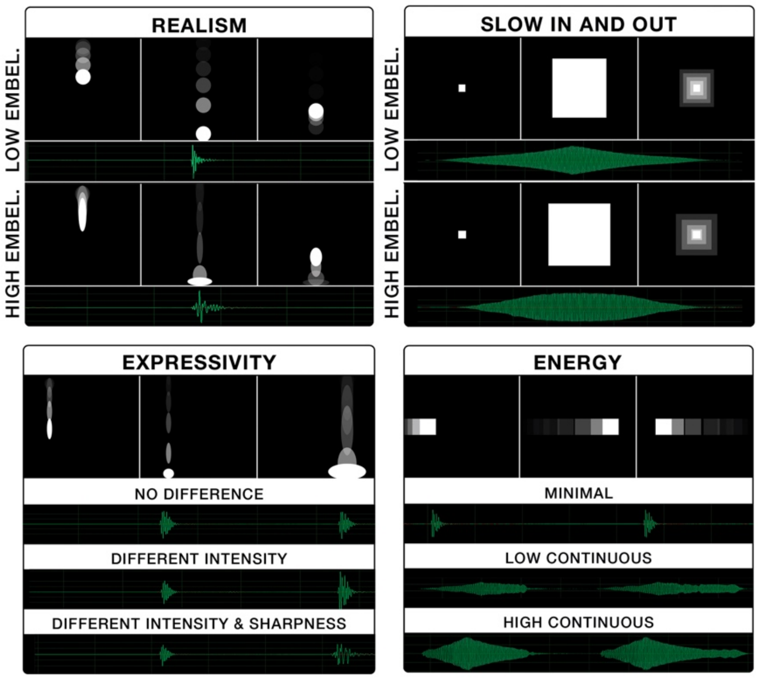


Figure 25 - Principles of Haptic Embellishments for Symbiont, data extracted based on Symbiont's objective - Original Figure Content by (Singhal & Schneider, 2021)

Incorporating these principles into the logic of soft robot object behavior not only resonates with the notion of bio-inspired design (the movement and behavior of soft robot objects are influenced by creatures) but also will create a better experience with the user[37]. My thesis creation, for example, relates very well to the term 'Realism', since I intend to design the object's behavior (and form) based on bioinspiration using metaphor, so that it reflects the real world.

3.2.3. Design for Tactile Interaction

Tactile Experiences Through Tactile Aesthetics

"The word aesthetic is derived from the αἰσθητικός (aisthētikós, 'perceptive, sensitive, pertaining to sensory perception'), which in turn comes from αἰσθάνομαι (aisthánomai, 'I perceive, sense, learn') and is related to αἴσθησις

(aísthēsis, 'perception, sensation')." ("Aesthetic (n.)," n.d.) In the Eighteenth Century, "the term 'aesthetic' has come to designate, among other things, a kind of object, a kind of judgment, a kind of attitude, a kind of experience, and a kind of value." (Shelley, 2022)

The topic of my thesis, which has been centred around object and sense, is intimately linked with the word aesthetics under this title, which, according to Britannica, "is an object of sensory experience and enjoyed as such: it is heard, seen, or (in the limiting case) imagined in sensory form." (Aesthetics | Definition, Approaches, Development, Meaning, Examples, & Facts | Britannica, n.d.) Stuart Walker in "Superficial Evidence" (Walker, 1995) included surface texture and tactile delineation to describe our aesthetic interpretations of objects. According to Walker, our appreciation of a product's tactile aesthetics arises in response to our experience of holding, using, and generally being in physical contact with the objects around us. According to Franker, "We experience a sense of pleasure or frustration through tactile interactions in three ways." (Frankel, 2023b)

Figure 26 - Emotional Meaning from Past Tactile Experiences, sketched by author, adopted from Open Library

[37] "Results indicate that juicy haptics can enhance enjoyability, aesthetic appeal, immersion, and meaning." , (Singhal & Schneider, 2021, p. 1)

The first is that we get pleasure from our positive interactions when we use products such as instruments to achieve our goals. Additionally, when we use the right materials for product surfaces, we can achieve our ideals at a non-instrumental level, resulting in feelings of ideo-pleasure. Lastly, we may enjoy our emotional memories (socio-pleasure) associated with past tactile experiences with materials that aid in our understanding of them. "We discover tangible information about a product through our sense of touch," (Frankel, 2023b) for example, a person can touch five different textures at once, such as a rough pebble, a smooth fabric, a fuzzy ball, and a bumpy wall, and detect differences in each, and that's because "our ability to form impressions about what we touch depends on our finely tuned tactile sensations." (Frankel, 2023b) We can also "perceive several stimuli in different places at the same time,"(Cholewiak & Collins, 2003) since touch has a great "sensitivity to directly measure and perceive the multiple nature characteristics of things, and it can precisely distinguish information about the shape, state, texture, texture, and material of things." (Lee et al., 2011)

Skin Sensation: Active, Passive, and Intra-active Touch

According to (Home Science Tools, n.d.) the somatosensory system controls our sense of touch through a large number of nerve endings and touch receptors in the skin. We feel all kinds of sensations in this system - cold, hot, smooth, rough, pressure, tickle, itch, pain, vibrations, etc. As well, we have mechanoreceptors that are very good at sensing the continuous pressure of an object touching or indenting our skin, which perceive sensations like pressure, vibrations, and texture. "We find two main types of touching play a part in demonstrating human product interaction: active and passive." (Sonneveld & Schifferstein, 2008)

Active touch refers to what is ordinarily called touching. "This ought to be distinguished from passive touch or being touched. In one case the impression on the skin is brought about by the perceiver himself and in the other case by some outside agency …. Active touch is an exploratory rather than a merely receptive sense." (Gibson, 1962)

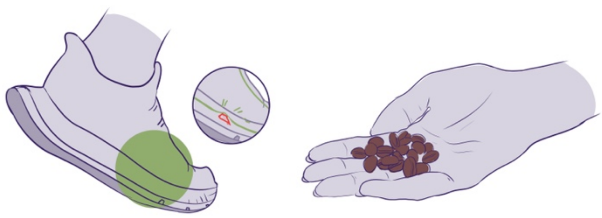


Figure 27 - Active Touch (left), Passive Touch (right), sketched by author, adopted from Open Library

Moreover, tactile experiences can also include intra-active touch. A clear example could be brushing your teeth. This happens when an individual actively manipulates an object while passively experiencing tactile sensations, often involving a part of their own body, or as Gibson called it, a "self-touch." (Gibson, 1962) It's a process where the organism is not a passive recipient of sensory inputs but an active participant that seeks out information to understand and interact with its environment effectively. This means that active perception includes both aspects: the act of touching to acquire information and responding to being touched, both of which are guided by the organism's intentions and the context of the interaction.

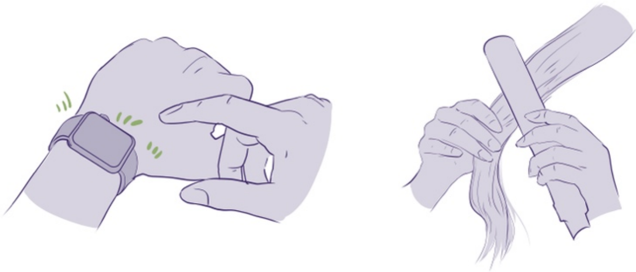


Figure 28 - Intra-active Touch, sketched by author, adopted from Open Library

The Observation of Being Touched and Touching

Active Touching as described through the lens of James J. Gibson's 1962 on an article titled, “Observations on Active Touch”, is the process of touching. "This ought to be distinguished from passive touch or being touched. In one case the impression on the skin is brought about by the perceiver himself and in the other case by some outside agency." (Gibson, 1962) In contrast, Active Perception is not just about touching or being touched, it "seeks to help achieve those goals by actively selecting and refining the sensations to give the appropriate perceptual information."(Bajcsy, 1988)

Active perception is characterized by a feedback loop that integrates sensation, perception and action, because "interpreting active perception as a closed-loop system that uses sensory feedback to control the state parameters of the sensor." (Lepora, 2015)

Communicative: Intrapersonal Touch

"Human beings constantly seek to stay one close to another and interact suggesting the need to feel connected and establish emotional bonds with others to create and maintain interpersonal relationships." (Leary, 2022) "Physical contact, mediated by the sense of touch, is an essential part of social communication providing the experience of actual togetherness, which can be defined as social presence." (Van Erp & Toet, 2015)

"Interpersonal affective touch, which refers to the emotional and motivational facets of tactile exchanges between social partners, has been shown to modulate psychological boundaries between the self and the others." (Gallace & Spence, 2014) In turn, this affects the feeling of social connection. It is a unique property of tactile interactions that touch is reciprocal in nature, involving a shared sensory experience between individuals, "and so it represents a privileged channel of communication that can convey immediate socio-emotional meanings and reinforce social bonds." (Morrison et al., 2010)

With the use of digital technology, we have been able to overcome the limitations of physical distances by providing increasingly sophisticated devices that allow people who are physically apart to stay connected, making it easier to develop and maintain global social networks. Conversely, increased use of mediated communication reduces non-verbal social cues, "in particular the opportunities of direct physical contact between people, which may represent a cost in terms of people’s understanding of others’ thoughts and feelings and perceived closeness." (Lieberman & Schroeder, 2020)

3.2.4. Biomorphic Design

“For a long time, nature has inspired human beings to find solutions to technological challenges ranging from the design of textiles, materials, reactor processes, electrochemical cells to means of transportation." (Bar-Cohen, 2006) Accordingly, Biomorphic forms and patterns are basically symbolic references to contoured, patterned, textured or numerical arrangements that we see in nature.

Biomorphic design, biophilic design, and biomimicry are all concepts derived from Biomorphism, which "is a compound of ‘bio,’ a complex term for life, lively phenomena, and biotics, and ‘morphism,’ the collective form or composition of an organ or part." (Alloway, 1975)

Wilson's biophilia hypothesis includes the claim that, as a consequence of evolution, humans have an “innate tendency to focus on life and lifelike processes.” (Gullone, 2000) This notion, along with other results from researchers like Joye, proposed that "it could even be true that biophilic design is psychologically “healthier” than other styles." (Joye, 2011, p. 32) In another research also suggested that Biophilic Design can improve people's health and mood, "in many senses, natural elements can positively influence human beings." (Joye & Van Locke, 2007)

"Biological inspiration does not imply that we attempt to copy nature. Rather, the goal is to understand the principles underlying the behaviour of animals and humans and transfer them to the development of robots." (Pfeifer et al., 2012) “The heart of successful bioinspired design is the abstraction of the underlying design principles found in biology and their implementation in robotics using state-of-the-art technology." (Kovač, 2014) Another successful example of a biophilic or bio-inspired concept in design would be the use of bone-inspired concepts, which "lead to fascinating advances in product design, architecture and garments, thanks to the bone’s exceptional combination of strength, toughness and lightness." (Buccino et al., 2021)

In soft robotics, the use of biophilic design, or more generally Biomorphism, has been linked from the first exploration of Octobot [38] (Appendix C - 2) to a study titled "It Brings the Good Vibes" (Section 3.1.2.) proposing soft Biomorphism design paradigms.

According to Pfeifer, “soft robots are made of compliant materials with mechanical similarities to soft biological tissue, and their design is often anchored in biomimicry and bioinspiration,"(Pfeifer et al., 2012) and ″while these dominating design approaches to soft robotics have succeeded in imbuing soft robots with impressive capabilities, they disregard the aesthetic dimension of robot design." (Christiansen et al., 2023)

[38] The first autonomous entirely soft robot by Harvard University, for more information: https://wyss.harvard.edu/news/the-first-autonomous-entirely-soft-robot/

3.2.5. Tactile Communication over the Internet

Tactile Internet: Definition and Principles

The advancement of the Internet of Things (IoT) has significantly transformed how we interact with our surroundings, leading to the emergence of concepts like the Tactile Internet (Fettweis, 2014) [39] (TI). The definition of the TI has been agreed within the IEEE 1918.1 WG as: "A network (or network of networks) for remotely accessing, perceiving, manipulating, or controlling real or virtual objects or processes in perceived real time by humans or machines." (Aijaz et al., 2018) The following elements are the most effective aspects in the context of my thesis, extracted from IEEE 1918's list of core aspects of Tactile Internet (Complete list of TI core aspects, Appendix C -1):

1. TI enables remote physical interactions, including the exchange of haptic information.
2. Interactions can occur between humans, machines, or both.
3. "Object" in TI can mean any physical entity, including humans and various machines or software.
4. Haptic information is categorized into tactile (skin-based perceptions like texture and temperature) and kinesthetic (body-based perceptions like force and position), often combined.

Through these principles, with their emphasis on low latency and reliable communication, the system is able to deliver haptic data without delay, enhancing the sense of presence and immediacy during remote interactions

MQTT Protocol

"Message Queuing Telemetry Transport (MQTT) is a publish/subscribe based messaging protocol," (Masdani & Darlis, 2018) which is both simple and effective. "Because of various factors, such as lightweight, modest bandwidth requirements, and open and straightforward implementation, it is often utilized for IoT systems with few resources." (M & C A, 2022) MQTT refers to the central server as the broker. The broker allows every device connected to it to be a publisher or a subscriber. A number of sensors regularly send their results to a subject address. Publishers transmit data to subscribers through the broker.

"The protocol's design principles are to minimize network bandwidth and device resource requirements whilst also attempting to ensure reliability and some degree of assurance of delivery." (Masdani & Darlis, 2018) "These principles make the protocol ideal for M2M (Machine to Machine) communications on Internet of Things devices, and also for mobile applications." (OASIS Standard, 2015)

The MQTT protocol is based on the TCP/IP protocol, and port 1883 is assigned by the Internet Assigned Numbers Authority (IANA). There are several local brokers for MQTT, including Mosquitto, Mosca, HiveMQ, etc. Public brokers include eclipse.org, test.mosquitto.org, broker.hivemq.com, www.cloudmqtt.com, and mqtt.dioty.co.

[39] The term Tactile Internet coined by Prof. Gerhard P. Fettweis in an article title, "The Tactile Internet: Applications and Challenges." (Fettweis, 2014)

3.3. Thesis Context

I have been driven by the goal of developing a nature-inspired soft robot that facilitates nonverbal interpersonal communication during the course of the thesis journey, as discussed before. I began my design process by asking myself which human senses could be used in this context, to extend human senses to create this nonverbal communication. This led me to delve into sensory design and haptic experience principles, as I consider the tactile and material aspects that can resonate with users on a nonverbal level. In my second question, I ask speculatively about the possibility of using soft robots as sensory objects to communicate nonverbally. The goal was to explore how soft robots could be used as a medium for such interaction as well as objects that can engage with users intuitively and sensibly. As a result, I consider biomorphic design, HCI and human-soft robot interaction, and aesthetics through sensory considerations.

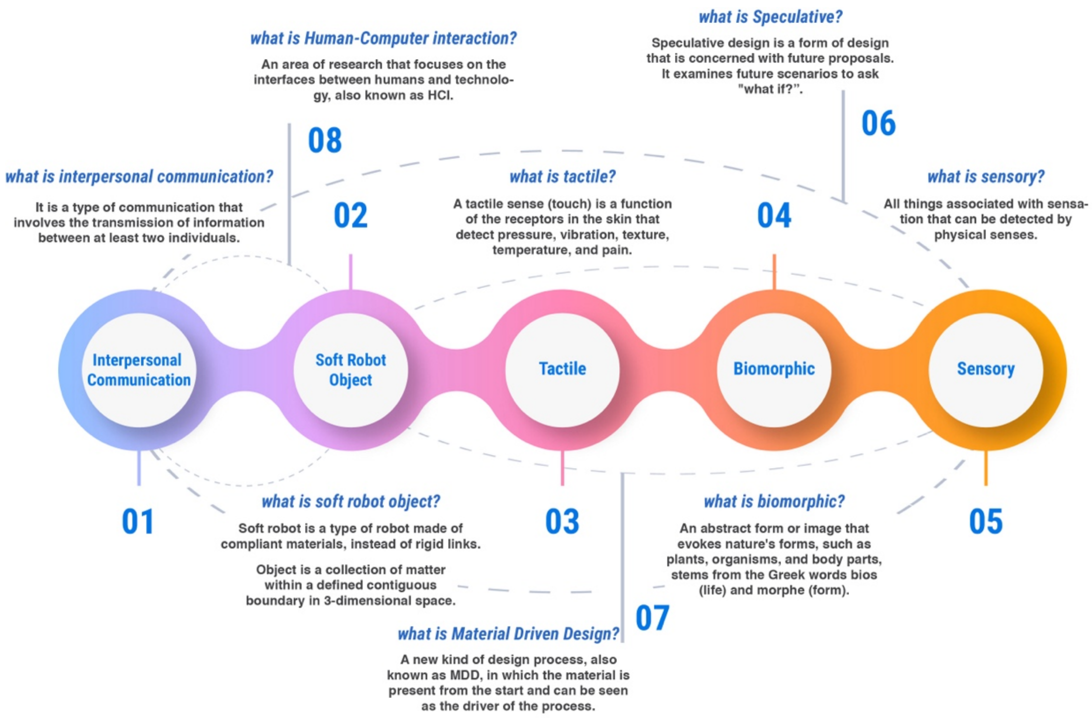


Figure 29 - Symbiont's Contexts, created by author

Because none of these methods, methodologies, and models were sufficient individually for my journey, I had to create my own by merging multiple models together. My third question addresses the methods, methodologies, and models I can build upon. In addition to guiding me in each step, it also helped me define more granular questions, which had an impact on my design and enhanced my knowledge and experience. Figure 29 shows the interconnectedness of my design contexts and the relationships between different elements in a context of three ovals, which represent different fields and contexts. I am interested in synthesising sensory experience, biomorphic principles through material and texture, and exploring nonverbal communication through soft robots.

In the next section, I present my annotations on these resources, including findings, outcomes, synthesizing, thinking processes and their relation to my thesis objective, as a culmination of my literature review and theoretical studies in this chapter. (Section 2.2.2.)

3.4. Thesis Framework's Annotations

Figure 30 - 'Define' Phase, Annotation on Thesis Frameworks – (Multisensory), annotated by author

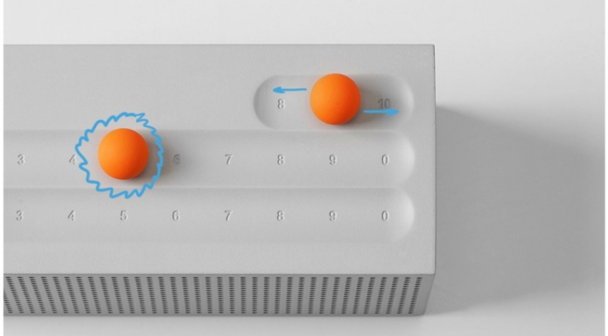
It has already created a unique sensation just by hearing about, seeing and touching my soft robot object's silicone skin. The material and specific properties of this soft robot object have already made it perceive that it is likely to be soft and squishy (obviously :)) as well as stretchable, based on its materiality and specific properties.

Would it make a difference if I added multiple textures to my object?

what about colors?
perhaps even a material?

What is the feeling of imagining a texture by observing it?

When designing sensory objects, color is just as important as material, ~~texture~~ and shape. It has its own way of cueing the senses!



The object can both be touched and touched! It is like something that one can touch and hold, yet at the same time, it can inspire one by its texture or even shape, if it accidentally touches the body.

Can I engage multiple senses with haptics or must I block other gates so that haptics is as strong as possible in this chain? Is it even possible to block a sense or will it eventually find its own way to perceive?

Figure 31 - 'Define' Phase, Annotation on Thesis Frameworks – (Sensory Objects), annotated by author

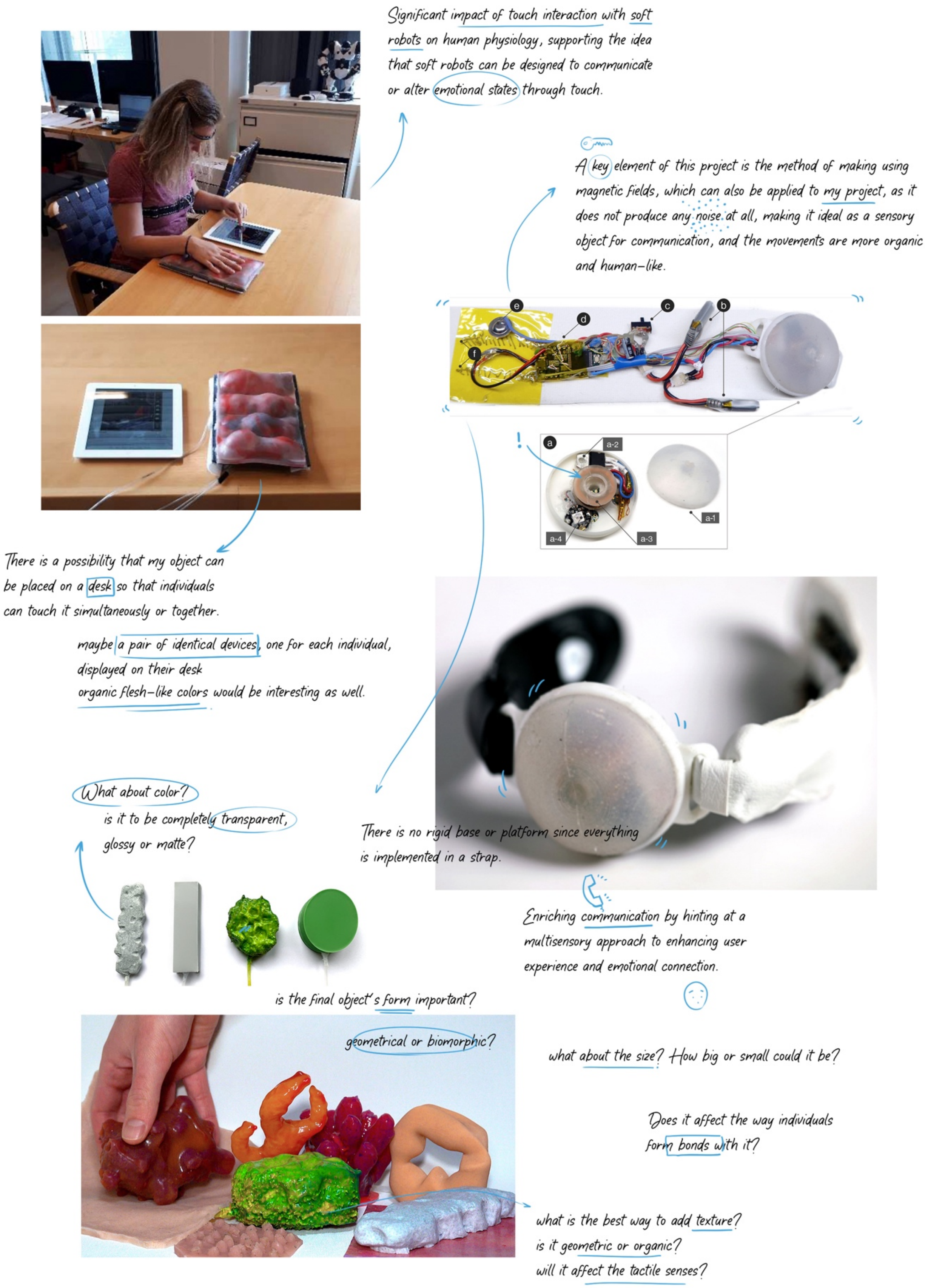
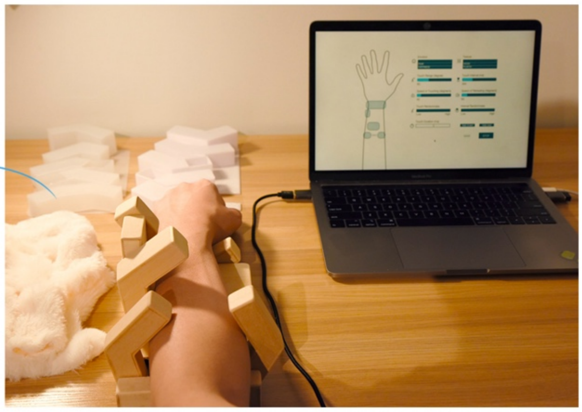


Figure 32 - 'Define' Phase, Annotation on Thesis Frameworks - (Human-Soft Robot Emotional Interaction), annotated by author

Mimicking human-like emotional touch, crucial for creating objects that support nuanced tactile communication



"All projects explore the interface between technology and the human sensory system, in the context of my thesis emphasizing the importance of sensory design in human-robot interaction."

