Live to Build, Build to Live
Organism-Machine Interfaces for Co-fabrication

by

Felix Kraemer
Bachelor of Arts, Burg Giebichenstein Halle, Germany (2014)

Submitted to the Program in Media Arts and Sciences, School of Architecture and Planning,
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Abstract

Recent attempts to fuse design with biologically-based building materials—even living organisms—are enabling us with opportunities to augment natural processes, resulting in new and potentially mutualistic relationships between us and the ecologies that surround us. Yet, the deep conceptual mismatch between the built and the grown has rendered such attempts to join large-scale design and biology a rarity. Extraction, refinement, and discrete handling of materials are still needed in design and fabrication environments, which makes a mutually beneficial relationship with nature difficult to achieve. This calls for a radically different approach to interfacing between machines and organisms across natural and artificial fabrication platforms.

In this thesis, I propose using an actuated/responsive interaction architecture, designed to *mediate* between stakeholders involved in a building process. I hypothesize that kinetic organism-machine interfaces of this sort will enable us to connect natural and artificial fabrication processes and products into architectural-scale co-fabrication.

Focusing on two insect species known to additively produce and modify their environment, I study *Bombyx mori* (silkworms) and *Apis mellifera* (honey bees) and present two model environments embodying—and expressing—lessons learned and guidelines established. Exploring a selection of imaging and sensing environments, and analyzing bees and silkworms under various environmental conditions, I lay the groundwork for the development of two interactive scenarios between organisms and machines. I demonstrate the design and realization of a biologically and robotically controlled kinetic fabrication environment with silkworms as fiber-spinning agents, to produce large-scale architectural structures.

The experiments conducted as part of this thesis demonstrate that the co-fabrication of large scale structures using responsive, kinetic production platforms is possible and suggests that there is potential for future work to contribute to this fabrication approach.

Finally, I investigate what type of interspecific relationship is established in the process and how it may be conceptually represented in a unifying framework.

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I dedicate this thesis to my father

Valentin Kraemer

"Care and Quality are internal and external aspects of the same thing. A person who sees Quality and feels it as he works is a person who cares. A person who cares about what he sees and does is a person who's bound to have some characteristic of quality."

—Robert M. Pirsig, Zen and the Art of Motorcycle Maintenance

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Thesis Organization

In the first part of this thesis, I present a selection of background literature related to the topic of new multi-scale fabrication technologies that involve living organisms.

After detailing the motivation for my focus on this topic, as well as the intricacies of relationships between stakeholders in a co-fabrication environment, two problems of interest are identified in **Problem Statement**.

In **Definitions**, the most prominent terminologies used throughout this work—such as Interface, Mutualism, Symbiosis, and Domestication—are defined.

In **Methods**, the research methodology (and thereby its approach) to the projects presented as part of this thesis is described. Specifically, I introduce two species, *Apis mellifera* (honey bees) and *Bombyx mori* (silkworms), on which the practical part of this thesis focuses.

In **Environments**, all experiments are discussed, including in-depth descriptions of both *Maiden Flight*, a module built to study queen bees in the context of microgravity (space travel), and Silk, a range of works examining the possibilities of combining robotics with natural silk production of *Bombyx mori*. A large-scale production platform is demonstrated, using living silkworms to construct an architectural-scale membrane.

In **Conclusions**, a unifying framework to guide learnings is presented, outlining the interactions present in a fabrication environment that incorporates living organisms.

The last chapter of this thesis **Future Work** contains an outlook on possible future work.

1. Background

1.1 Related Works

Generative algorithms and fabrication technologies such as 3D printing have opened the doors to new construction methods that follow growth patterns we can observe in nature[1]. Biological processes or physical principles are modeled with methods such as the finite elements method (FEM) or cell growth algorithms to develop designs that interact with living materials. For example, 3D printed organ-like vessels (Fig. 1) have been designed to support embedded synthetic micro-organisms[2].

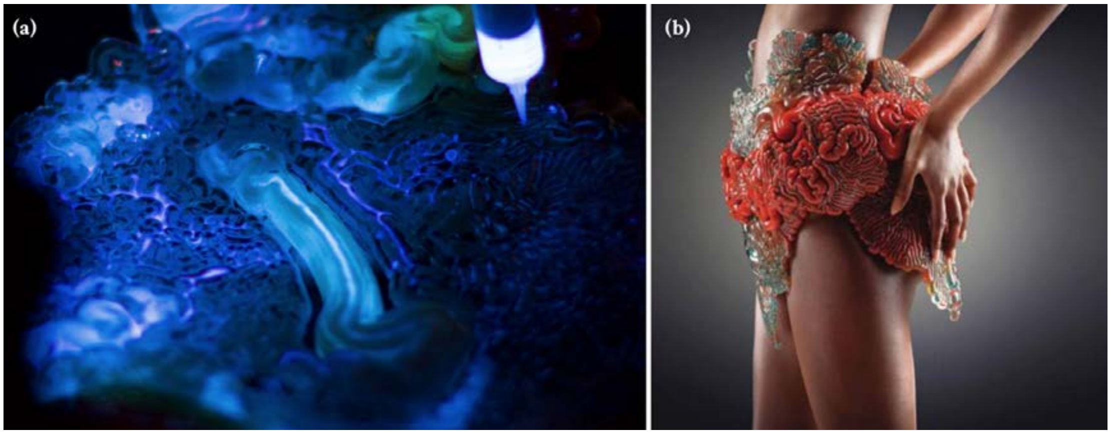

Figure 1: **(a)** Microfluidic channel structure filled with chemiluminescent liquid for visualization **(b)** *Wanderers* by Neri Oxman and the Mediated Matter Group, 2016[2].

As a result, design solutions may form a built-as-grown approach that lets a built model interact with natural processes. However, the fabrication technology used to materialize the models often remains part of a system of discrete materials and steps that are not tied to the natural ecology or its niches. While these approaches physically connect artificial and natural processes, they focus only on the molecular scale to body scale and are therefore not yet applicable in the field of architecture.

Co-fabrication techniques at the architectural scale reveal a set of projects in which organisms are 'agents' in a grown-as-built approach. Here, fungi or insects, for example, are directed to build material structures according to a set of bounds determined by the designer. For example, the MycoTree (Fig. 2) uses a building technology comprising a load-bearing branching structure, produced by mycelium fungi in a mold-like fabrication process that is partially based on the use of industrial bio-waste[3].