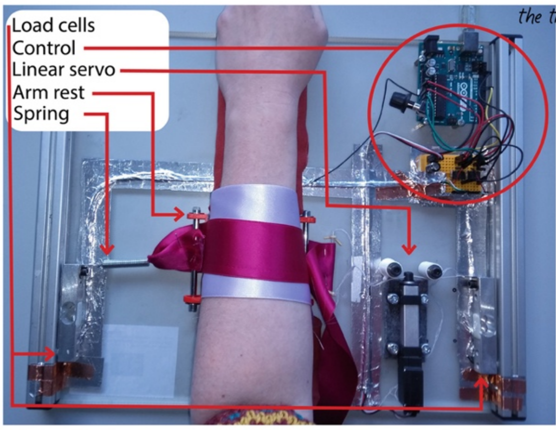
Using technology to replicate human touch.

The potential of soft robotics in replicating subtle yet powerful forms of communication.

If you are watching your hand or any part of your body being touched by a stranger, and at the same time feeling your hand actually being touched in real life, but you cannot observe your actual arm, how does it feel? Your haptics receptors and spatial senses are used to perceive this sensation.

How the absence of touch or the simulation of touch can still convey meaningful communication through soft robotics.

What if one put their hand, leg, or even an ear into my object which is like a box, and then transmiting signals to another individual using their haptic senses? If so, how does the material affect this ambiguous experience? Does the transparent or opaque material make any difference?



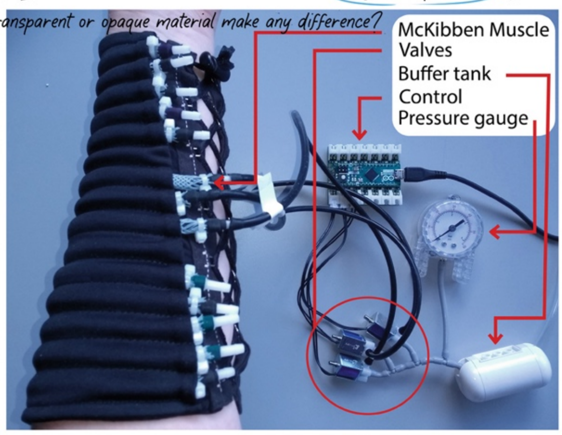
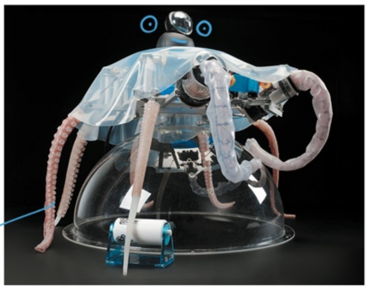
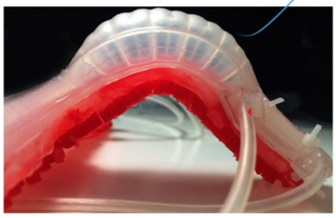


Figure 33 - 'Define' Phase, Annotation on Thesis Frameworks - (Virtual Touch), annotated by author

It's big bubbly head is so inspiring! And the way the lines of vain are spread all over the body is elegant!



Colors and forms that resemble flesh, organic and worm-like, how do these feelings and thoughts influence my design and imagination?



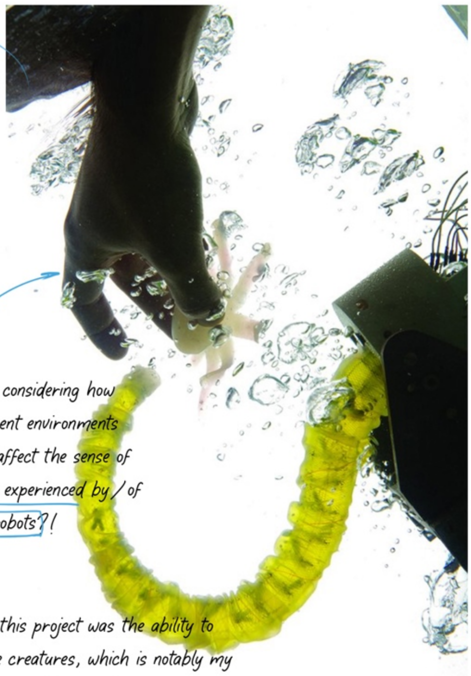
One is biomorphic design of an object, the other is metaphorical use of nature for designing an object, both are fascinating but very different, which is more relevant to my object?

Considering how each scenario might affect the perception of touch (active or passive), as well as the interaction experience, each scenario would have an entirely different design process and outcome.

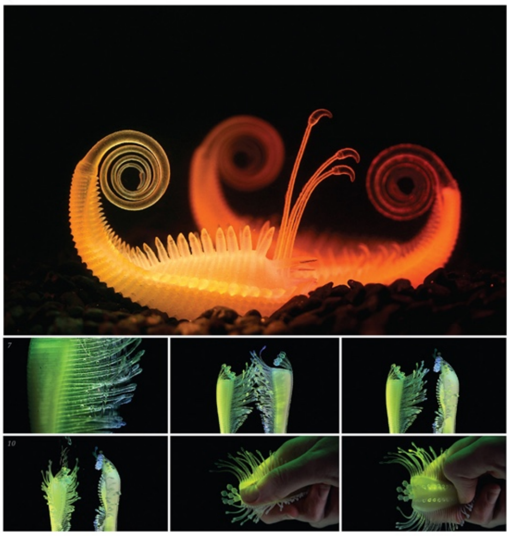
In my opinion, having these tentacles is a fascinating characteristic for a lot of designers, as it is for me. Would I prefer using these tentacles in conjunction with my hands or in place of my hands? This is essential to understanding how this soft robot object and human interact.

It is as if you are bringing a creature back to its origins when you observe soft robots under the water!

Upon first encountering this project, I was blown away by the amount of effort and the exquisite and delicate designs that were implemented. Designer was successful in creating these creatures in such a way that one is able to emotionally bond with them and feel as if they already exist in a world of their own. I consider aesthetics to be a key element.. it makes a considerable difference to my sense of finality!



I am considering how different environments may affect the sense of touch experienced by/of soft robots?!



The success of this project was the ability to 3D print these creatures, which is notably my thesis limitation since I do not have access to such technologies, but in the future, it will make a great deal of difference in the field of soft robotics.

Figure 34 - 'Define' Phase, Annotation on Thesis Frameworks - (Soft Material Aesthetics), annotated by author

Chapter 4. Design Process: Research Through Iteration, Reflection and Creation

In this chapter, I present different methods and techniques I used in each phase of my thesis including Discover, Define, Develop and Deliver which were outlined earlier in the Thesis Approach section. After conducting a reflective practice on my recent projects, creating a mood board, and collecting interesting academic literature that influenced me during my master's degree, I discovered the areas of my interest. My exploration continues with diverging ideas in order to define my objective, methodology, and frameworks. During all four phases of my design process, I use multiple methods, including mind maps, force associations, science fiction prototyping, annotation portfolios, autobiography diaries, rapid prototyping, design by metaphor, and morphological analysis.

A third phase called develop acts as a branch rooted in the foundations that were established earlier by making five different prototypes. Ultimately, the chapter concludes with the creation of Symbiont during the delivery phase of the project, which includes its morphological design analysis, fabrication process, system-level design, and final presentation at OCAD University's Digital Futures Thesis Exhibition.

4.1. Discover (topics and interests)

4.1.1. Forced Association and Mind Map

I used this technique to generate new ideas for my thesis topic in this phase, as discussed in the methods chapter. "The method can also be carried out by using an existing mind map about the topic and randomly selecting keywords from it." (Kokotovich, 2004) As a result, I drew a mind map (Appendix A - 2) from a few keywords, highlighted some ideas and concepts, and used forced association to connect those two points together. My anchors on the Forced Association diagram were 'sense' and 'biomorphic', which were in the middle.

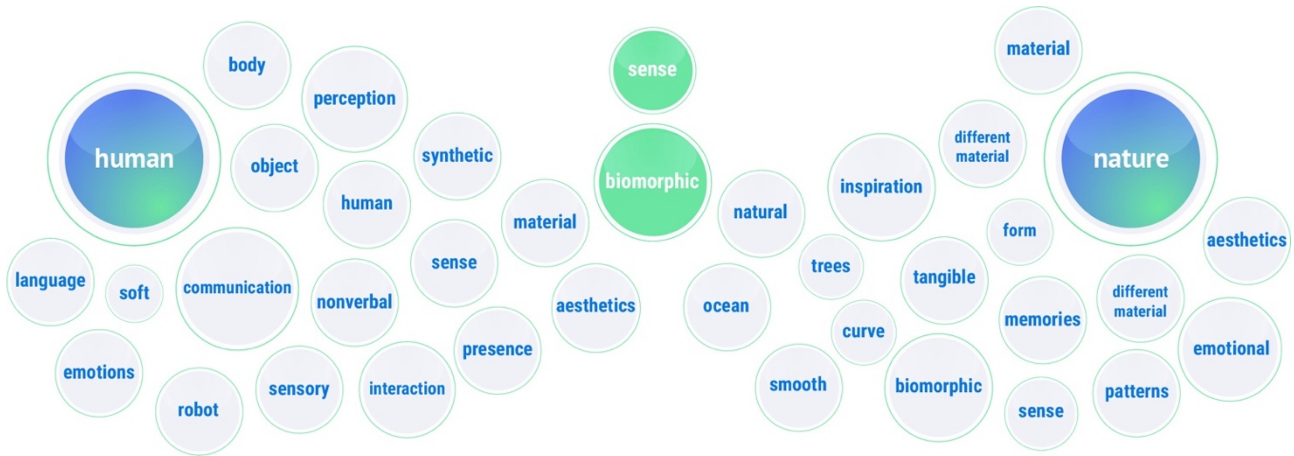


Figure 35 - Symbiont's Force Association Diagram - created by author

Further exploration and steps were taken through visual annotations and reflective practices. These steps are outlined in the Appendix and include the following:

- Aesthetics Mood Board: Appendix A - 3
- Ideas and Projects Board: Appendix A - 4
- Readings Board: Appendix A - 5
- Annotations on Previous Projects: Appendix A - 6

4.2. Define (objective, questions, research)

This chapter as outlined before (Section 2.2.2) served as a tool for further exploring the chosen concept and ideas of the thesis outcome from the Discover phase, which was informed by objectives, questions, as well as literature, contextual and theoretical reviews. Moreover, other creative methods including annotating and reflecting on findings were also part of this phase and are presented in the Appendix as follows.

- Engagement through Other Project as Reflective Practice: Appendix C - 3
- Autobiography Diaries I: Appendix A - 7
- Autobiography Diaries II: Appendix A - 8

4.2.1. Annotation on Science Fiction Prototyping

I used Midjourney (*Midjourney*, n.d.), which is generative artificial intelligence program, to explore unconventional possibilities using this method, as described in Section 2.2.2. By enabling thought processes without constraints, this approach enabled the imagination to develop diverse scenarios, even those that may seem far-fetched or technologically distant. I refined the key terms most effectively describing my envisioned concepts through iterative testing. In order to translate my thoughts into visuals closely aligned with my imagination, these terms were then crafted into prompts that were both intelligible to the AI and effective at translating them. Annotations in Figure 36 describe the outcomes, notes, elements, and cues that influenced my design process.

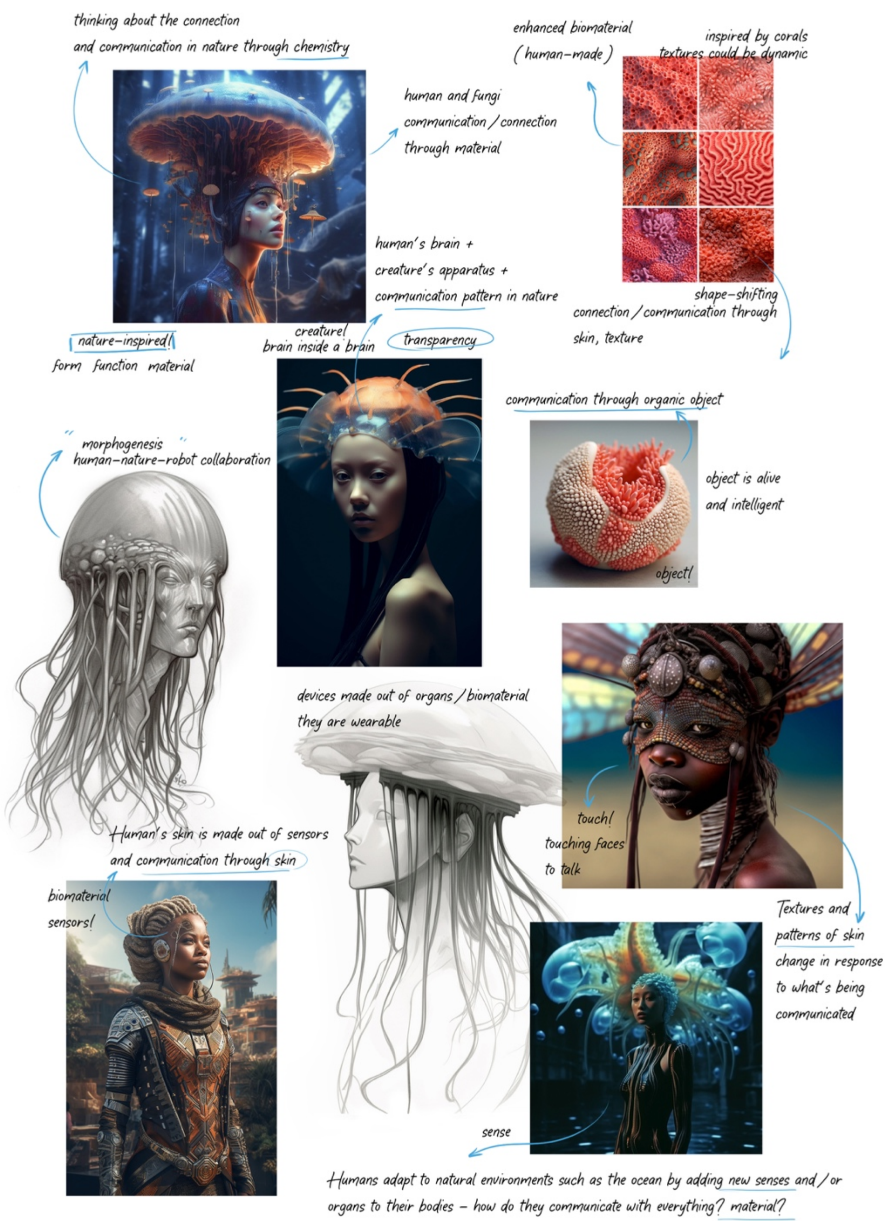


Figure 36 - 'Define' Phase, Annotations on Science Fiction Prototyping, Images: AI generated by author, annotated by author

4.3. Develop (idea generation, iteration, prototype)

4.3.1. Prototype I – Hello World!

Process and Self Reflection

Since fabricating the actuator requires many steps and several different materials, as well as taking a considerable amount of time, I chose to devote most of my attention to it as the first step. It was important to select an appropriate method for producing soft actuators. Two primary options were considered: 3D-printed silicone or laser-cut molds cast with silicone-like materials. It was the complexity and scope of the project that determined the choice between these methods. Ultimately, I chose the mold-fabrication route, which involved a systematic approach:

- Mold Fabrication: Transparent acrylic sheets were chosen for their laser-cutting compatibility and adhesive properties. The top, middle, and bottom sections were precision-cut using lasers and then assembled to form a cohesive mold.
- Actuator Creation: In the next phase, Ecoflex 0030 or 0050 silicone was mixed in equal parts by weight or volume with components A and B. After the mold were filling with this mixture, the molds were fabricated.

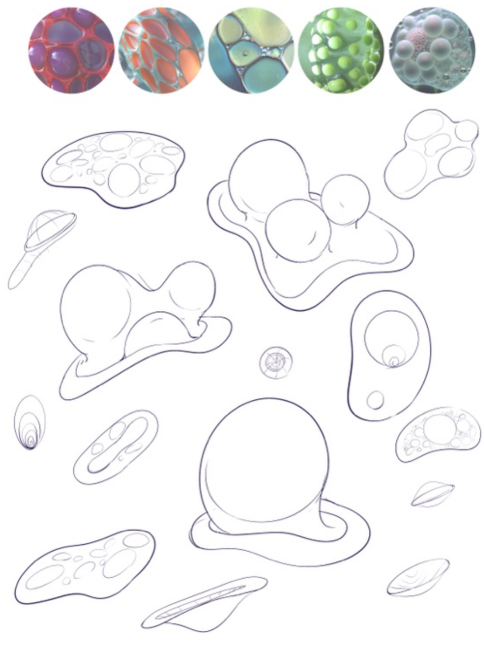


Figure 37 - Prototype I Concept Design Process, Sketching - sketched by author

In addition to gaining hands-on experience fabricating soft actuators, this prototype provided me with an opportunity to gain a solid understanding of soft robotics. I also gained a deeper understanding of the challenges involved in crafting a soft actuator as well as enhanced my ability to plan and execute subsequent prototypes as I developed my thesis.

Figure 38 - Prototype I Fabrication Process - fabricated and photographed by author

The Programmable Air (Programmable Air, n.d.) was used along with the Soft Robotics Tool Kit (Soft Robotics Toolkit, n.d.). To become familiar with soft robotics functions, processes, and different aspects, I reviewed all the projects and resources available on these two platforms to gain an understanding of soft robotics operations and applications. Programmable Air is used to control the soft actuator in this prototype by responding to two distinct buttons. Each button serves a distinct purpose in controlling the pneumatic system.

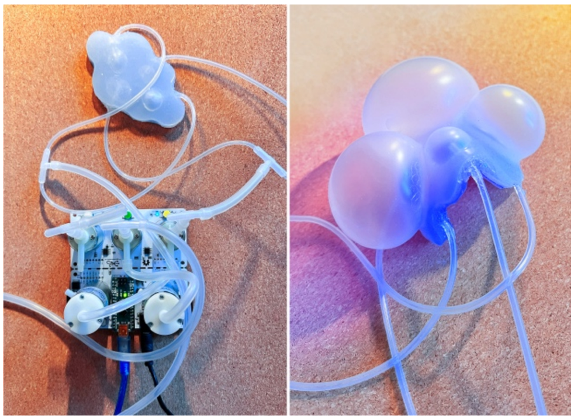


Figure 39 - Prototype I Pneumatic System - fabricated and photographed by author

The default setup for Programmable Air was to initiate inflation with the red button and deflation with the blue. However, due to the inclusion of dual actuators in my prototype, I reprogrammed and modified the system and the code to manipulate the actuator's movements via either button. The pattern of button engagement and release controls the actuator's behavior, channeling air pressure as needed. Consequently, inflation is button-activated, while deflation is a manual process, a workaround necessitated by the DC pump’s operational constraints.

Figure 40 - Prototype I, inflate and deflate states - fabricated and photographed by author

Since this is not the original function for which the Programmable Air Kit was designed and DC Motors (Pumps) are only one-way, it is not possible to inflate and deflate a device using a single pump. To inflate the actuator, I must fill the other way of the valve's outlet, and when I release my hand, the actuator will deflate automatically. Having experienced many limitations with the kit, I decided to do further testing of my ideas by building my own pneumatic circuit which is the next section.

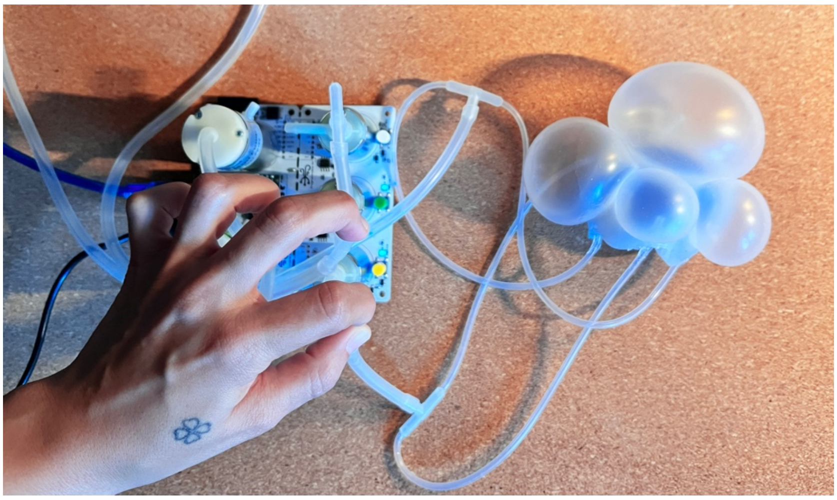


Figure 41 - Prototype I, limitations in modification -fabricated and photographed by author

4.3.2. Prototype II – HaiPalm, version I

Process and Self Reflection

During the development of my second prototype, I was primarily interested in creating a wearable soft actuator that would enable nonverbal communication without physical contact between people. The system was developed specifically to eliminate the need for direct contact between individuals during interpersonal interactions.

As a result of the Covid-19 pandemic, which significantly disrupted traditional modes of socialization and interaction, this project was born. During this period, the popularity of gestures such as handshakes declined, reflecting broader social norms as well as debates over whether to continue such physical gestures. There was a conflict between maintaining politeness and maintaining safety, highlighting a widespread dilemma.

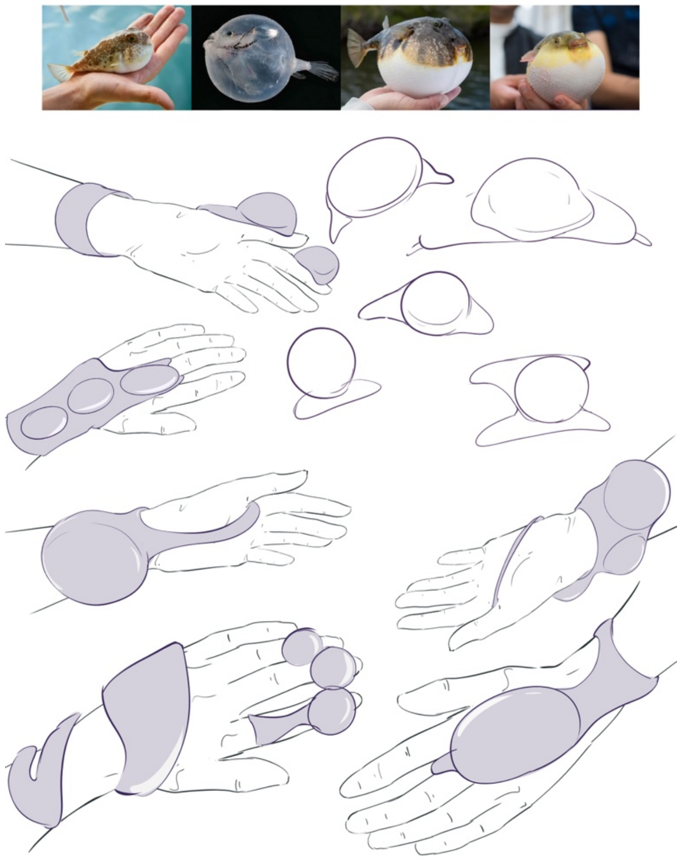


Figure 42 - Prototype II Concept Design Process, Sketching - sketched by author

Aiming to address this unique period in interpersonal communication, I created "HiPalm," a soft robot that acts as an intermediary communicator. By inflating to display a "Hi" sign, it indicates respect and interest in others. In addition, it can deflate to mimic a handshake, adding a synthetic layer over the user's hand. Using techniques similar to those used in my initial prototype, I designed this actuator with wearability, comfort, and sensor implementation in mind.

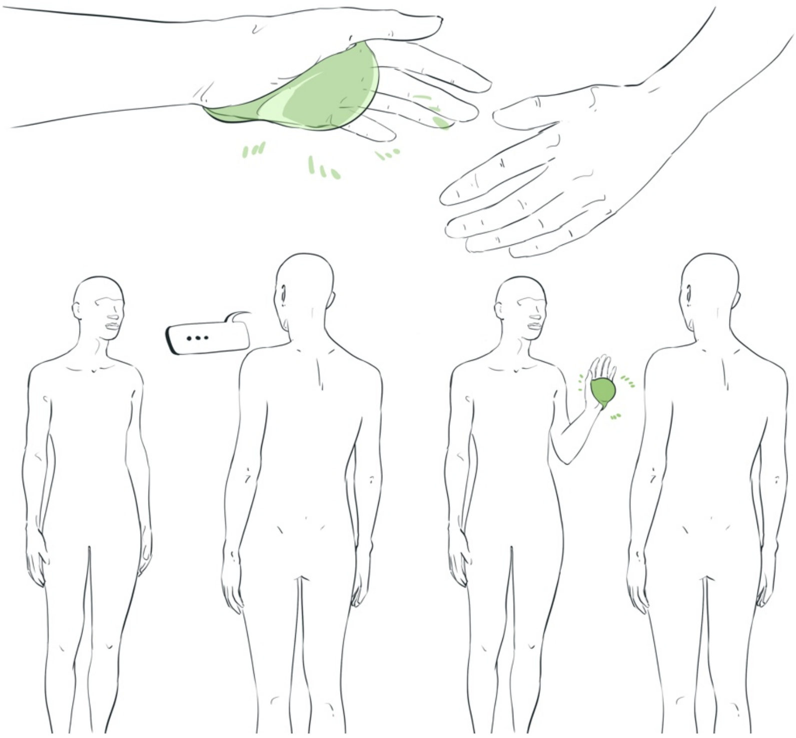


Figure 43 - Prototype II Interaction Concept, sketched by author

Figure 44 - Prototype II Fabrication Process - fabricated and photographed by author

Its inflation and deflation are controlled by an ultrasonic sensor, HC-SR04, in response to the proximity of another person's hand within a specified distance.

- Object distance to the sensor <= half of the sensor's range triggers inflation.
- Object distance to the sensor > half of the sensor's range triggers deflation.

Figure 45 - Prototype II, HiPalm Inflated, designed, fabricated and photographed by author

Throughout the development process, I considered the tactile experience of interacting with the soft robot for both the wearer and others, reflecting on how this synthetic material influences interpersonal communication. Wearability was a high priority in the prototype design, exploring design options for easy usage by individuals, and designing it in such a way that it looks strange attached to the body but also feels organic.

From left to right, these are the components I used to develop version II of this prototype:

- Programmable Air Kit
- HC-SR04 Ultrasonic Sensor

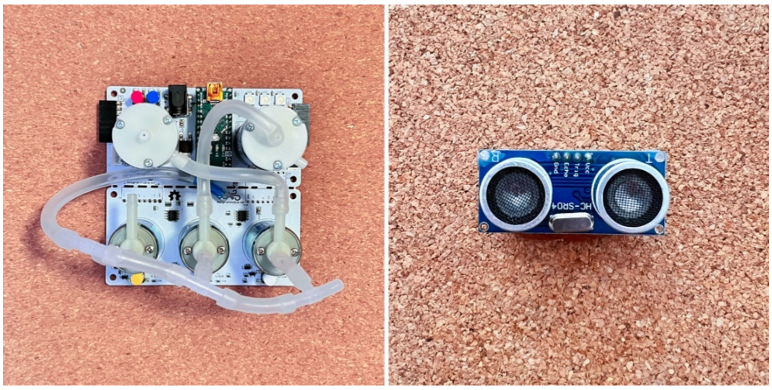


Figure 46 - Prototype II Pneumatic System and Sensor - photographed by author

I was also inspired to think more broadly about creating objects that facilitate open-ended communication between people than predefined ones as a result of this endeavor, which led me to reflect on the particular design and purpose of "HiPalm." The reflection on wearability and the objective of my design guided my future design decisions, seeking to create designs that enhance interpersonal interaction without focusing on specific functions or body parts.

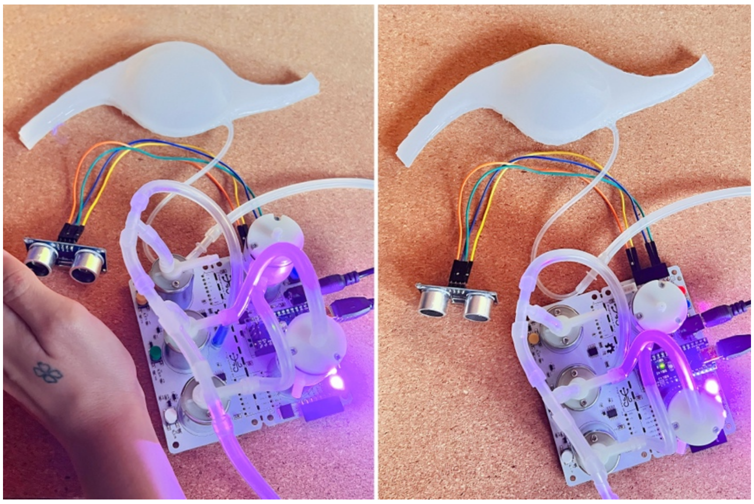


Figure 47 - Prototype II Pneumatic System and Sensor in Interaction - designed, fabricated and photographed by author

4.3.3. Prototype II – HaiPalm, version II

Process and Self Reflection

As a second version of this prototype, I decided to use air pumps and valves to create the same circuit and concept. To make this version wearable and lighter, I considered finding out other pneumatic components that would better suit my design criteria. The pumps I tired over this process were:

Photo	Name	Supplier	Flow Rate	Max Pressure	Power
Left	Air pump and vacuum DC motor	Adafruit	2.5 LPM	-55 kpa	4.5 V
Middle	370 mini vacuum pump	DFrobot	2.2 LPM	-58 kpa	5 V
Right	Negative pressure low flow air pump	Artsbu	0.5 LPM	-50 kpa	3 V

Table 3 - List of Air Pumps Testes in HiPalm, version II

Figure 49 - Air Pumps Tested in Prototype II, version II, photographed by author

From left to right, these are the components I used to develop version II of this prototype:

- Relay Shield for Arduino v2.1
- Arduino UNO R3
- 6V 2-Position 3-Way Air Valve for Arduino
- HC-SR04 Ultrasonic Sensor

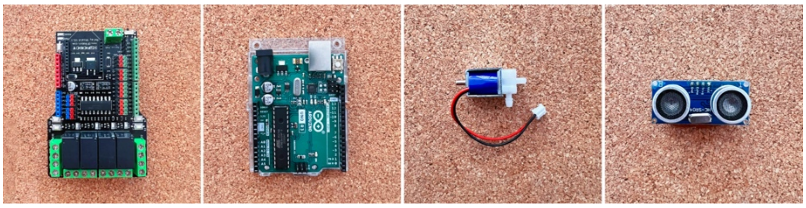


Figure 50 - Prototype II, version II, Electronics, photographed by author

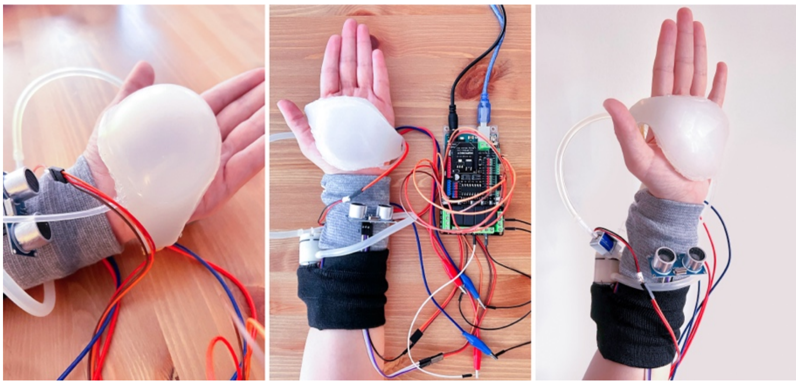


Figure 51 - Final Prototype II in use, version II, designed, fabricated and photographed by author

Despite making the second version using my designed circuit instead of the previous kit, it was still insufficient, since I wanted my design to be as intricate, light, and elegant as possible, both visually and functionally, but none of the versions using pneumatic soft actuators were adequate. Thus, I came up with my second prototype named "EmoLink."

4.3.4. Prototype III – EmoLink, version I

Process and Self Reflection

During this step, which acted as a core of my design process, my perspective and approach to electronics, concepts, techniques, connections, and circuit design changed significantly. In order to make my object less noisy, less bulky, and lighter, I decided to look for possible ways to do so. I also began to think about communication that was more connected to the human body and intentional communication between individuals, so I developed a concept for a device that would include several parts, each worn on a specific part of the body, that individuals could use to communicate over distances.

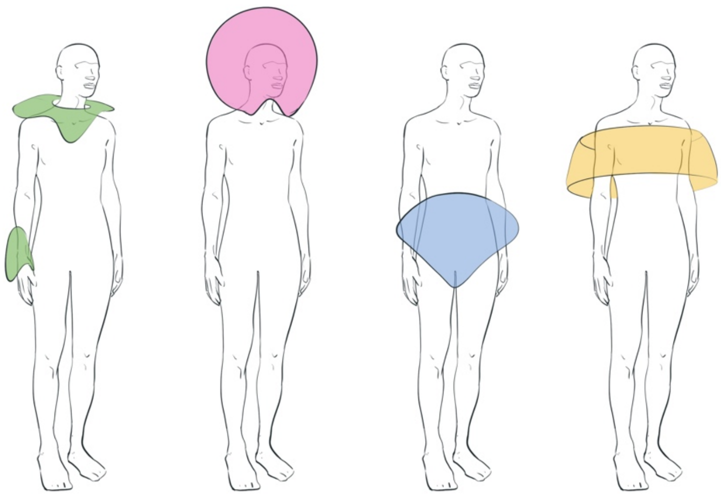


Figure 52 - Prototype III, chosen parts of the body based on Research - sketched by author

> According to Biga et al., "Somatosensorial is the group of sensory modalities that are associated with touch and limb position. These modalities include pressure, vibration, light touch, tickle, itch, temperature, pain, proprioception, and kinesthesia. This means that its receptors are not associated with a specialized organ but are instead spread throughout the body in a variety of organs."(Biga et al., 2019)

This helped me develop my concept around this idea that each of the parts could be worn in different places on the body. According to Dougherty and Tsuchitani, "the somatosensory systems process information about, and represent, several modalities of somatic sensation (i.e., pain, temperature, touch, proprioception). Each of these modalities can be divided into sub-modalities." (Dougherty & Tsuchitani, 2020) Among all modalities, I chose Touch and Temperature due to their ability to be artificially created as well as their association with touch. The following table shows the sub-sub modalities of each system.

Selected Sensory Modalities in Designing Symbiont		
Modality	**Sub Modality**	**Sub-Sub Modality**
Temperature	Warm/Hot	-
Touch	Discriminitive Touch	Touch
		Pressure
		Flutter
		Vibration

Table 4 - Prototype III Sensory Modalities, created by author, adopted from (Dougherty & Tsuchitani, 2020)

"The Tactile Emoticon (TE) system[40] included three haptic sensations, vibration, pressure and temperature, chosen based on affective touch literature as the main emotion discriminative features, being strongly related to skin receptors, and given the evidence for strong links between thermal skin changes and emotion." (Raison et al., 2015) "These are also common digitally implementable modalities that have not been explored collectively in a context where users can design touch by integrating these tactile sensations."(Price et al., 2022) For my thesis, I have created these two following tables based on the process and findings of another article named "The Making of Meaning through Dyadic Haptic Affective Touch."

Tactile Interaction	Modalities and Affective Meanings
Pressure	Sense of presence
	Sense of skin touching
Temperature	Identity
	Sense of skin touching
	Metaphorical mapping between emotion and temperature
Vibration	Extend physical touch

Table 5 - Modalities and Affective Meanings in Tactile Interaction in prototype III, created my author, adopted from (Price et al., 2022)

[40] The TE system comprises a pair of linked purpose-built interactive devices that enable two people to communicate remotely through touch. (Price et al., 2022, p. 21:8)

Tactile Interaction	Means of Realizing These Dimensions
Presence	Sense of bidirectional touch during interaction.
	Sense of touch interaction from the past.
	Levels of presence vs. presence/absence signal.
	Uncontrolled reactions (e.g., flinching) to touch and be touched.
Identity	Ownership of the body/hand.
	A person's idiosyncratic touch characteristics.
	A person's tactile preferences.
Sense of Control and Privacy	Having control over being touched.
	Controlling the body part that can be touched.
	Being able to offer a body part to be touched.

Table 6 - Key Design Requirements, created by author, adopted from (Price et al., 2022)

As I associated each of those modalities with specific sensors and actuators, I was able to design my prototype so that two individuals can communicate through these modalities using their devices or objects. Throughout the course of this prototype and my thesis, I have intended to design objects to communicate nonverbally and through sense, and this process is considered an open-ended feedback loop, in which one receives a signal and then responds with another signal. I chose sensors and actuators based on their size, flexibility, and form (small, flexible, thin). This association can be seen in the diagram below:

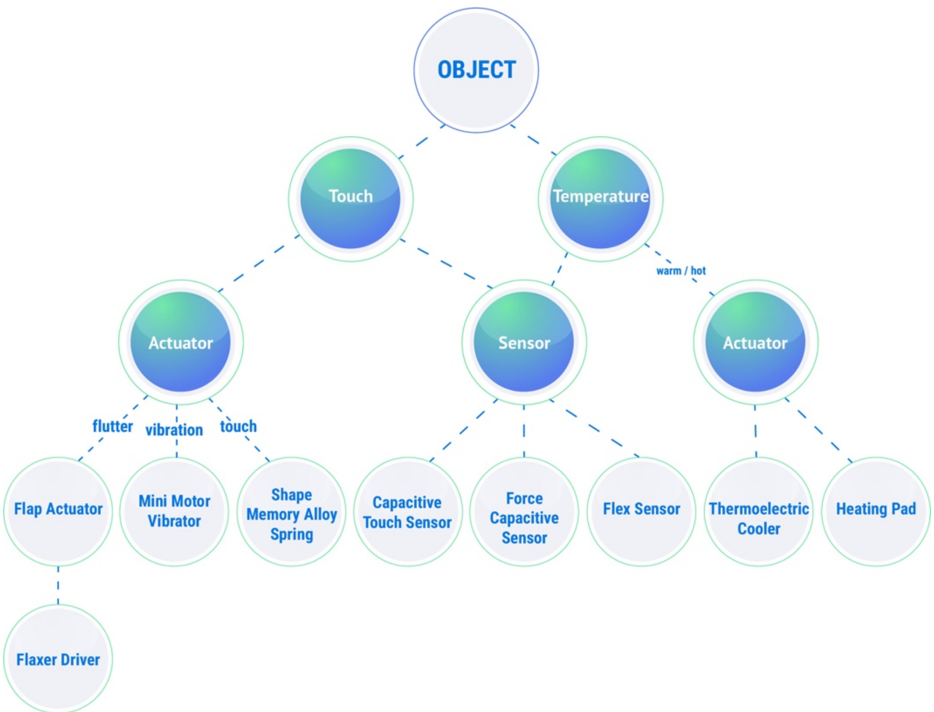


Figure 53 - Diagram of Chosen Sensors and Actuators based on their Associated Sensory Modalities, created by author

Also as mentioned before, having experience with pneumatic systems I learned for my thesis I need explore more to possibilities for controlling soft actuators. Even though they are not many based on my research provided in literature reviews, all are innovative but more complex and require much more effort to build, design, and program the control logic. Using an electromagnetic field-driven soft actuator to drive a custom voice coil matched my concept well due to its light, minimal setup, and silent operation. Using that, I would be able to design my object more in harmony with the human body and more appealing aesthetically, which has been my gear from the beginning, since the biggest concern with pneumatic actuators was their loud functions, heavy weight, and aesthetics. These are the components I used to develop this prototype from top left to right:

- Arduino Nano 33 IoT
- Mini Motor Vibrator
- Adafruit DRV2605L Haptic Motor Driver
- Flap Actuator (equipped with 10mm N52 neodymium magnet and planar copper windings)
- Spectrasymbol Flex Sensor
- Microbots Driver (H-bridge Module)
- Trill Flex Capacitive Touch Sensor
- Electric Heating Pad (10cm * 5cm)

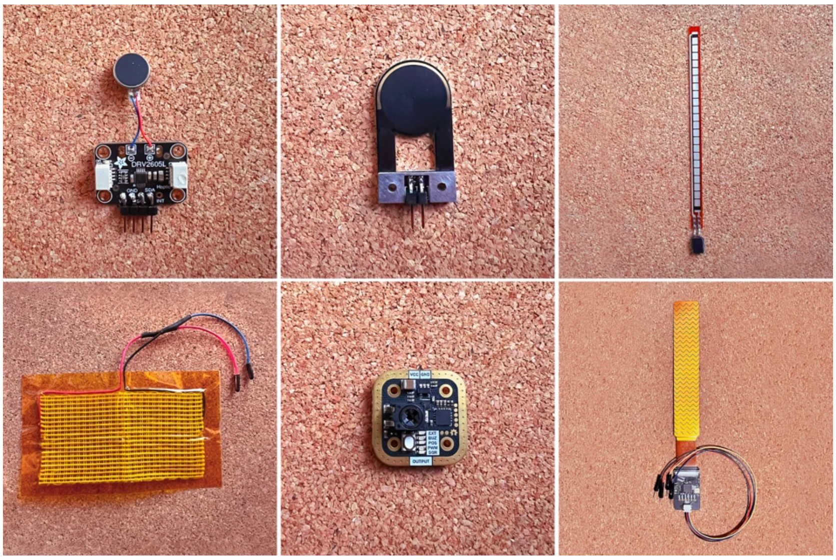


Figure 54 - Prototype III Electronics, version I, photographed by author

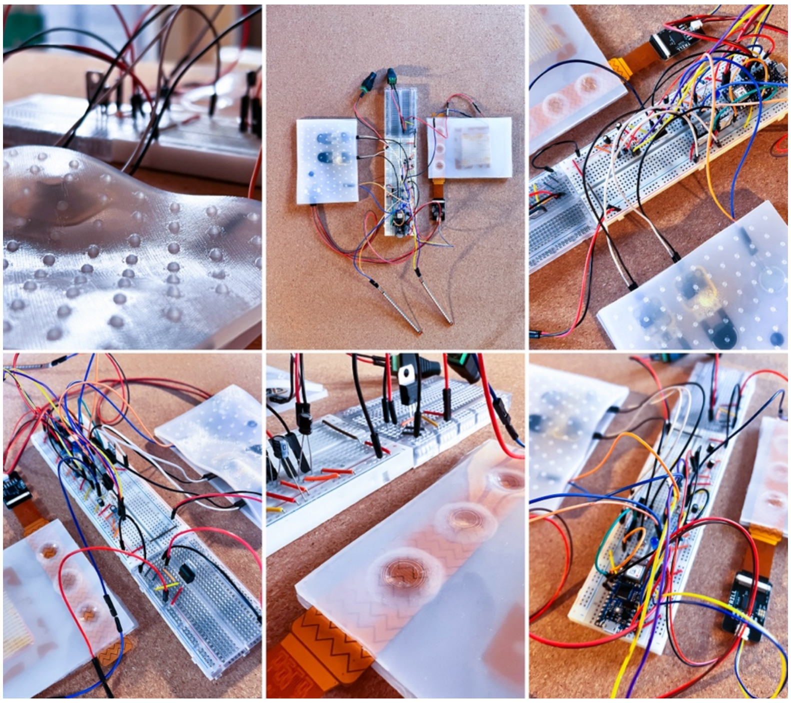


Figure 55 - Prototype III Circuit and Electronics, version I, designed, fabricated and photographed by author

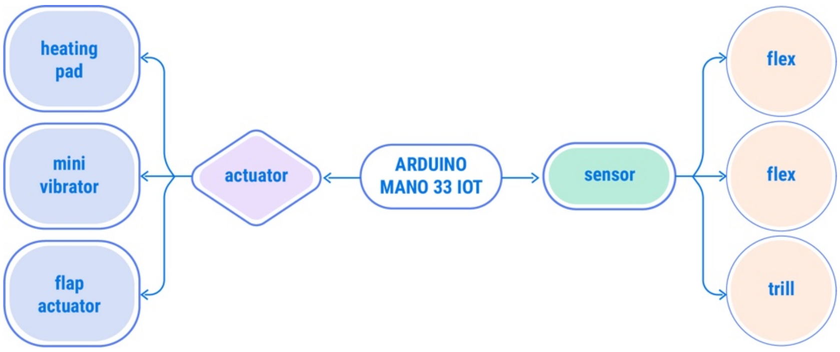


Figure 56 - Prototype III, version I, Logic Diagram, created by author

I decided for the first prototype to design a circuit that included all the sensors and actuators in one, despite the idea of developing two objects to communicate. Initially, I developed the logic, which I then implemented in two separate circuits, one for actuators and one for sensors. To allow the circuit containing the sensors to control the circuit containing the actuators, I used serial communication between the two circuits and common ground.

Figure 57 - Prototype III Interaction Concept, version II, sketched by author

My sketches began with ideas about design objects that would be attached to various parts of the body. As the prototype progressed, I focused more on developing the functional circuit and selecting reliable electronics, so I kept the fabrication process and aesthetics simple to allow more time for programming and circuit design. In addition, I also added texture to the silicone skin to investigate the sensation as well as the aesthetics of having texture in the design. Consequently, I also gained experience designing and adding texture to fabrication processes, which requires more consideration in design. Adding texture to the silicone actuator was very appealing and provided an additional layer of engagement, especially when in contact with vibration activation.

The fabrication process for this prototype includes not only making the soft skin I am designing, but also fabricating multiple 3D-printed molds to test various forms, thicknesses, textures, and even adding colours during casting. During this step, I intend to be able to make more informed decisions about my next prototype, which will serve as my last prototype. It is also important to examine the material in different conditions and study how it affects and is affected by other components, in particular different sensors, and actuators in the circuit. As a result, I will need to perform more silicone tests (forms, textures, colours) to bring my prototype closer to the final design, especially in terms of forms (tentacles, flat, etc.), texture (pattern and scale), embedded bubbles, colour, and material transparency.

4.3.5. Prototype III – EmoLink, version II

Process and Self Reflection

The first changed element in this prototype was excluding the heating pad due to its in-harmonic relationship to other components. Although selecting that as a part of the previous prototypes was based on the design criteria and research, I chose to center the concept more around the materiality of tactile sensation as the design progressed, so temperature no longer served that purpose. Upon excluding that, I began to implement Shape Memory Alloy springs, which are described at the beginning of this section. Therefore, all behavior in the design was perfectly aligned with my intentions for this object. Additionally, the SMA springs - called nitinol-short for nickel-titanium - were activated at a slow rate, which made them seem even more organic. Added texture to the silicone skin made the silicone skin moving over the body feel more like the passive touch of a creature. This allowed a metaphorical meaning to be conveyed to the other end of the communication.

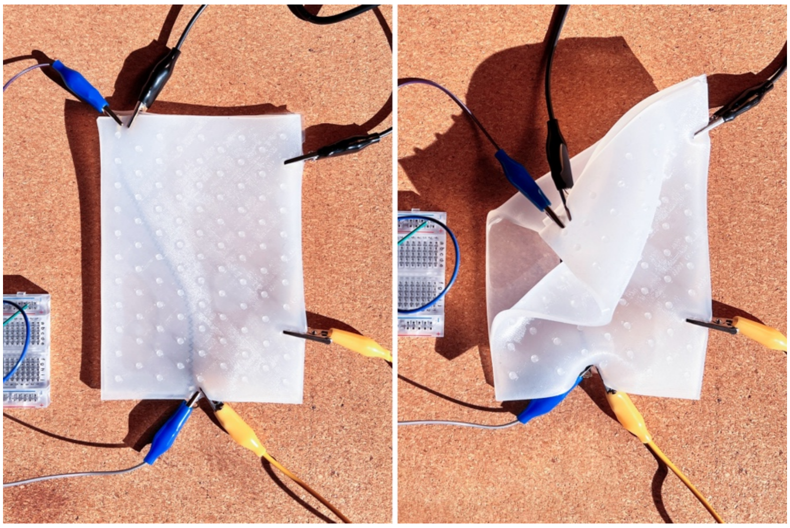


Figure 58 - Prototype III, version II, Activating SMA spring, fabricated, tested and photographed by author

As mentioned before, I wanted to further develop the previous version by tweaking the communication logic to bring it one step closer to the final goal, which was to communicate over the internet in accordance with tactile internet considerations that were discussed in chapter 3 of the theoretical review, including reliability and real-time feedback. Therefore, I designed two separate circuits, each with the same sensors and actuators, which communicate over the internet using MQTT protocol. Sensors on each circuit could control actuators on other circuits, so individuals could send and receive tactile signals simultaneously through their objects.

The Trill Capacitive Touch Sensor was another component I had to replace due to its tendency to detect changes in capacitance because of an object near the sensor surface that is either conductive or dielectric. Since I must embed the sensor in silicone skin, which significantly decreases the sensor's performance, I decided instead to use Force-Sensitive Resistors instead, which convert applied force into an electrical signal that can be measured. Although I made multiple silicone skins with different thicknesses (from 1.5 mm to 4 mm), the trill sensor wasn't able to accurately detect a touch in any of them. Although it mostly worked well enough, it wasn't reliable enough like other sensors. Additionally, I had to conduct many tests and different logic to adjust the sensor and its threshold so that it could detect touch from beneath the silicone skin, which isn't something it's made for. A FSR's resistance decreases when a force is applied to its active surface, thus making it a good choice based on my concept, material, and criteria. These are the components I used in version II of EmoLink Prototype:

- Arduino Nano 33 IoT
- Microbots CoilPad (equipped with 10mm N52 neodymium magnet and planar copper windings)
- Mini Motor Vibrator
- Microbots DriveCell (H-bridge Module)
- Flexinol Spring (40±6 coils, 0.015” (0.38mm) wireØ, 90°C)
- Ohmit Force Sensing Resistor FSR06
- Spectrasymbol Flex Sensor

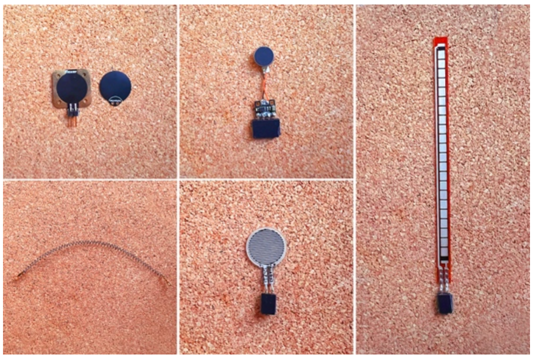


Figure 61 - Prototype III Electronics, version II, photographed by author

In this setup, each circuit is connected to a total of 6 MQTT topics, with a division between publishing sensor data and subscribing to receive actuator commands:

1. **Publishing Topics (Sensor Data Outgoing)**: Each circuit publishes the data from its sensors to three distinct topics, one for each sensor. These topics are used to transmit the sensor readings to the MQTT broker, from where they can be distributed to any subscribed clients (in this case, the other object).
2. **Subscribing Topics (Actuator Commands Incoming)**: Each circuit also subscribes to three topics to receive commands that control its actuators. These commands are based on sensor data from the other device. By subscribing to these topics, the object can receive updated values and adjust the actuators accordingly.

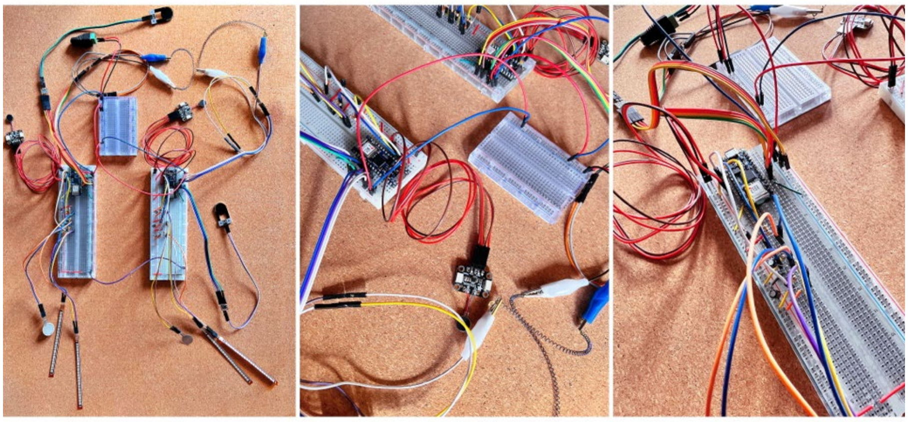


Figure 62 - Prototype III Circuit and Electronics, version II, designed, fabricated and photographed by author

Each object is actively communicating through 6 MQTT topics - 3 for publishing its own sensor data and 3 for receiving sensor information from other objects so that it can control its actuators. As a result of this bidirectional communication, the two devices can react in real-time to each other's sensor inputs through interactive and responsive tactile feedback.

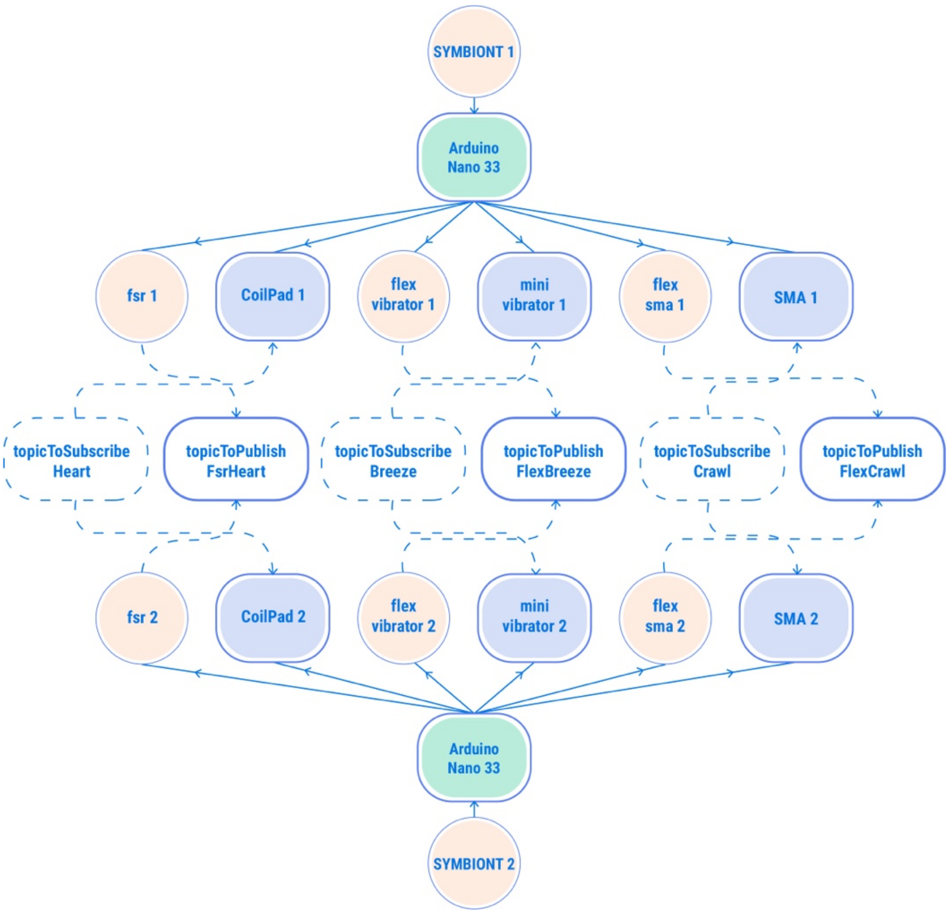


Figure 59 - Prototype III, version II, Logic Diagram, created b author

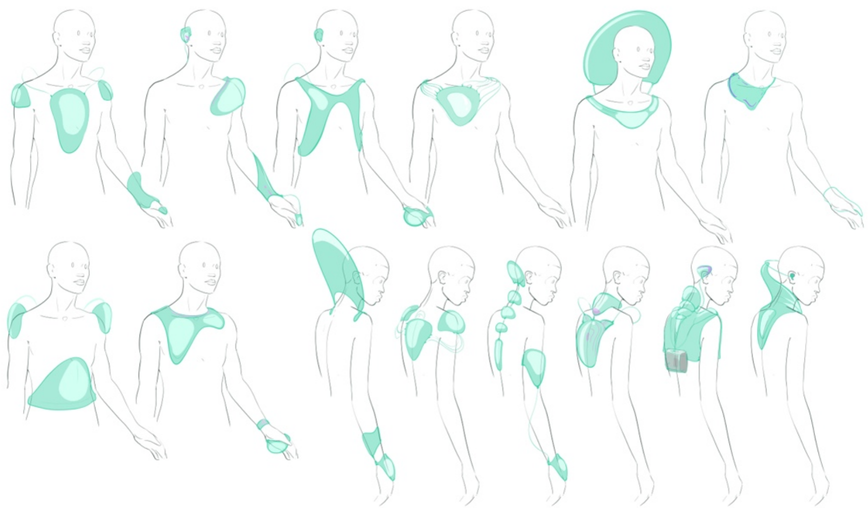


Figure 60 - Prototype III Concept Design, version II, Wearable EmoLink, sketched by author

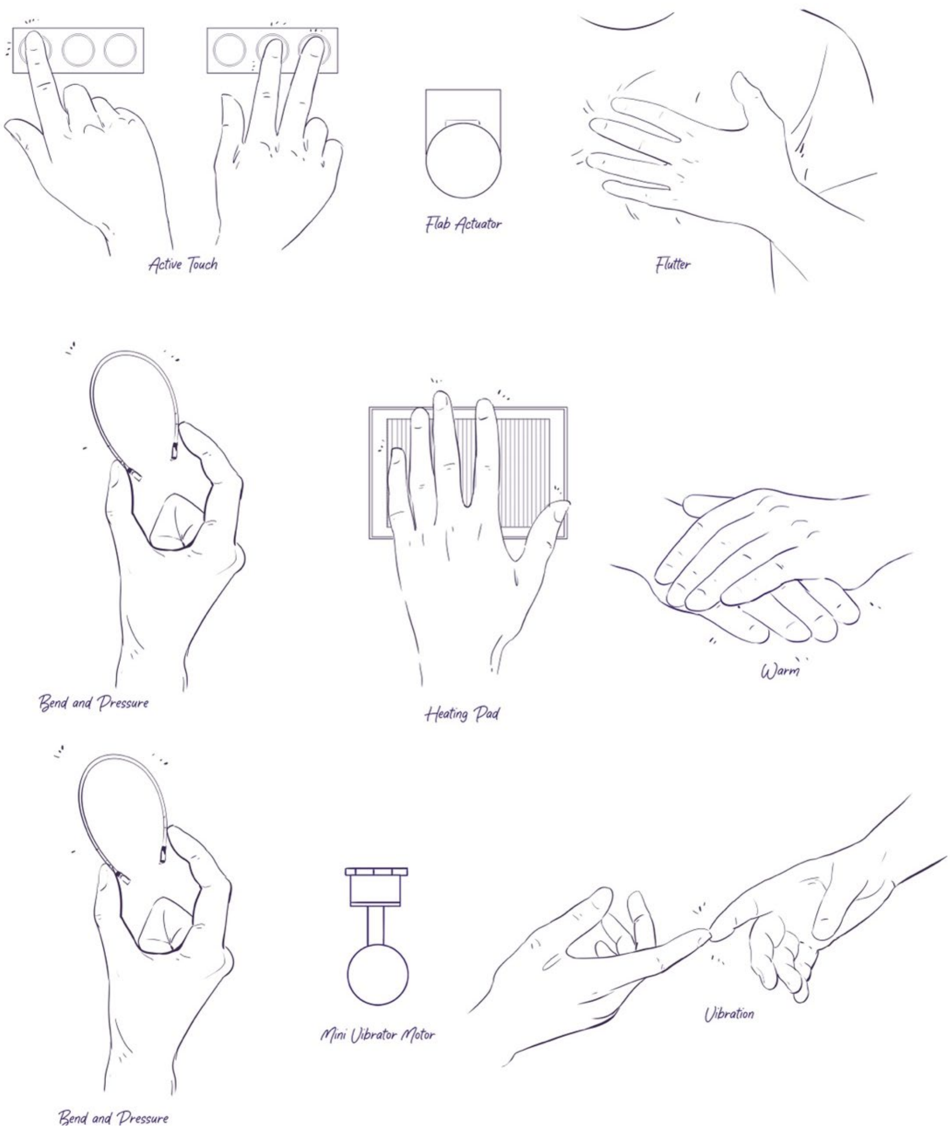


Figure 61 - Prototype III Interaction Sketch with Used Components, version II, sketched by author

4.3.6. Prototype IV – OctoTouch

Process and Self Reflection

During the previous prototype, EmoLink version II, I developed a functional and reliable system along with components that I aimed for initially even before writing my thesis. It was designed to be worn easily anywhere on the body, and the individual could engage in tactile communication by using their offered body part.

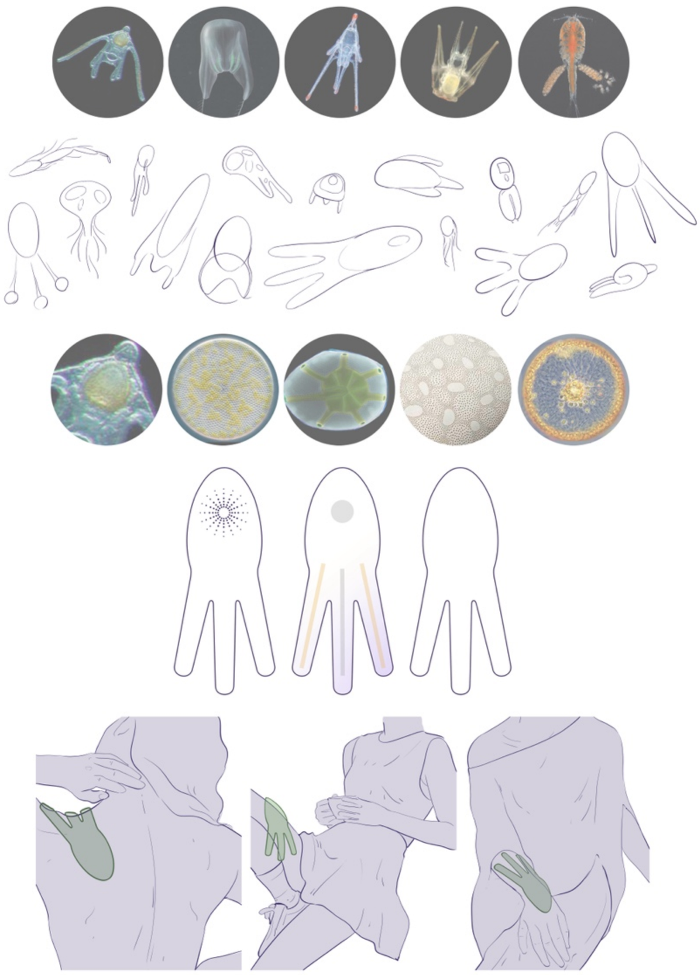


Figure 62 - Prototype IV Interaction Concept and Concept Design, sketched by author

Using the same electronics from the previous prototype, OctoTouch enables both individuals to send and receive documents simultaneously due to the reliability of MQTT communication protocol. Biomorphic design significantly affects the form and texture of the soft robot body. The intention was to create a sensory tactile object using texture and soft materials.

Following the criteria that was mentioned in the previous prototype regarding the modalities and means through specific tactile interaction and dimensions, I defined three metaphorical states (section 4.4.7.) including vibration, flutter, and touch (passive touch) and connected each sensor and actuator to its associated emotional states of touch:

- Flex Sensor > Control SMA Sparing >> Passive Touch of something/someone on the body.
- Flex Sensor > Control CoilPad >> Flutter of Heart.
- FSR Sensor > Control Mini Motor Vibrator >> Vibration (Passive/Active Touch and Pressure).

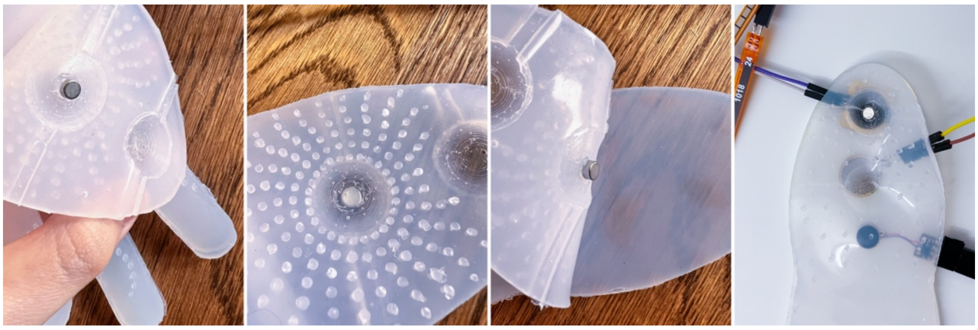


Figure 63 - Prototype IV, Heart in OctoTouch Function using CoilPad and Magnet, fabricated photographed by author

In this phase, I became more focused on the oceanic creature using it as my mood board and visual inspiration and then designing my object with an association with the form of my components (sensor and actuator), since everything related to circuit design, logic of control, component behavior, has already been designed in the previous step. I also decided to use a geometrical pattern for the texture of this prototype. I encountered some difficulties in terms of my technique of making soft actuators using 3D printing molds. In all of my prototypes, at least one side was flat, which worked fine at first, but I need a more dynamic form, which I'd like to explore and work on more to design something that is both nature inspired and versatile enough for any environment!

Figure 64 - Prototype IV Fabrication and Placing Components, designed, fabricated and photographed by author

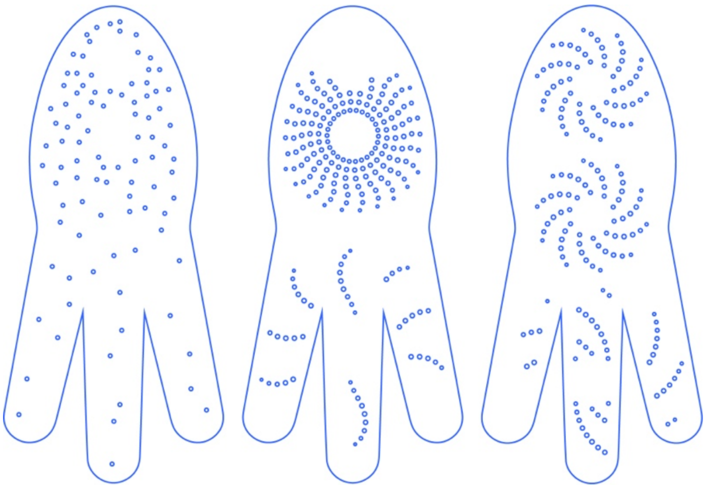


Figure 65 - Prototype IV, texture, and mold design, designed by author

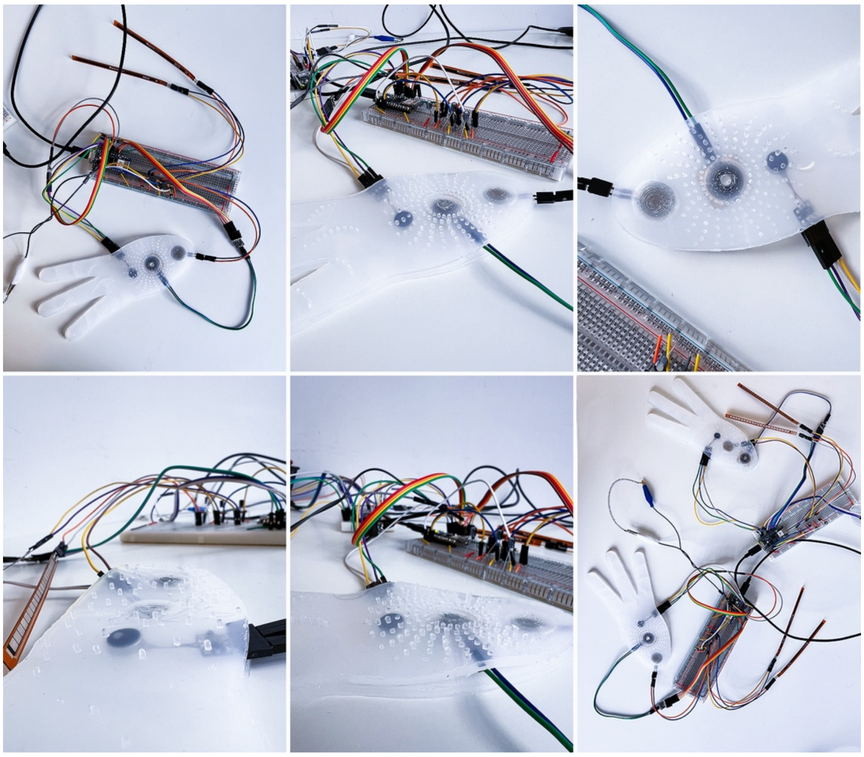


Figure 66 - Prototype IV, Final OctoTouch Setup, designed, fabricated and photographed by author

4.3.7. Prototype V – Rapid Prototyping, Mini-Circuits

Besides making the 4 prototypes, I also used rapid prototyping to create mini-circuits tests to explore and experiment with different types of electronics and how they are utilized and arranged. The steps involved direct 3D printing actuators using clear engineering resin and mold making with 3D printing like the other prototypes.

This process began with sketches, followed by detailed 3D modelling, and finally 3D printing of the molds for silicone casting. Using this method, I experimented with different forms, thicknesses, textures, and colors to test various components. Hands-on experimentation was crucial since it allowed me to explore and refine the material use and functionality of components in a real setup. With this iterative process, the final Symbiont could be designed and functioned more accurately, resulting in a more accurate integration of material properties with component behavior.

Figure 67 - Rapid Prototyping Fabrication Process, sketched, 3d modelled, fabricated and photographed by author

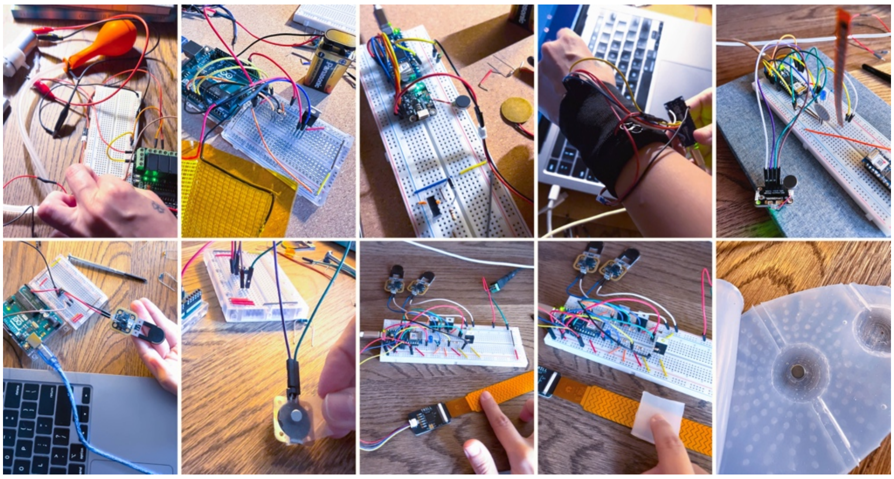


Figure 68 - Experimenting with Different Components and Ideas through Mini-Circuits, designed, made and photographed by author

I began designing these 3D-printed actuators (material: transparent engineering resin) with sketches of the various sensors and actuators. As a result, I was able to conceptualize a body that accommodated not only their functions and forms but also considered the use of translucent materials. To explore the tactile and visual impact of textures at different scales—both large and small—I opted to depart from traditional geometrical patterns in favour of organic ones. In addition, I intended to examine how a completely biomorphic body, inspired by microorganisms would affect the experience.

3D Printed Prototypes: Modelling Logic and Process

I designed this model with a series of lines on the body, where points were placed along these lines, eventually evolving into protrusions. The first step was to differentiate three types of point placements organically, which differed based on their beginnings. Some started with points closer together, while others were farther apart. The typology of these placements plays a critical role in the subsequent steps.

In the next step, the points were transformed into volumes using an algorithm named Cocoon. However, this transformation into volumes occurred after a specific operation on determining the force field between points in each strand. As an example, if points are closer to one another, their volumes seem to attract each other. As a result, point strands begin to take on an organic appearance, resembling fluid. Considering the distance between each point in each strand, the algorithm models them separately. The first part of the algorithm sorts of points into three distinct types, specifically designed to achieve varied organic shapes in the outputs.

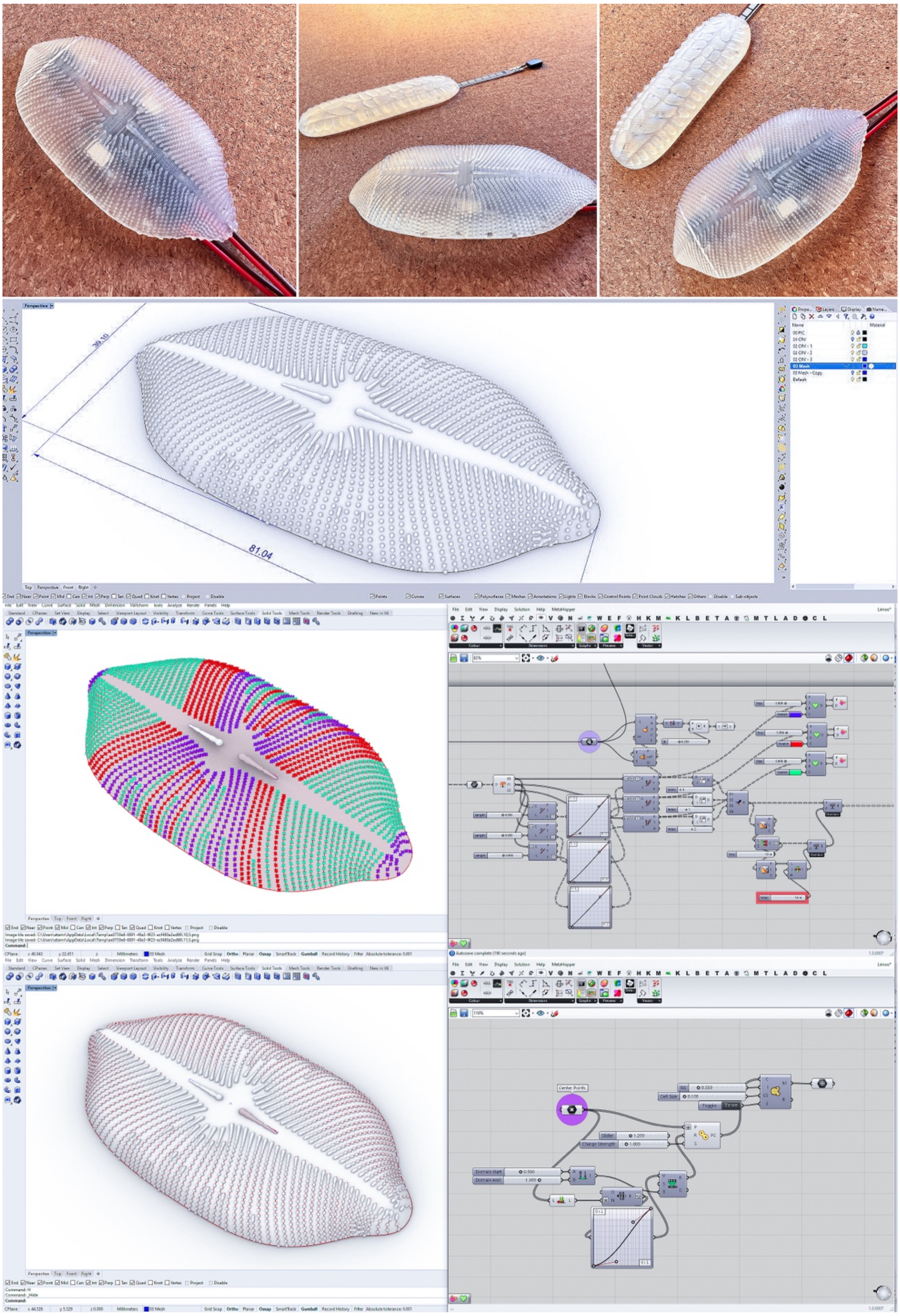


Figure 69 - 3D Printed Prototype Modelling Process Using Rhinoceros version 8, designed, 3D modelled and printed by author

4.4. Deliver (SYMBIONT creation)

4.4.1. Building upon Prototypes: Annotation

Prototype Version	Image	Outcomes - Notes
Prototype I Hello World!		• It's too loud and bulky. • Modifying the kit was challenging due to the lack of proper documentation regarding component connections and specific pin mappings. • An object with numerous tubes may become even more peculiar, which is great, but must be managed with caution. • Although it's necessary, placing fabric under the silicone skin creates a somewhat disjointed feel, both in terms of material aesthetics and tactile experience.
Prototype II HiPalm		• Holding the pumps against the body became quite challenging once they were activated due to their intense sensation. • The touch and visual experience proved interesting, reflecting both my own observations and feedback from others. • The soft and translucent material was visually appealing on the body, creating an organic-like tactile experience. It even resembled a creature's flesh, especially when inflated! • Placing the device on the palm was considered an intriguing decision, as noted by feedback from others. • Even after designing my own circuit to accommodate two pumps, the setup still felt bulky and noisy.
Prototype III EmoLink		• With a 5V power supply, the contraction phase took approximately 6 seconds, and the cooling down period lasted 3 seconds. • The capacitive touch sensor was highly responsive; however, it failed to detect touch through even a very thin silicone skin due to its touch-based sensitivity. • Its texture gave it a lifelike appearance, resembling a real creature. • The springiness of the behavior felt natural, akin to a creature in motion, which I plan to refine through coding logic. • Texture interaction during the contraction of the skin was ideal for passive touch. • The texture was both touchable and visually pleasing, striking the right balance.
Prototype IV OctoTouch		• Experimentation was guided by the properties of the materials. • MQTT proved to be very reliable overall, though there were occasional disconnections when using cellphone data. • The circuit design, connections, and code have been finalized for the Symbiont. • The capabilities of both sensors and actuators have seen significant improvements. • The sensation of touching embedded bubbles in the material was highly satisfying!
Prototype V Rapid Prototypes and Mini Circuits		3D print tests: • The material had a yellowish hue and lacked full transparency. • The material's rigidity and lack of flexibility compared to silicone hindered the functionality of sensors and actuators. • Conducted 3D printing tests with diverse forms and textures, such as bubbles, geometrical shapes, natural patterns, and even experimented with color. • The organic-like textures felt pleasant to the touch. Rapid Prototyping and Mini Circuits: • Experimenting with a variety of circuits and code for each component was immensely beneficial. • Monitoring the behaviors and thresholds of sensors and actuators was a critical part of the process. • The sensors and actuators exhibited engaging and tangible behaviors. • Testing and experimenting with different forms and textures has been immensely helpful in creating a clear plan for designing the Symbiont. This includes both the design aspects and the way components interact with material properties.

Table 7 - Outcomes and Annotation on Prototypes, created by author

4.4.2. Process and Self Reflection

As a result of many prototypes developed, reflections and findings (Section 4.4.1), I was able to design and make my Symbionts by starting to collect another mood board (Appendix - 9). I collected this mood board based on my latest navigation through thesis which was inspirations from the transparent body of deep oceanic creatures, (I have always been inspired in them as mentioned in section 4.3.6.) which is very similar to silicone aesthetics. In addition, their minimal internal organisms were another reason I related them to my concept since I was trying to achieve a complex functional design while keeping the final look minimalist.[41]

Following the collection and analysis of visual inspirations through annotation, I developed a morphology chart that compares the different forms and textures associated with each component (sensors and actuators) according to their forms and functions. Finally, I designed Symbiont's aesthetic by merging and synthesizing 28 different ideas derived from morphology charts and in accordance with the metaphorical means I designed before.

As mentioned earlier, Design by Metaphor was one of my thesis approaches. All three metaphors, including active touch, passive touch, and intra-active touch (section 4.4.7.) have contributed to the creation of this sensory experience through Symbionts, which enable individuals to communicate together, either based a predefined meaning (between them) or in a highly nuanced fashion.

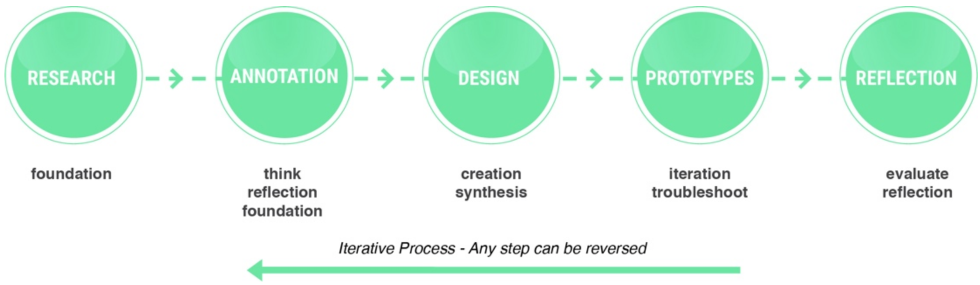


Figure 70 - Symbiont's design through Iterations and Steps, created by author

Through iterations, (as shown in Figure 70 - going back to any stage to reflect, think, and ideate again was part of iteration as well), each prototype, reflection, and annotation shaped the final design. In essence, Symbiont is the outcome of all these steps. For instance, the logic and communication and circuit control were honed with EmoLink prototype version II (Section 4.3.5), while testing and adjustments with circuits embedded in silicone skin were explored through the OctoTouch prototype (Section 4.3.6). Also, the final sensor thresholds, skin thickness, textures and components' adjustments came together after several rapid prototypes throughout the Develop phase.

[41] For researchers and designers in soft robotics field, sea creatures have always been a source of inspiration because of their movements and flexible bodies. (Early Soft Robot, Appendix C - 2)

4.4.3. Symbiont's Mood Board Annotations

As mentioned earlier, and mirroring my prototyping process, I began by creating a mood board (Appendix -9). I then annotated the board based on my design process and objectives, which is presented in Figure 74.

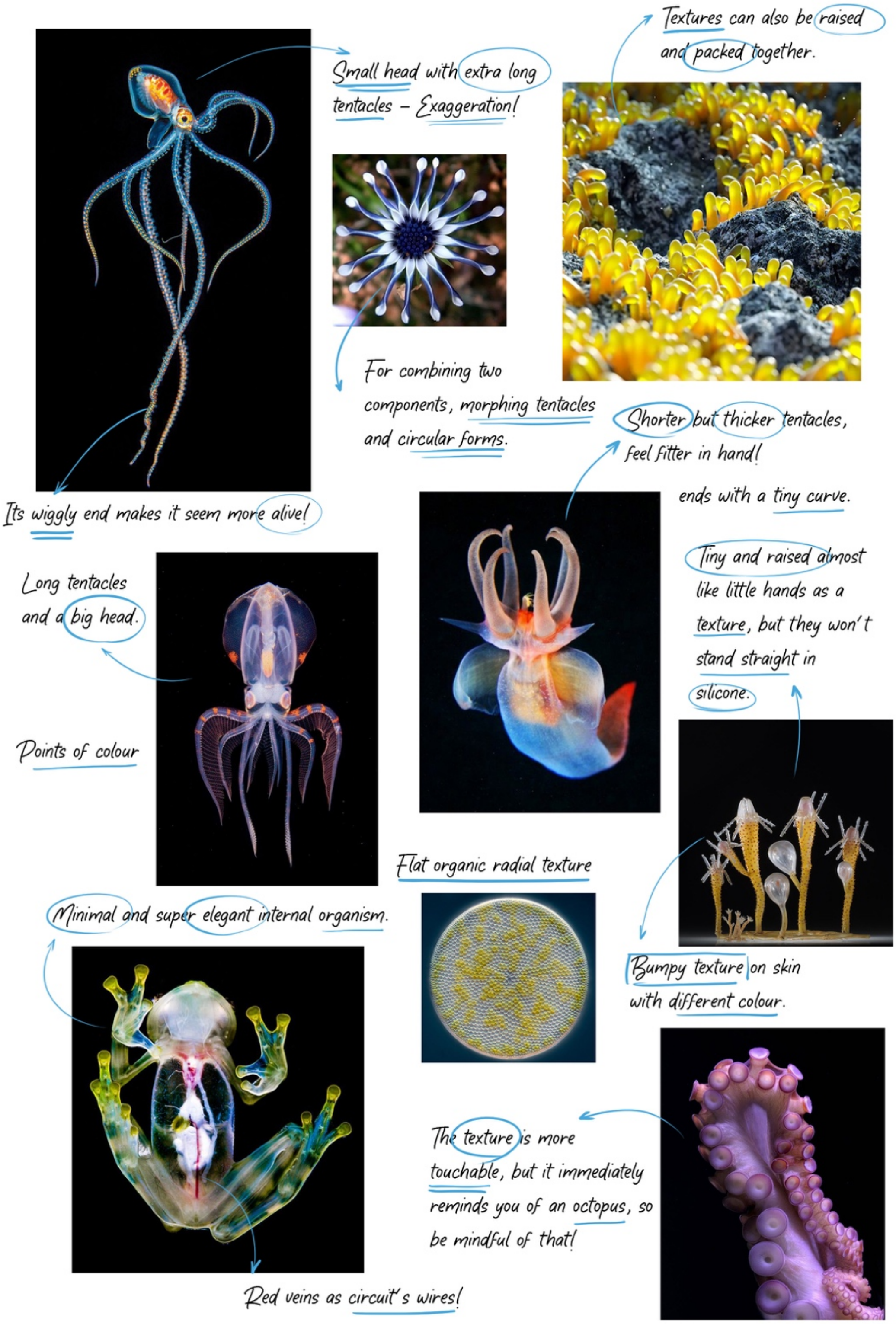


Figure 71 - Symbiont's Moodboard Annotations, created and annotated by author

4.4.4. Morphological Chart

By categorizing sensors and actuators according to their shapes and functions, I created a morphology chart to illustrate the various forms and textures associated with each component. I based this step on the visual inspirations I drew from my mood board and other findings throughout the process. During the aesthetic design process, it was important to consider sensors and actuators, especially due to their sensitive and intricate functions and behaviours.

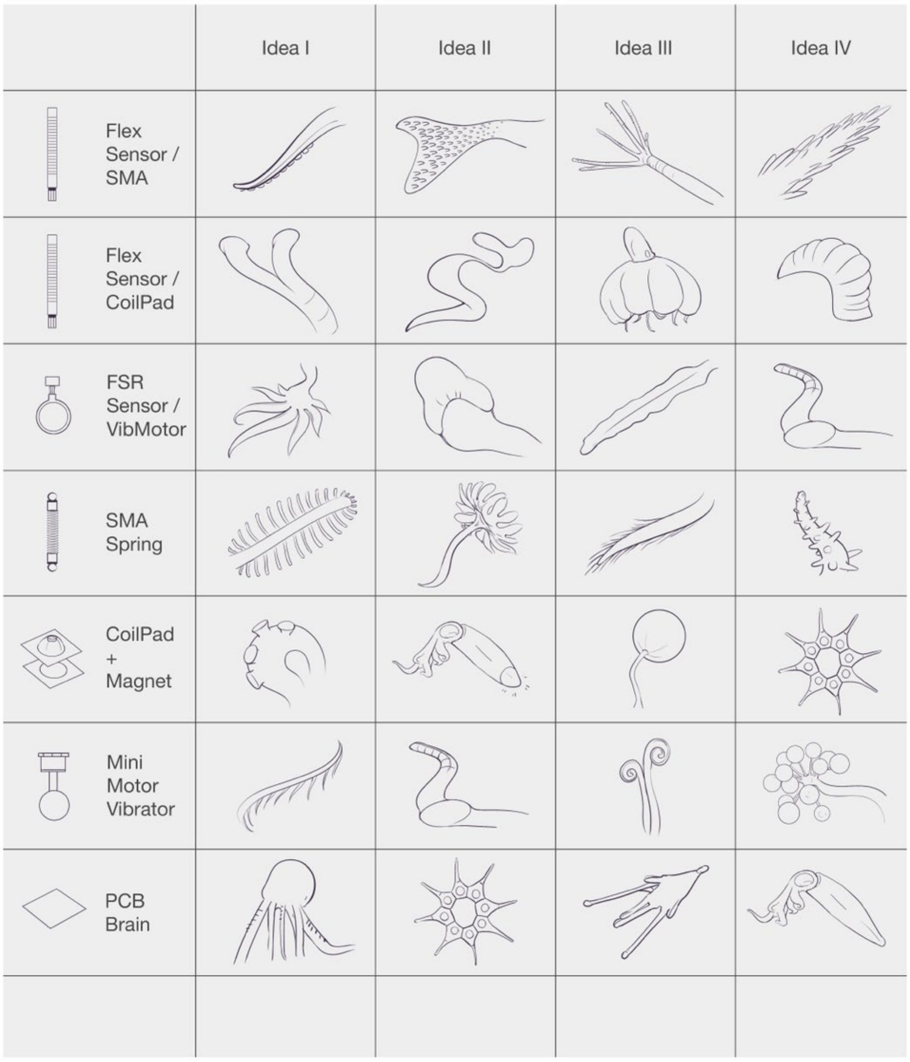


Figure 72 - Symbiont's Morphological Chart, created and sketched by author

4.4.5. Morphological Analysis

The analysis employs the morphological analysis methodology outlined in section 2.2.4. Presented below are the outcomes and results of this method in designing the Symbiont.

Elements	Components
Define the Problem	The design aims to create a biomorphic soft robot object named Symbiont to facilitate tactile communication between two individuals.
Identify Parameters	Table 8.
Develop a Morphological Box	Figure 75.
Populate the Matrix	Table 8.
Implement Evaluation Strategies	• Minimal in aesthetics • Function links to associated metaphor • Visual links to component's forms and function • Biomorphic texture • Engaging touch pattern • Nature-Inspired, not replicated
Generate Solution Concepts	Figure 75.
Analyze and Select Solutions	Figure 75.
Detail Selected Solution	Analyzing the results of the morphological chart and analysis, I generated ideas about the form and texture of the Symbiont through sketches shown in figure 78.

Table 8 - Symbiont's Morphological Analysis Steps based on (Evbuomwan, 1995), created by author

Parameters	Detail	Possible Ideas from Chart	
Sensor links to form and function	*Prototype IV*	Flex (SMA)	1 / 3 / 4
		Flex (CoilPad)	5 / 6 / 8
		FSR	9 / 10 / 12
Actuator links to form and function	*Table 3*	SMA	13 / 14 / 15 / 16
		CoilPad	19 / 20
		Mini Motor Vibrator	22 / 23 / 24
Sensor links to associated metaphor	*Table 3*	Flex (SMA)	1 / 3 / 4
		Flex (CoilPad)	5 / 6 / 7 / 8
		FSR	9 / 10 / 12
Actuator links to associated metaphor	*Table 3*	SMA	13 / 14 / 15 / 16
		CoilPad	17 / 18 / 19 / 20
		Mini Motor Vibrator	21 / 22 / 23 / 24
General biomorphic aesthetic design (Form and Texture)	*Table 3*	All ideas	
Silicone as skin material		All ideas	
No Color and Translucent-white		All ideas	
Minimal aesthetic - not replicating a living creature		5 / 6 / 9 / 10 / 11 / 12 / 13 / 15 / 16 / 19 / 20 / 21 / 22 / 26 / 27	
Tactile Sensory object		All ideas	
Communication through tactile		All ideas	
Brain space for embedding circuit into silicone skin		25 / 26 / 27 / 28	
Easy to assemble/disassemble		All ideas	
Power management	Section 4.4.8.	-	

Table 9 - Symbiont's Morphological Analysis, created by author

Developed in the morphology box, which then was evaluated through morphological analysis and aligned with the thesis objectives, Figure 77 represents the culmination of 28 distinct ideas for designing Symbiont's various parts. Multiple long components, like flex sensors and SMA springs, were included in the design selected for Symbiont. As part of my decision, the scope and fabrication considerations were also taken into account, in order to make sure the design was both doable and well suited to my goals.

Figure 73 - Symbiont's Morphological Chart Results and New Ideas, sketched by author

4.4.6. Communication Between Two Symbionts

Symbiont is the designation for a soft robot object I designed to facilitate interpersonal communication through tactile means. Through many iterations, my thesis culminated in the creation of two biomorphic soft objects. These objects allow individuals to not only explore various textures and sensations but also to communicate with one another via tactile signals. Although this form of communication may not convey specific messages like verbal communication, it fosters a unique layer of interaction and communication. My aim was to design these objects to intrigue and engage humans through their sensory elements, texture, biomorphic shapes, and metaphorical meanings. I envisioned Symbiont to provide an experience, regardless of whether it is shared in the same space. Furthermore, I intended for Symbiont to be versatile, enabling users to place it anywhere on their body, thus allowing everyone to interact with, communicate through, and experience Symbiont in myriad ways.

Figure 74 - Two young men communicate together by sending tactile signals through their Symbionts while sitting in different places., illustrated by author

4.4.7. Touch Patterns Design through Metaphor

In section 4.3.4., I have identified three distinct touch patterns upon which the Symbiont's interactions with humans are built. These patterns were chosen for their metaphorical meanings, which, without conveying specific messages, allow anyone to fully understand and resonate with the sensations they produce. There are three actuators illustrated in the accompanying sketch: a Heartbeat, a Mini Haptic Motor, and a SMA spring. Each of these actuators produces a unique tactile experience and tactile signal.

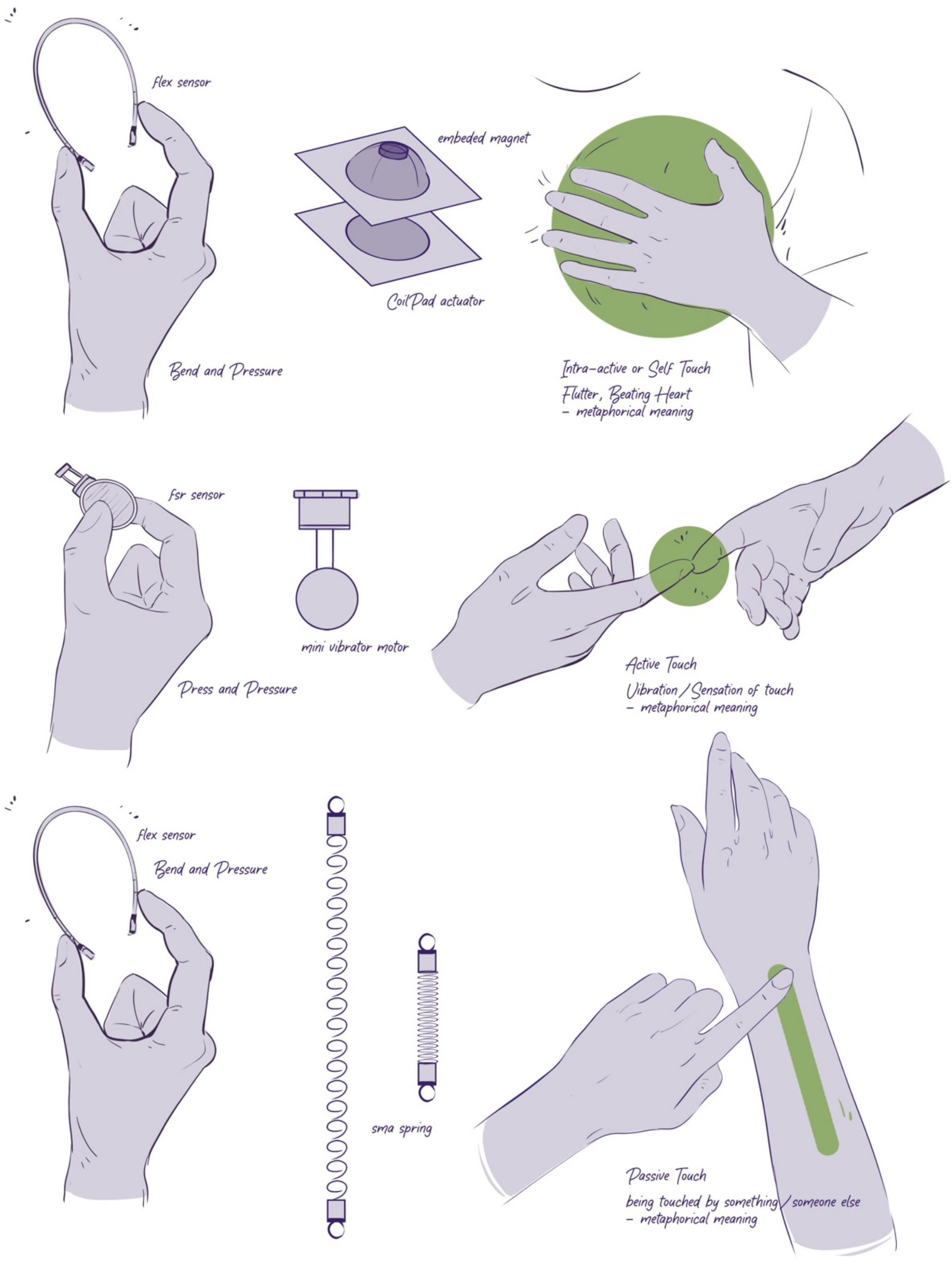


Figure 75 - Symbiont's Touch Patterns through Metaphor, created and sketched by author

4.4.8. Circuit Design

The primary goal is to simulate the metaphorical touch patterns described earlier, including the vibration of touch, the feeling of a heartbeat and the motion of crawling or something/someone touching the body, through responsive and dynamic touch-based feedback. The inputs directly influence actuators like Shape Memory Alloy (SMA) springs and haptic motors. This setup not only ensures precise control but also optimizes power management. For the system to last as long as possible and respond quickly, the power consumption of each component is carefully considered.

The rationale behind this design revolves around the need for synchronous and responsive interactions within a compact hardware setup. By using the MQTT protocol, devices can communicate in real-time, ensuring immediate and synchronized tactile responses. Through the built-in LED blinking mechanism, the system gives a visual indication that data is being transmitted, as well as delivering a signal to another Symbiont, reinforcing its interactive nature.

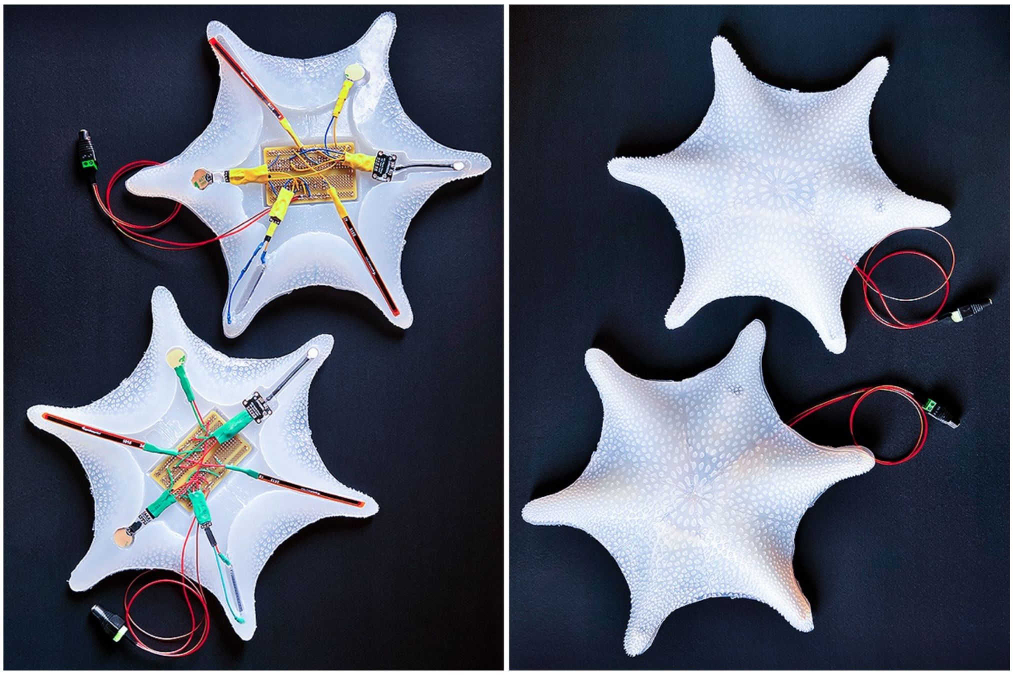


Figure 76 - Symbiont's Body, designed, fabricated and made by author

Components

- Arduino Nano 33 IoT
- Spectrasymbol Flex Sensor
- Ohmit Force Sensing Resistor FSR06
- Flexinol Spring (40±6 coils, 0.015” (0.38mm) wireØ, 90°C)
- Adafruit DRV2605 Haptic Motor Driver
- Microbots CoilPad +10mm N52 Neodymium magnet
- Microbots DriveCell (H-bridge Module)

Power Management

In order to ensure that all components work properly without the risk of power shortages or hardware damage, I use two power supplies to ensure effective power management. In this way, the high current draw of the SMA Spring does not cause voltage drops that could reset or malfunction the microcontroller. Separate power sources also reduce electrical noise (especially due to the SMA spring) and make operation more stable.

Power source for SMA spring:

Using a separate power adapter with a barrel jack, providing 5V and up to 3A, exclusively for the SMA Spring. The SMA Spring requires a significant amount of power, approximately 2.25A. Using a dedicated source ensures that the high current demand of the SMA Spring is met without affecting the stability of the power supplied to other components.

Power sources for the rest of the components:

The rest of the circuit, including the Arduino Nano 33 IoT, Flex Sensors, FSR Sensor, CoilPad, and the mini motor vibrator, is powered by a USB Micro-B Connector Breakout Board. This board is connected to a 5V, 3A USB power supply, which is more than sufficient to handle the lower power demands of these components.

Components	Number	Connection	Power Source	Required Voltage	Current Draw
Flex Sensor	**2**	Arduino	Arduino	3.3 V	0.0003 mA
FSR Sensor	**1**	Arduino	Arduino	3.3 V	5 mA
Mini Motor Haptic Vibrator	**1**	Haptic Driver	Arduino	3.3 V	70 mA
CoilPad	**1**	Microbots Driver	Arduino	3.3 V	150 mA
SMA Spring	**1**	Microbots Driver	5V	5 V / 3 A	2250 mA
Arduino Nano 33 IoT	**1**	Power / USB	5V	3.3 V	150mA
Total current for SMA Spring: 2250 mA (power source I) Total current for the rest of the circuit: 393.3 mA (power source II)					

Table 10 - Detailed Power Managements for Symbiont's Circuit, created by author

Touch Patterns and Code Logic

Active Touch Behavior

As mentioned in section 4.4.7. I articulated three touch metaphors based on research on different touch patterns and their affective meanings. Below is a table describing each of these touch patterns and their functions and behavior in designed circuit.

Touch Pattern	Components	Functionality	Circuit Logic
Active Touch	• FSR Sensor • Haptic Motor	Detects the applied force and provides immediate haptic feedback via the mini motor vibrator.	FSR connects to an analog pin to gauge pressure levels. Upon exceeding a threshold, the DRV2605 is activated via I2C to deliver a tactile pattern simulating heartbeat or other feedback.
Passive Touch	• Flex Sensor • SMA Spring	The flex sensor detects bending motions, and the corresponding SMA spring reacts to simulate movements such as a crawling action, providing a physical representation of the bending motion.	Flex sensor readings are taken from an analog pin. When bent, readings trigger the DriveCells via digital pins, causing the SMA spring to contract and create movement.
Intra-Active Touch	• FSR Sensor • Magnet and CoilPad	Utilizes the bending motion detected by the flex sensor to control an embedded magnet via CoilPads, creating dynamic magnetic fields that can simulate various textures or forces.	Activation of CoilPads through digital outputs based on flex sensor inputs, manipulating the magnet in ways that emulate interactive tactile sensations.

Table 11 - Symbiont's Touch Patterns Design, created by author

Communication Feedback via LED

- Functionality: The built-in LED on the Arduino blinks to indicate data transmission between devices, providing visual feedback that communication is ongoing.
- Circuit Logic: Whenever sensor data is read and transmitted via MQTT, the LED blinks at a consistent interval (e.g., 500 ms).
- This function is tied to the MQTT publishing actions, blinking the LED when data is sent, or an actuator is triggered remotely.

```
void blinkLED(bool active) {
    static unsigned long lastBlinkTime = 0;
    const long blinkInterval = 500; // Blink every 500 milliseconds
    static bool ledState = LOW;

    if (active) {
        unsigned long currentMillis = millis();
        if (currentMillis - lastBlinkTime >= blinkInterval) {
            lastBlinkTime = currentMillis;
            ledState = !ledState;
            digitalWrite(LED_BUILTIN, ledState);
        }
    } else {
        digitalWrite(LED_BUILTIN, LOW); // Turn off LED when not active
        ledState = LOW; // Reset LED state
    }
}
```

Figure 77 - Symbiont's Code Snippet I - Communication Feedback via LED, written by author

Mapping Realistic Behaviour and The Logic of Control

Delays were added to the functions in the Arduino program to try to enhance the realism in touch perception, maintain distinct and understandable signals, and ensure precise control over sensory feedback.

Vibration | In the code mentioned as Breeze (active touch): The vibration intensity is controlled by using PWM in order to create a breeze-like sensation by adjusting the motor's speed in response to sensor changes, controlled by the Force Sensitive Resistor (FSR). The snippet below from updateActuatorState function checks the sensor value and compares it against a threshold to control the DRV2605 haptic motor driver. It starts or stops the motor based on the sensor input, using a haptic effect defined by the setWaveform method.

- **Intensity mapping:** The more force applied to the sensor, the stronger the vibration. This mapping ensures that tactile feedback is proportional to force exertion.
- **Gradual intensity adjustment:** A gradual increase or decrease in vibration intensity mimics natural touch sensations more realistically.

```
void updateActuatorState(String topic, int value) {
    if (topic == topicToSubscribeBreeze) {
        if (value > 500 && !previousBreezeState) {
            breezeController.setWaveform(0, 88); // Start haptic effect
            breezeController.go();
            Serial.println("Breeze ON " + String(value));
            previousBreezeState = true;
        } else if (value <= 500 && previousBreezeState) {
            breezeController.stop();
            Serial.println("Breeze OFF");
            previousBreezeState = false;
        }
    }
}
```

Figure 78 - Symbiont's Code Snippet II - Vibration as Active Touch named "Breeze Function", written by author

Crawl (passive touch): This function actuates SMA spring based on the bending detected by a flex sensor. It uses a non-blocking approach with a timer to control the duration of the actuation, ensuring that the springs mimic natural crawling motion. To ensure full actuation and a natural movement sensation, SMA springs are allowed to cool and heat properly using delays, this also affects the creation of subtle movements both in terms of time and ways of moving.

- When the flex sensor detects bending, there is an initial delay of about 2000 milliseconds (2 seconds) so that the SMA can warm up and start contracting as needed for crawling. To complete the crawl, the SMA spring maintains its contraction for 10000 milliseconds (10 seconds).

- After deactivation, a 5-second cooling period is enforced before the SMA can be reactivated. This is managed by the coolDownStartTime timer.

```
void controlCrawl(int sensorValue) {
    static unsigned long activationStartTime = 0;
    static unsigned long coolDownStartTime = 0; // Track the start time of the cooling period
    static bool cycleComplete = false;
    unsigned long currentMillis = millis();

    if (sensorValue > flexCrawlThreshold && !cycleComplete) {
        if (activationStartTime == 0) {
            activationStartTime = currentMillis;
            Serial.println("SMA Spring checking...");
        } else if (currentMillis - activationStartTime > 2000) { // Warm-up delay
            digitalWrite(SMA_IN1_pin, HIGH);
            digitalWrite(SMA_IN2_pin, LOW);
            Serial.println("SMA Spring ON, value: " + String(sensorValue));
            if (currentMillis - activationStartTime > 12000) { // Activation for 10 seconds
                digitalWrite(SMA_IN1_pin, LOW);
                digitalWrite(SMA_IN2_pin, LOW);
                Serial.println("SMA Spring OFF, value: " + String(sensorValue));
                coolDownStartTime = currentMillis; // Begin cooling period
                cycleComplete = true;
            }
        }
    } else if (sensorValue <= flexCrawlThreshold || currentMillis - coolDownStartTime > 5000) {
        // Ensure a cooling period of 5 seconds before reactivating
        activationStartTime = 0;
        cycleComplete = false;
    }
}
```

Figure 79 - Symbiont's Code Snippet III - Crawl as Passive Touch named "Crawl Function", written by author

Heartbeat (intra-active touch): It simulates a heartbeat rhythm, slightly faster than 60 beats per minute, with two pulses of 100 milliseconds followed by a pause of 700 milliseconds, creating a perceptible and realistic haptic experience.

- **State Machine:** The Heartbeat function uses a state machine within the loop() function to manage the timing of the heartbeat pulses and the pauses in between.
- **Pulse Generation:** The first and second pulses are generated by toggling the output pins connected to a haptic driver or motor controller. The pulses are controlled by setting one pin high and another low, which presumably activates the motor or driver.
- **Timing Control:** The timing between the transitions of the heartbeat states is managed using millis(), ensuring non-blocking delays. Each state (pulse or pause) lasts for a specific duration before moving to the next state.
- **State Transition:**
    - State 1 and State 3: These states manage the actual pulses, each lasting 100 milliseconds.
    - State 2: This is a brief pause between the two pulses, also lasting 100 milliseconds.
    - State 4: This is the longer pause after the second pulse, lasting 700 milliseconds, before the cycle resets.

```
void loop() {
  if (heartbeatActive) {
    unsigned long currentTime = millis();
    switch (heartbeatState) {
      case 1: // First pulse
        digitalWrite(IN1_pin, LOW);
        digitalWrite(IN2_pin, HIGH);
        if (currentTime - heartbeatStartTime >= 100) {
          heartbeatStartTime = currentTime;
          heartbeatState = 2;
        }
        break;
      case 2: // Pause between pulses
        digitalWrite(IN2_pin, LOW); // Turn off to prepare for next pulse
        if (currentTime - heartbeatStartTime >= 100) {
          heartbeatStartTime = currentTime;
          heartbeatState = 3;
        }
        break;
      case 3: // Second pulse
        digitalWrite(IN1_pin, LOW);
        digitalWrite(IN2_pin, HIGH);
        if (currentTime - heartbeatStartTime >= 100) {
          heartbeatStartTime = currentTime;
          heartbeatState = 4;
        }
        break;
      case 4: // Long pause
        digitalWrite(IN2_pin, LOW); // Ensure it's off during the pause
        if (currentTime - heartbeatStartTime >= 700) {
          heartbeatState = 0; // Reset to waiting state
          heartbeatActive = false; // Stop the heartbeat unless triggered again
        }
        break;
    }
  }
}
```

Figure 80 - Symbiont's Code Snippet IV - Heart Beat as Intra-Active Touch named "HeartBeat Function", written by author

Sensory Interaction Chart

The chart below illustrates the sequence of activation and response for the interactions facilitated by the Symbiont. These interactions, which mimic real-life sensory experiences, are initiated by specific sensor inputs, which in turn activate corresponding actuators.

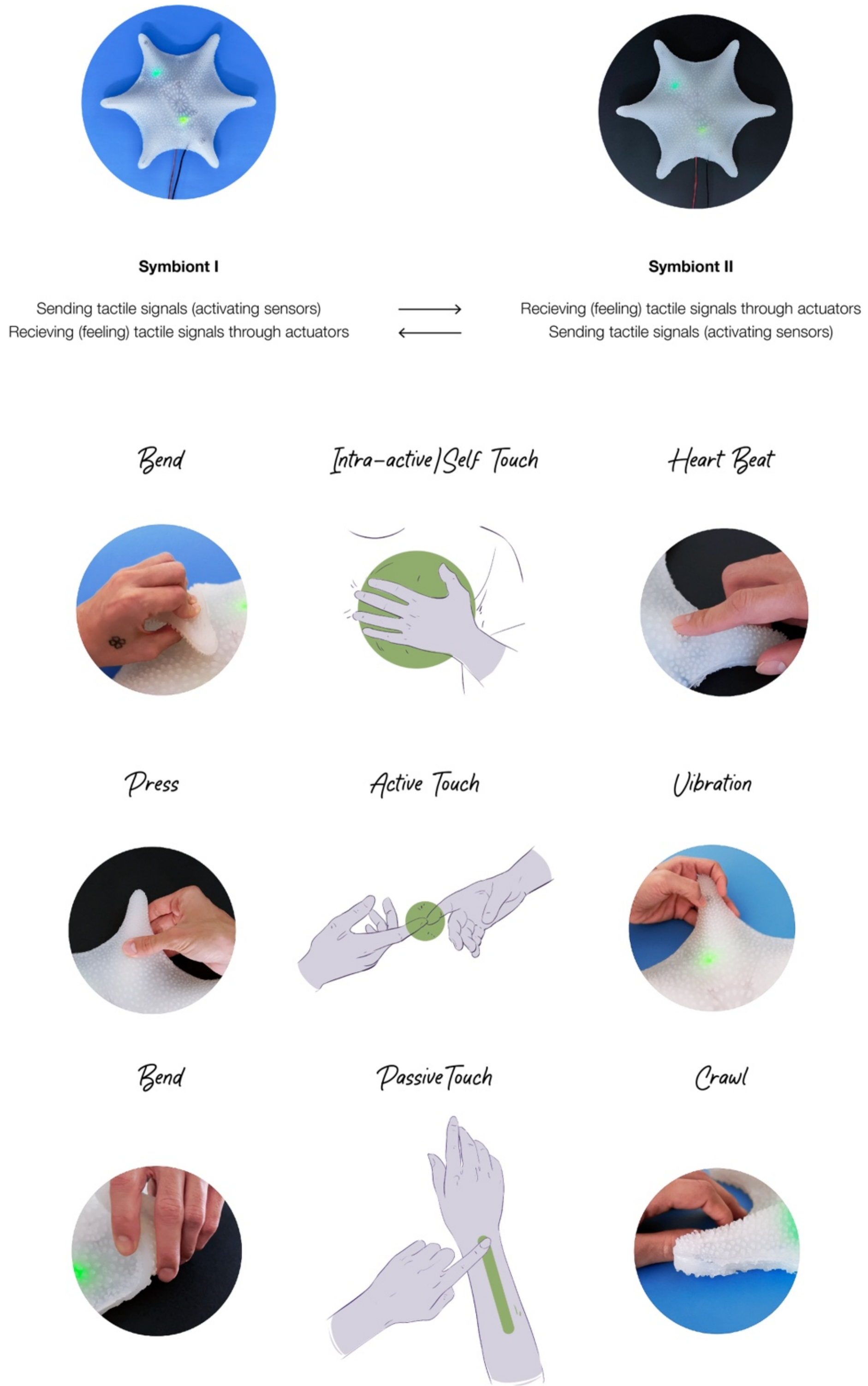


Figure 81 - Symbiont's Sensory Interactions Chart, sketched and photographed by author

4.4.9. Fabrication Parameters

3D Modelling Process

As a first step, I created a 1/12 low poly skeleton segment. By adjusting the placement of these segments, I was able to control the angles and overall volume of the Symbiont. This skeleton was then transformed into the full shell skeleton of the Symbiont using a rotary array.

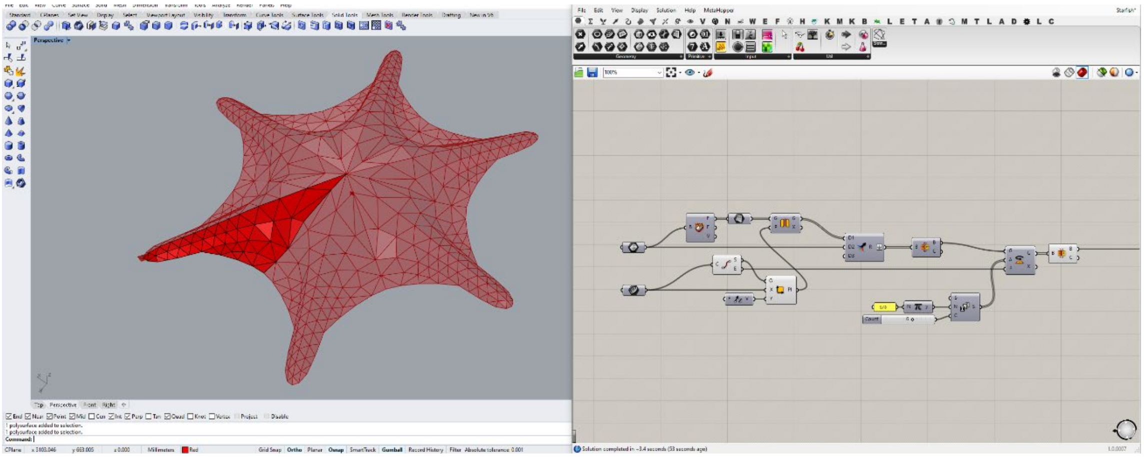


Figure 82 - Symbiont's 3D Modelling Process, Low-Poly 1/12 Skeleton Segment, 3D modelled by author

After creating the skeleton, I selected two different subdivision types for the top and bottom of the model. As shown in the figure 63, the Symbiont's body is subdivided using the Catmull-Clark algorithm, which creates additional segments. These segments were later used to create the fine hairs on the body. At this stage, I applied a Laplacian smoothing algorithm to further soften the body, making it resemble the organic shape of a living creature more closely.

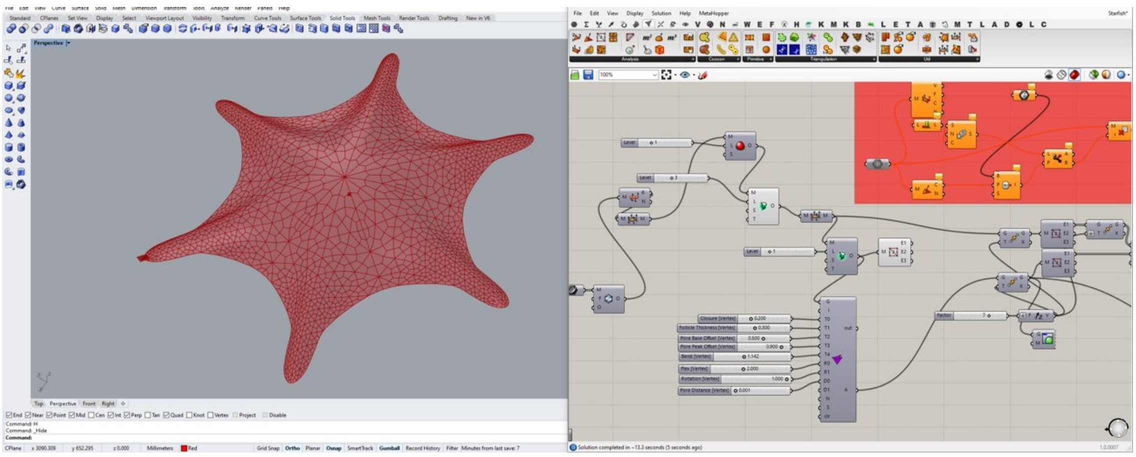


Figure 83 - Symbiont's 3D Modelling Process, Catmull-Clark and Laplacian Algorithms, 3D modelled by author

Based on the annotations on Symbiont's aesthetics mood board and previous tests in 4.3.7., I applied a bumpy biomorphic texture to Symbiont's body using a modification algorithm. Numerous parameters were involved at this stage, influencing both the design and the fabrication process. After several tests, I finalized the optimal shape for both the top and bottom textures.

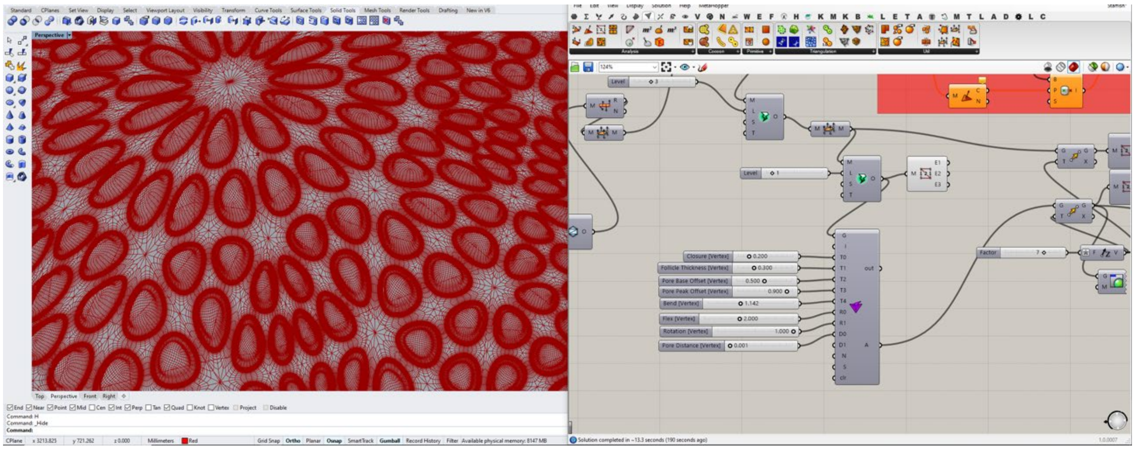


Figure 84 - Symbiont's 3D Modelling Process, Algorithm Modification Based on Final Texture, 3D modelled by author

Fabrication Parameters

The first part of the process was to 3D model the Symbiont's body using Rhinoceros version 8, in accurate measurements based on the components and circuit design. Afterward, I designed the mold in two parts, as well as a bone structure to create a cavity in the top part of the Symbiont's body for electronics, which I will discuss in more detail later.

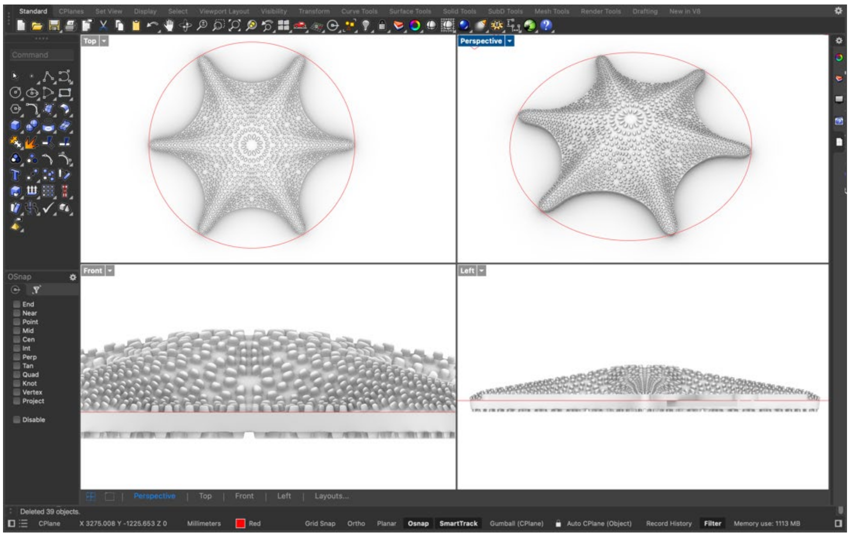


Figure 85 - Symbiont's Body 3D Modelling - Form and Texture, designed and 3D modelled by author

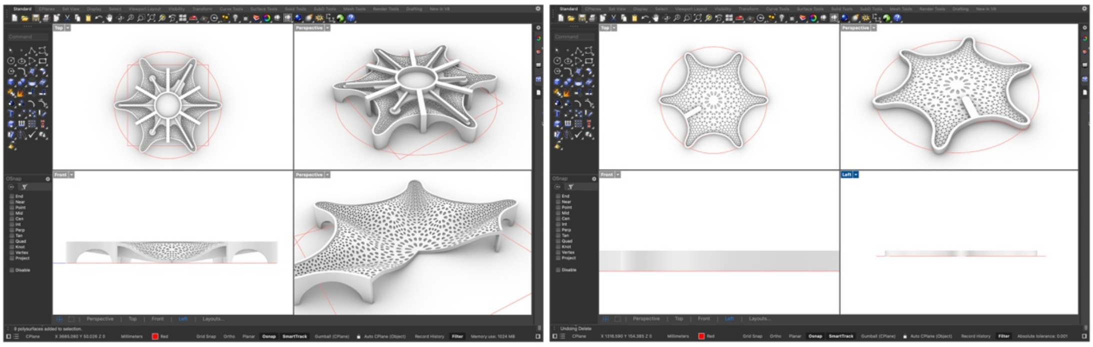


Figure 86 - Symbiont's Mold Design, Left Image: Top Part - Right Image: Bottom Part, designed and 3D modelled by author

Due to limited access to a 3D printer with a sufficiently large print bed, I encountered several limitations during the fabrication phase of my project. While the actual length of Symbiont (as an object and not the mold) is 36 cm, the available printer had a plate size of 13.5 x 13.5 cm, requiring the Symbiont's mold to be designed in two parts, each includes multiple symmetrical parts. As a result, the molds were printed in sections, assembled with adhesive to ensure efficient batch printing, maximizing the printer's capacity.

Figure 87 - Symbiont's Mold - Top Part, Right Image: single part before and after removing 3D print's supports, designed and fabricated by author

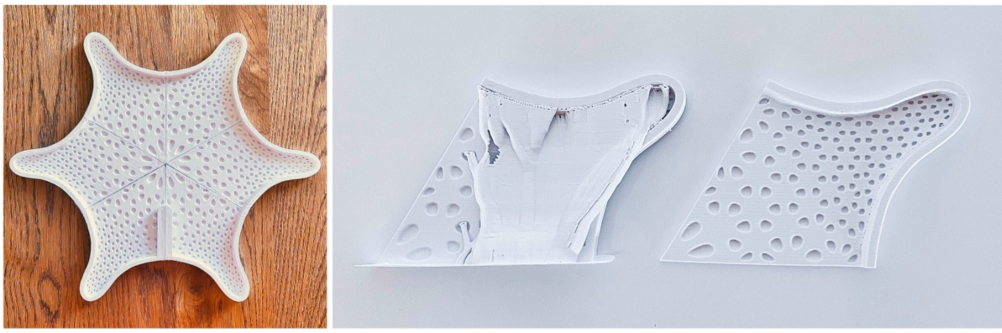


Figure 88 - Symbiont's Mold - Bottom Part, Right Image: single part before and after removing 3D print's supports, designed and fabricated by author

To reduce the amount of material needed for printing, in the 3D modeling of the top part mold, I incorporated a curve in the wall. This design adjustment minimizes the necessity for extensive support structures typically required for printing vertical walls at 90 degrees. This results in a more efficient, time- and cost-effective process.

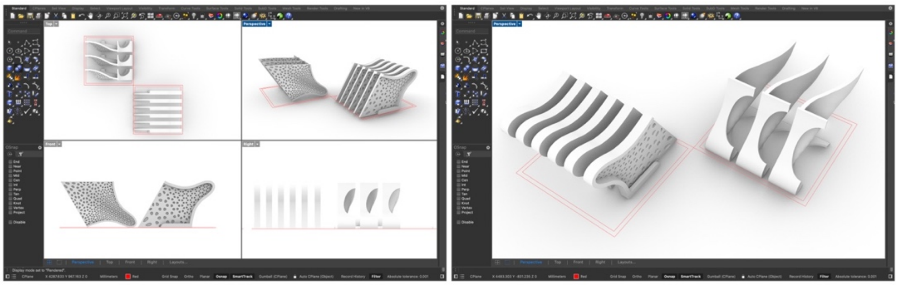


Figure 89 - Symbiont's Mold Design, Single Parts ready for 3D print, designed and 3D modelled by author

Also, the Symbiont's body had to be thick enough to protect the internal components, while not obstructing their functionality during interaction, as a result of affecting their sensitivity. As a solution, I designed a bone structure, based on each component's form, function, and sensitivity, that could securely house the electronics without affecting their sensitivity or functionality, and allow for easy and safe interaction between users and Symbiont.

Figure 90 - Symbiont's Mold - Creating Cavity using Bone Structure and Casting the Body, designed and fabricated by author

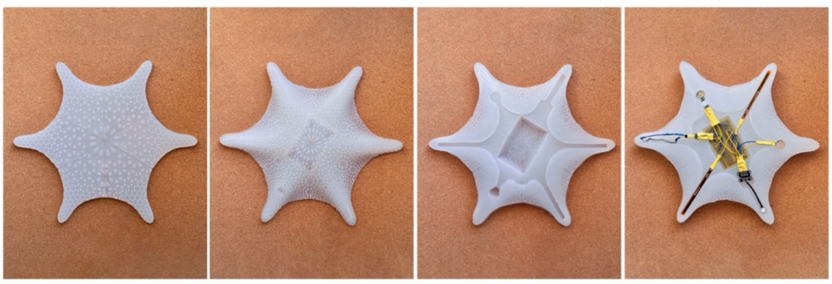


Figure 91 - Symbiont's Mold - Left to Right: Bottom, Top, Cavity, Embedded Electronics, designed and fabricated by author

Below is a visual representation of the layout of electronics in each Symbiont's body, as well as an exploded view of molds and casted parts.

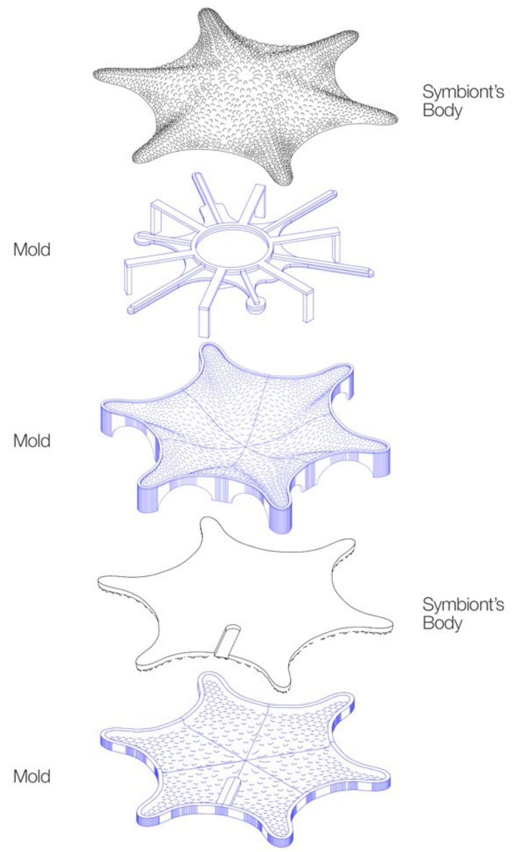


Figure 92 - - Symbiont's Exploded View from Mold and Casted Parts, designed and 3D modelled by author

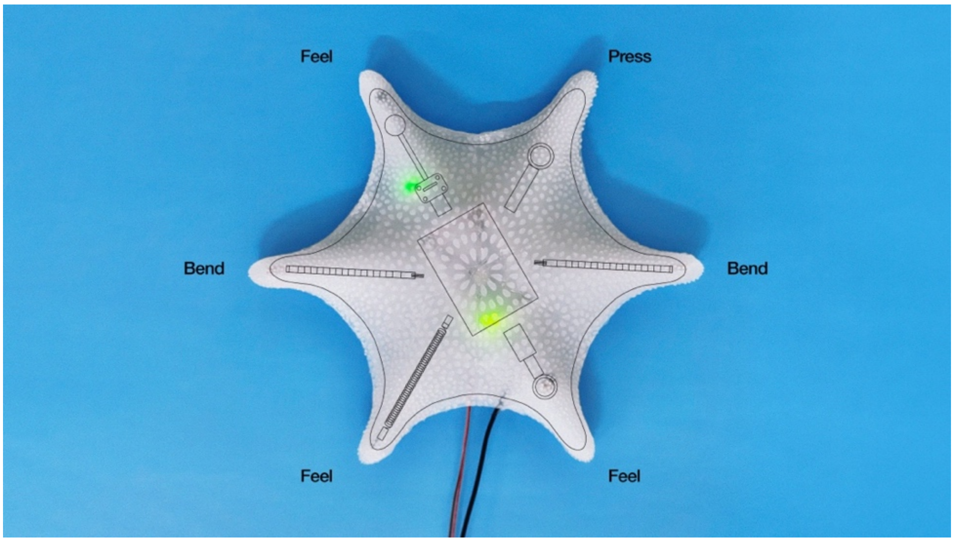


Figure 93 - Symbiont's Electronics Layout, created by author

4.4.10. Thesis Exhibition

The pair of final Symbiont prototypes were shared with the general public in the Digital Futures Graduate Thesis Exhibition. In the exhibition, there were two tables, each designed to engage visitors in a different aspect of the project. The first table showcased prototypes and material exploration. These samples were presented without its electronic components to encourage visitors to engage with these prototypes physically materials in isolation. This setup was intended to foster an exploratory tactile experience and aimed to stimulate discussion and self-reflection about how tactile sensations affect perception. A color-printed booklet (More information Appendices) accompanying this display provided information about the conceptual framework as well as the design's developmental journey, allowing visitors to gain a deeper understanding of the project from its beginnings.

The pair of Symbionts were arranged on the second table so that people could interact with them directly. It was designed to accommodate two people, allowing them to engage with each other while sitting or standing at opposite sides of a long table. In addition to demonstrating the interaction capabilities of the Symbionts, this setup also demonstrated the ability of these devices to augment human communication. To enhance visitor understanding, a video was displayed on a monitor at the table, presenting the whole concept and the interactions in more detail, allowing the audience to visualize the concept and interaction. Additionally, printed instructions were placed under each Symbiont to guide users through the experience and explain how to interact with them effectively.

Figure 94 - Symbiont's Setup at Exhibition, photographed by author

Figure 95 - Symbiont at Digital Futures Graduate Public Exhibition, first and second row: photographed by Daniel Huszar - third and fourth row: photographed by author

In this chapter, I've detailed the culmination of my thesis work, presenting Symbiont. The next chapter will provide more insight on the exhibition's impact, including my personal reflections, feedback, and observations. In addition, I will discuss the development phases of the Symbiont and outline my research plans.

Chapter 5. Conclusion and Further Discussions

5.1. Reflection on Process, Scope, and Design

The course of my thesis provided me with the opportunity to acquire valuable knowledge and experience in a variety of fields, including soft robotics, sensory design, and biomorphic design. Combining these fields to design Symbiont has been a profoundly impactful experience. Below, I explained how I approached my thesis objective and questions:

Thesis Objective

How can I design a nature-inspired soft robot object to facilitate nonverbal interpersonal communication?

Question I: What approaches, methods and methodologies could be used to achieve the transdisciplinary objective of my thesis?

It was necessary for me to examine my objective through the lens of different contexts such as aesthetics, material, sense, human-computer interaction, communication, etc., to develop the approach that fits my thesis' multidisciplinary nature. (Section 2.3)

Question II: Which human senses might best be extended through a soft robot for nonverbal interpersonal communication?

Based on my objective, I aimed to facilitate communication through a nonverbal sensory medium, and because soft robots were also a part of this thread, my decision was automatically drawn to haptics, since I could have designed a sensory object in a way that its material properties are also impactful, so it could be used to create soft robots as well. Eventually, after further research (Section 3.2.3.), I settled on tactile communication as my final choice.

Question III: How might a soft robot could serve as a sensory object for nonverbal interpersonal communication?

During the creation of soft robots, silicone is a primary material, partly because of its potential for interaction with humans (see section 3.1.2.), as well as because of its characteristic of touch, which can be used to communicate and convey different meanings in the context of my thesis. (Sections 3.2.2. and 3.2.3.) Further, I decided to also incorporate metaphorical (Section 2.3.3.) and biomorphic elements (Section 2.1.3.) into its design so as to stimulate the tactile sensation of the user, which results in a higher level of engagement, which ultimately results in a better communication loop between individuals and an interaction between the object and the user.

During my thesis, I learned more about the importance of building the design upon and through research, since not only does it contribute to knowledge creation, but it also shapes and directs design toward decisions that are more suitable for the specific purpose of that design. One of the biggest limitations I encountered during my research was the inability to create Symbionts using 3D-printed silicone. With this method, intricate forms and textures can be produced at a high resolution, even on a very small scale, which would have greatly benefited my project.

My aim for altering my decision from using a pneumatic system to using flexible and lightweight electronics was based on my intention to design Symbiont as quiet, delicate, and organic as possible. Therefore, I used flexible, thin, and sensitive components, but due to the facts mentioned in section 4.4.7., I had to create the body of Symbiont heavier than what I initially planned to, and I wasn't able to print a larger scale 3D printed mold so that I could embed some components including all sensors and a mini haptic motor into the silicone while casting the body. With this method, not only could the body be non-symmetrical and not uniform, but also it would be thinner therefore lighter in weight. As a means of maximizing sensor utility, it is possible to configure a single sensor to function in two directions, triggering a different actuator for each direction it bends. This approach not only reduces the size of the Symbiont but could also more effectively utilize the full potential of the components. However, it would require further experimentation and user testing to optimize interactions.

It may also be worthwhile to consider using a stronger SMA spring. Although I only had access to one type of spring and aimed to manage power consumption efficiently, using multiple springs or a single stronger spring could enhance the visibility and clarity of the Symbiont's movements. As was seen in prototypes III and IV, the silicone skin was much lighter than the Symbiont's body, and the spring was able to pucker the silicone completely. Similarly, enhancing the sensitivity of the CoilPad and magnet setup may contribute to improved responsiveness. However, it is crucial to maintain the subtlety and delicacy of these elements to align with the overall design objectives.

Further reflections on the design and various possibilities will be discussed in the next section, drawing on observations made during Symbiont's exhibition.

5.2. Reflection on Exhibition

Participants' initial interactions and understanding of the project were significantly influenced by the exhibition setup, especially the material exploration table according to their feedback and my observation. In their experience, interacting with the materials, touching different textures, forms and experimenting with their various and unique perceptions through touch was quite valuable and effective, and prepared them well to interact with Symbiont, as well as their assumptions about tactile communication, since it was something quite unfamiliar for most of them.

Some participants were confused by the combination of visual and verbal instructions on the first day. As a result, I simplified the instructions to mostly visuals and used just a few keywords like bend, press, and sense, aligning with the project's emphasis on nonverbal communication and improving interaction.

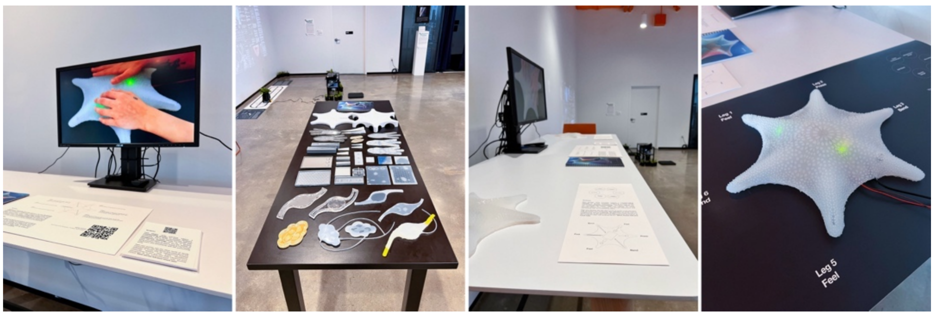


Figure 96 - Symbiont Exhibition Setup - Left to Right: Symbiont's Table, Material Exploration Table, Initial Interaction Setup, Modified Interaction Setup - created and photographed by author

Many visitors initially mistook the Symbionts as personal devices instead of tools for interpersonal communication, despite extensive introductory materials, such as material exploration, video displays, paper instructions and a booklet. It is as if bending or pressing sensors results in something happening in their Symbiont rather than communication with another person. This could highlight the ongoing standard assumption based on the way we used to interact and connect to the world around us.

A number of people, from different disciplines, such as product and UI/UX designer, jewellery designer, psychologist, teacher, sculptor, architect, and computer scientist, have expressed the feeling that Symbiont made them feel calm, and that there was plenty to explore its therapeutic potential. I found these feedback very interesting since Symbiont was designed to be a sensory experience, appealing, organic-like, and inviting for people to engage and communicate with it through their senses, which aligns with my intentions, but I still need to formally study, test, and create Symbiont in order to make it accurate enough for consistent and reliable tactile communication.

Figure 97 - Different Experiences at the Exhibition - Personal Interaction, Communication, Touch Experiment, photographed by author

The following are some of the other feedback and discussions I had with exhibition guests:

- Symbiont as a wearable, such as a piece of garment, gloves, etc.
- Give Symbiont intelligence, so people can live with, communicate with, and talk to it.
- Use them to create a therapeutic device for children with autism, or anyone with social anxiety, etc.
- Develop Symbiont as a tool for remote collaboration, where tactile signals convey non-verbal cues or instructions.
- It can enhance immersion and realism in the metaverse and experience making in that world.
- Help anyone far from home and workstation, like astronauts communicate with their families, or even assist with device operation.

As I interacted with participants throughout the exhibition, I realized the need for more clear communication about the project's concept. This experience led me to consider future improvements, such as making the design of Symbiont components visually represent their interconnected functions through distinct colors, textures, or forms - a concept originally planned but adjusted due to project constraints, which were mentioned earlier in this chapter and Section 4.4.9.

This reflection sets the stage for the next sections, where I'll go into greater detail about the potential next steps for the project.

5.3. Next Steps

Given the scope and limitations of my thesis, there was a limited opportunity to explore the full potential of Symbionts in some areas such as telepresence, which has not yet been explored. The next phase in my process will be driven by user testing to assess whether these sensory objects can also facilitate telepresence in tactile interpersonal communication.

This exploration will involve two distinct approaches to determine their influence on outcomes and user experiences. One strategy will incorporate structured testing sessions under observation, while the other will engage participants in 48-hour unmoderated trials, giving participants the freedom to interact with the Symbionts in their daily environment and record their experiences through personal narratives. Through this dual-method testing, I aim to examine the potential of Symbionts in creating a sense of presence and communication through touch in everyday contexts.

In addition, following the exhibition of my work, I realized that Symbiont's current design could be improved to clarify the relationship between sensors and actuators, based on the complexities observed. Symbiont's tactile communication concept is unfamiliar to many people, which suggests there is a need to make these connections more apparent and understandable through design. I aim to develop a design in future iterations that has less symmetry and is more organic, moving away from uniformity to better reflect the natural variability found in biological design. The different parts of the Symbiont (tentacles) can be made more relatable through color, form, and/or texture. This will help people better comprehend how the sender (sensor) and receiver (actuator) interrelate.

5.4. Future Path

In my thesis, nature has been one of my strongest driving forces, leading me to embrace biomorphic design. This approach aligns with my preference for working with flexible and soft materials. However, concerned about the synthetic nature of these materials, I am considering integrating biomaterials or even a hybrid of synthetic and bio-based materials into my future research. This interest stems from a noticeable gap in the use of biomaterials within other fields such as soft robotics, which I am eager to explore further.

Throughout my master's and thesis studies, I also developed a keen interest in exploring the "senses" within and beyond a human-centric perspective. Through multisensory mediums and material exploration, I am curious about other forms of existence, experience, and telepresence (which I first learned about in an article titled "Physical Telepresence" (Leithinger et al., 2014)). Likewise, I intend to explore the concept of "Third Life," [42] (Capucci, 2021) which explores the coexistence and integration between natural and synthetic life forms, resulting in an entirely new hybrid ecosystem where biological and technological entities coexist and thrive simultaneously.

To conclude, I would like to say that my thesis not only marks the end of my master's degree, but also the beginning of an exciting exploration in my research and design path, which I am so curious and passionate about!

[42] According to (Capucci, 2021), “Third Life” is poised to redefine the boundaries of life as we know it. The organic will be infused with the inorganic, fostering new living constructs that can thrive in both natural and engineered environments.

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Appendices

Appendices A

Appendix A – 1. Ten Principles of haptic embellishments

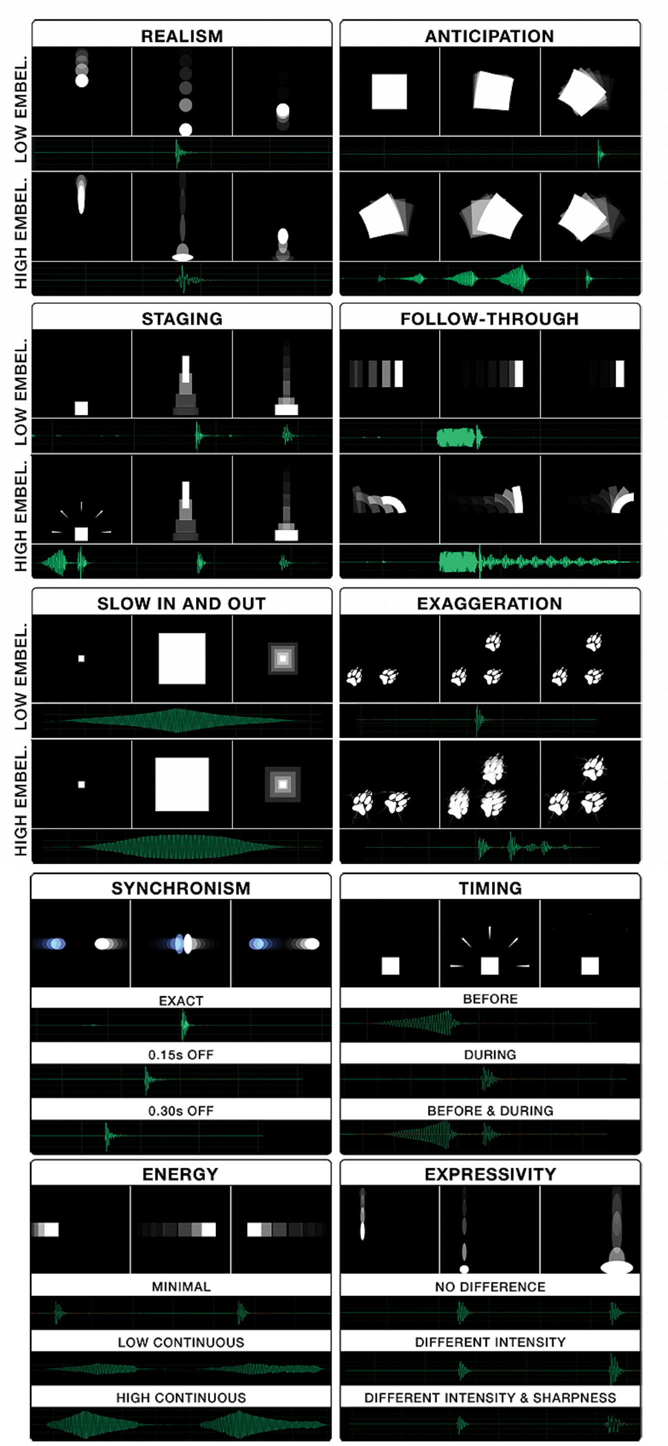

Figure 98 - 10 principles of haptic embellishments by (Singhal & Schneider, 2021)

Appendix A – 2. Symbiont's Mind Map

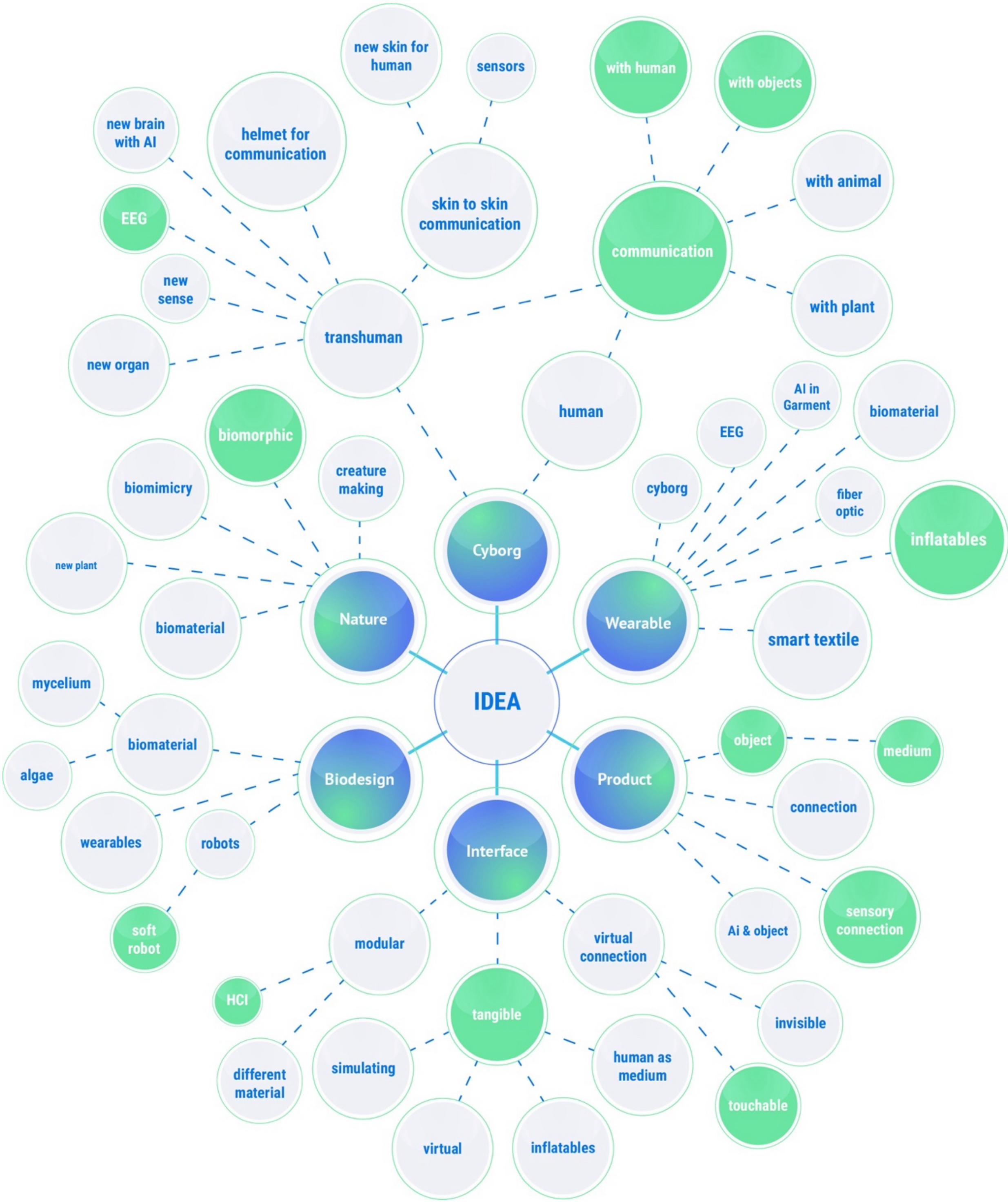

Figure 99 - Symbiont's Mind Map Diagram - created by author

Appendix A – 3. Discover phase, Aesthetics Moodboard

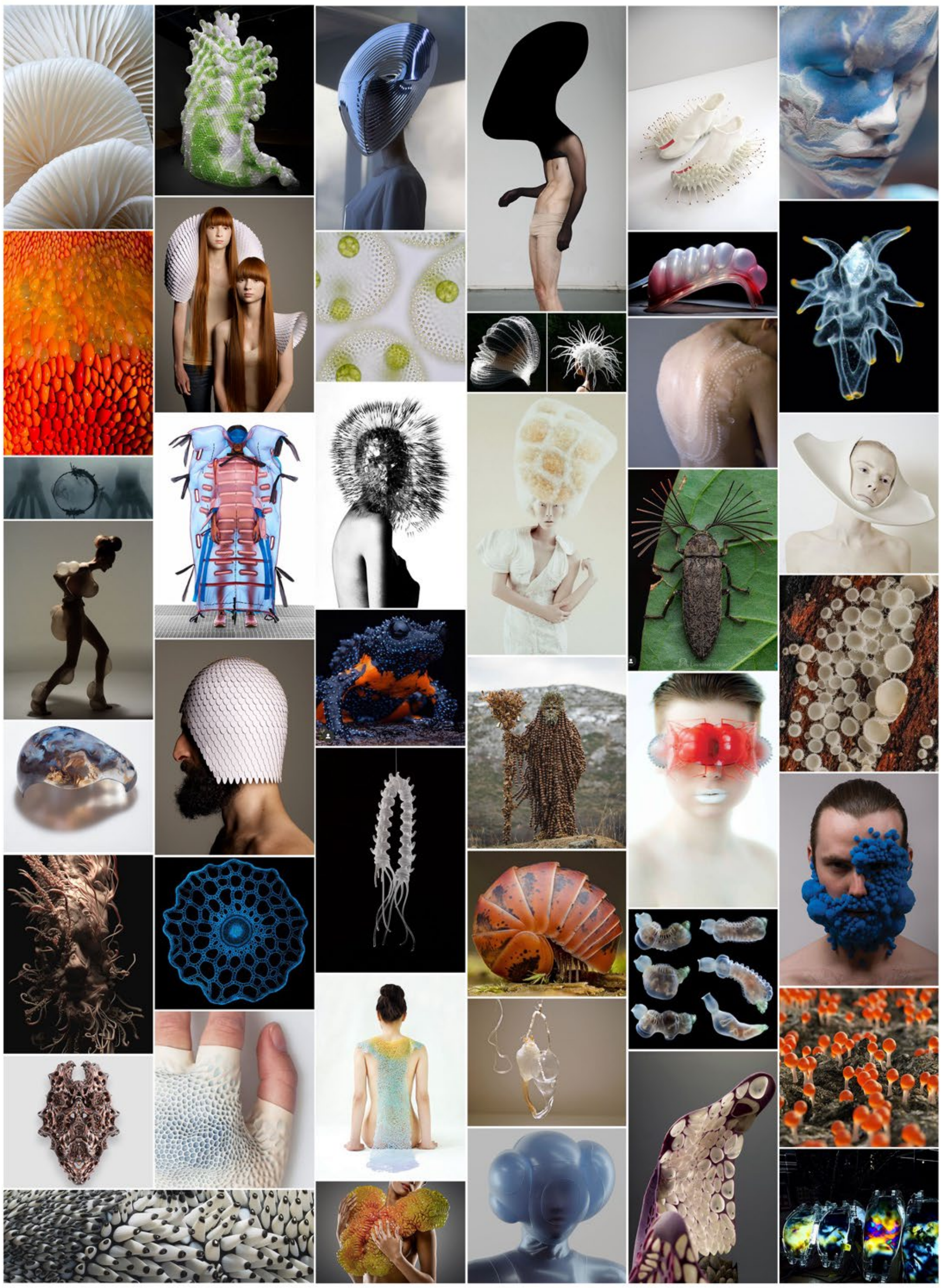

Figure 100 - 'Discover' Phase, Aesthetics Mood Board, collected and created by author

Appendix A – 4. Discover phase, Ideas and Designs Board

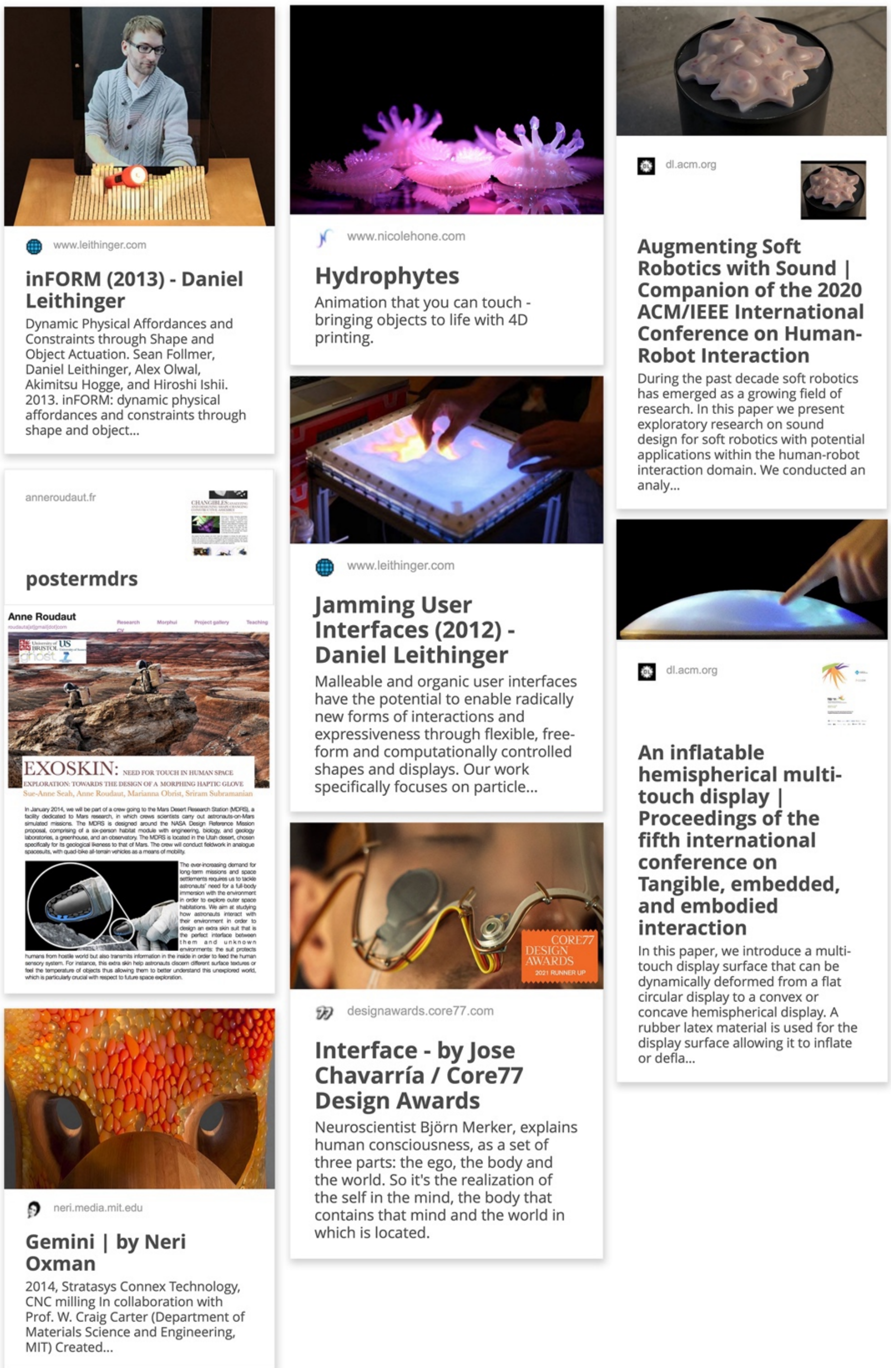

Figure 101 - 'Discover' Phase, Ideas and Designs Board, collected and created by author

Appendix A – 5. Discover phase, Readings Board

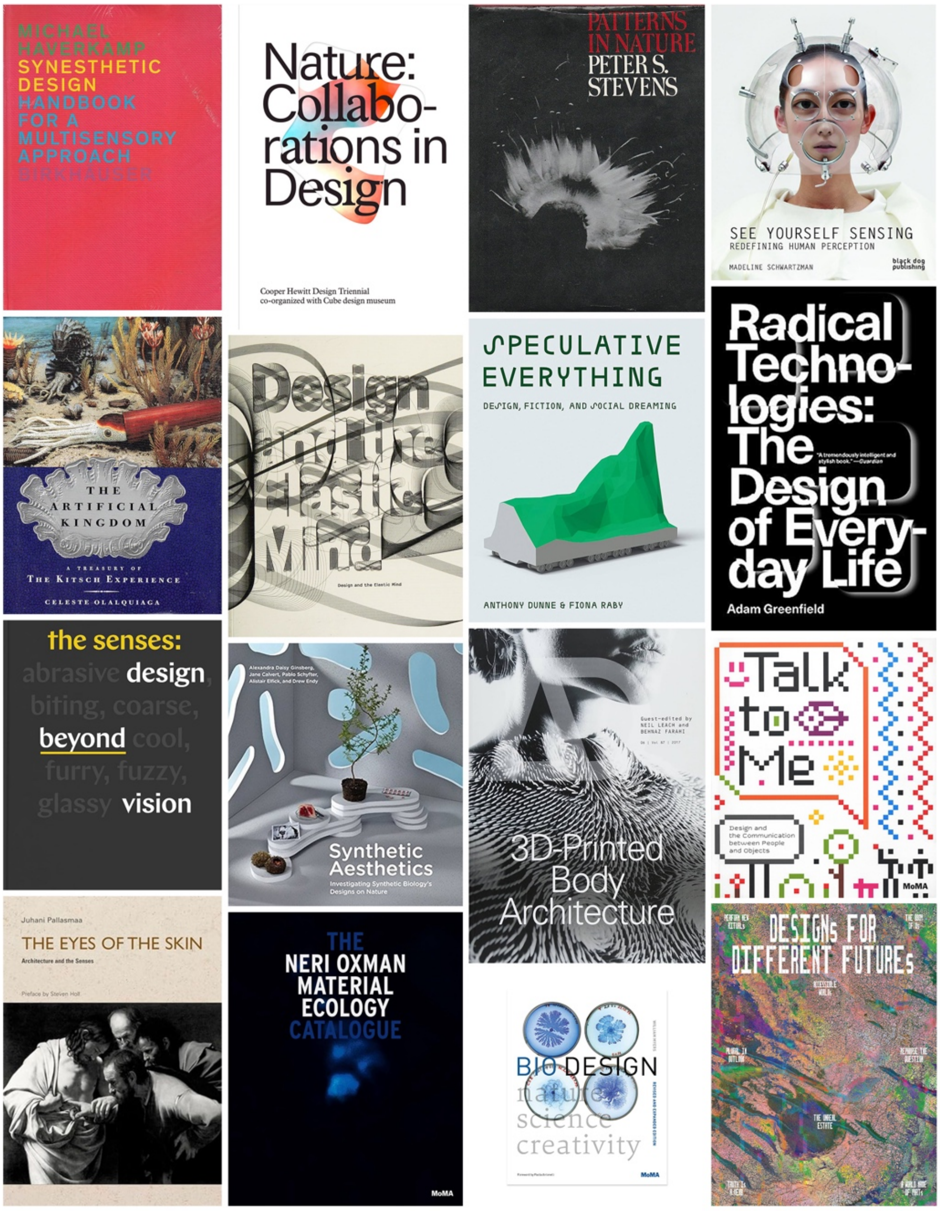

Figure 102 - 'Discover' Phase, Readings Board, collected and created by author

Appendix A – 6. Discover phase, Annotations on Previous Projects

Figure 103 - 'Discover' Phase, Annotation on Previous Experiences as Reflective Practice, created by author

Appendix A – 7. Define phase. Autobiography Diaries I

Figure 104 - 'Define' Phase, Autobiography Diaries I, created by author

Appendix A – 8. Define phase. Autobiography Diaries II

Figure 105 - 'Define' Phase, Autobiography Diaries II, created by author

Appendix A – 9. Symbiont's Mood Board

Figure 106 - 'Deliver' Phase, Symbiont's Mood Board, collected and created by author

Appendices B

Appendix B – 1. Three Models of Design Inquiry

	Mode 1: Process (Reflective Practitioner)	**Mode 2: Research (Design-Based Research)**	**Mode 3: Politics (Critical Design)**
Indeterminate Situation *What kinds of questions can be?*	**Starts with** • Client's problems • User's practice • Designers's own practice	**Starts with** • Lack of knowledge on domain • Questions about domain	**Starts with** • Designers identification of issue • Non-awareness of/careless about a political issue amongst citizens
Controlled/directed Transformation *What does the inquiry aim to change?*	**Aims to** • Solve issues for the target users • Solve the client's problem • Improve practice for the designer	**Aims to** • Gain knowledge about domain • Solve issues for the users	**Aims to** • Raise awareness of structure • Make the issue actionable • Look like a real design
Assumption/Knowledge *What does design build upon?*	**Assumptions Are Made Based on** • Experience • Empirical observations • and possibly theory	**Assumptions Are Made Based on** • Theories about the domain and empirical knowledge	**Assumptions Are Made Based on** • Research knowledge about (tech) development for the future • Or knowledge about consequences of past choices
Method Applied *How does design determinate its distinctions and relations?*	**Approach to Problem** • Iterative process going from knowledge of the domain to lab, to intervention, to reflection that leads to new insights about the domain	**Approach to Problem** • Iterative process going from knowledge of the domain lab, to intervention, to reflections that leads to new insights about the domain	**Approach to Problem** • Tracing and projecting tactics (both analytical and synthesizing)
The Mode's Objective *What is regarded as a determinate/stable situation?*	**Goal** • Designer solve the issue • .. and become a better designer	**Goal** • Design knowledge and principles are found and tested • The intervention is implemented	**Goal** • Public are raised in relation to the issue
My Thesis	**Research *Through* Design**	**Research *For* Design**	-

Table 12 - 'Three Models of Design Inquiry' - graphic by author, adopted from (Ejsing-Duun & Skovbjerg, 2019)

Appendix B – 2. The Process of Generating Metaphor

Steps	Definition	Symbiont's Use and Process
Functional Definition	A thorough understanding of the workings of the system which involves understanding not only what it is capable of doing, but also when and how quickly it can accomplish it.	Identification of the technology I'm implementing and communication medium for technologies using TI (Tactile Internet)
Identify User's Problem	A system is designed to determine which functionalities are unfamiliar to users and which might seem familiar, but work differently. Observing how users interact with similar systems, explaining what they're doing, and using prototypes can be effective ways to discover these problems.	With prototyping, an iterative process, and annotation, I am discovering patterns in the technologies and components I am using that I assume are unfamiliar/might seem familiar to users.
Metaphor Generation	Metaphors are generated by identifying those that are already embedded in the problem description.	Throughout my description, I introduce three elements, which are object, soft robot, and tactile, which all relate to metaphors in different fields, respectively, physicality, material, and technology, and sense and communication.

Table 13 - The process of generating interface metaphor, created by author, based on 'Working with interface metaphor' (Erickson, 1995)

Appendix B – 3. Ten Principles of Haptic Embellishments

Principle	Definition	Relation with Visuo-Haptic Figure	Example
Realism	Use of haptic parameters to mimic an object's physical qualities.	In animation, realism is achieved by matching visual cues with appropriate haptic feedback to enhance the perception of the material properties of objects.	*A squishy ball bouncing is paired with low frequency vibrations, while a marble ball bouncing comes with high frequency feedback.*
Anticipation	Haptics build anticipation for an upcoming action.	Haptic feedback can create a buildup before a significant event, mirroring the anticipation technique in animation for dramatic effect.	*A ramp-up vibration in an alarm before it rings, or a baseball player's swing buildup before hitting the ball.*
Staging	Design haptic feedback to focus attention on specific elements.	Uses haptic feedback to highlight important elements or actions, akin to zooming or highlighting in visual content.	*Haptic feedback drawing attention to a character about to perform an important action in an animation scene.*
Follow-Through	Haptic feedback to communicate continuation of motion after an action.	Enhances the realism and fluidity of movements with haptic feedback that simulates after-effects, emphasizing the inertia and continuation of motion.	*After a slingshot is released, the continuing vibration of the elastic bands is communicated through oscillating feedback.*
Slow In and Out	Implementing gradual acceleration and deceleration in haptic feedback.	Making movements more natural by adjusting the intensity of haptic feedback gradually, akin to the easing in and out in animation.	*Gradual increase in vibration intensity as a car starts moving, then a gradual decrease as it stops.*
Exaggeration	Enhancing elements with haptic feedback for emphasis.	Using intense haptic cues to dramatize actions or characteristics, making them more pronounced and impactful, augmenting the animation principle of exaggeration.	*Very intense rumbles accompany the footsteps of a giant in an animation, emphasizing its enormous size and impact.*
Synchronism	Precise timing of haptic feedback with other sensory feedback.	Aligning haptic feedback with visual and auditory elements is crucial for a cohesive and immersive experience, reflecting the importance of synchronization in animation.	*Haptic feedback synchronized with the visual impact of a punch in an action scene.*
Timing	Playing with the timing of haptic feedback for effect.	Varying haptic feedback timing can enhance storytelling and emotional impact, similar to animation, where timing is key for pacing and narrative structure.	*Delayed vibration after a visual event to emphasize the follow-through or aftermath.*
Energy	Matching haptic feedback intensity with the visual energy of an object.	Haptic feedback reinforces the energy of a scene or object by matching or amplifying the perceived energy through the intensity and frequency of vibrations.	*Faster-paced, more intense vibrations paired with a visually pulsating object demanding attention.*
Expressivity	Distinct haptic feedback for different interactions or events.	Providing varied haptic responses to different actions or events, adding depth and a richer sensory experience, akin to how visual and auditory variations are employed in animation.	*Differentiated haptic feedback for a small pebble and a large boulder falling, reflecting their impact and aftermath.*

Table 14 - Ten Principles of Haptic Embellishments, created by author, data extracted from (Singhal & Schneider, 2021)

Appendices C – Supplementary Description

Appendix C – 1. Core Aspects of Tactile Internet

According to IEEE 1918.1, the following are seven core aspects of Tactile Internet that I distilled into seven principles (Aijaz et al., 2018):

1- TI enables remote physical interactions, including the exchange of haptic information.

2- Interactions can occur between humans, machines, or both.

3- "Object" in TI can mean any physical entity, including humans and various machines or software.

4- TI aims for indistinguishable experiences in local vs. remote task execution through bilateral haptic teleoperation.

5- Machine interactions within TI seek to replicate direct interactions with objects, regardless of location.

6- Haptic information is categorized into tactile (skin-based perceptions like texture and temperature) and kinesthetic (body-based perceptions like force and position), often combined.

7- "Perceived real time" varies between humans and machines, depending on the specific use case.

Appendix C – 2. Early Soft Robots

Harvard University has developed a series of pneumatic-actuated soft robots, which included “Multigait soft robot” (Shepherd et al., 2011) starfish-like with no hard internal skeleton and tentacle-like robot (Martinez et al., 2013) servs as a flexible gripper that can deform and camouflage.

Figure 107 - Left image: 'Multigait soft robot' by (Shepherd et al., 2011) - right image: 'Flexible octopus-like robot arm', photographed by Massimo Brega

Upon its publication in March 2014, the scientific journal Soft Robotics, was launched, the editor commented: “By building soft materials into the fundamental design of machines, or by building them completely from soft materials, we add a new dimension for design and create an untapped resource for entirely new types of machinery.” (Trimmer, 2014) “Soft robots are devoid of rigid components and have several mechanical advantages over classically structured robots such as the ability to squeeze, stretch, and stiff.” (Laschi et al., 2016) "Octopuses are notorious escape artists, able to squeeze and squish themselves into and around nearly any obstacle they encounter. In an ode to these crafty cephalopods, researchers have created the first completely soft-bodied robot, dubbed the Octobot." (“Octobot” Is the World’s First Soft-Bodied Robot, n.d.)

Figure 108 - Octobot, soft autonomous robot by Harvard University (Wehner et al., 2016)

It is a great challenge to develop fully soft, autonomous robots because, “it requires soft analogues of the control and power hardware currently used." (Wehner et al., 2016) A small reservoir of hydrogen peroxide powers the Octobot, unlike other soft robots that have at least some hard components, such as batteries or wires. Inflating and flexing the robot's arms is the result of the chemical reaction produced by hydrogen peroxide washing over platinum flecks embedded within the Octobot.

Appendix C – 3. Engagement through Other Projects as Reflective Practice

Pneumatics Systems (inflatable soft robot)

One of the ways I explored and examined my topic in my thesis was through my independent study on soft robotics, whose results are discussed in 'Prototype I - Hello World!' and 'Prototype II - Prototype HiPalm'.

Brain-Computer Interaction Application

During the Neuro Alberta Tech Hackathon in November 2023, I engaged in a rich learning environment packed with workshops and challenges centered on neurotechnology. Our group partnered with the Alberta Health Services on creating BCI Beats[43] a music creation app enabling children with motor impairments to use brainwaves for music creation. This experience significantly enhanced my understanding and skills in employing Electroencephalogy (EEG) sensors and engaging with Brain-Computer Interface (BCI) technology. I had been considering integrating this technology into my thesis prior to the hackathon, recognizing its potential as a tool for facilitating nonverbal communication. The technology's limitations, such as its bulky design, inability to be easily used, lack of reliability, and difficulty in modifying connections and components (due to the specific requirements for body connection) led me to reconsider its applicability for my thesis.

Figure 109 - Image from University of Alberta during Neuro Alberta Tech Hackathon (NeurAlbertaTech, n.d.)

[43] We were able to achieve second place winner in the problem provider division. (NeurAlbertaTech, 2023)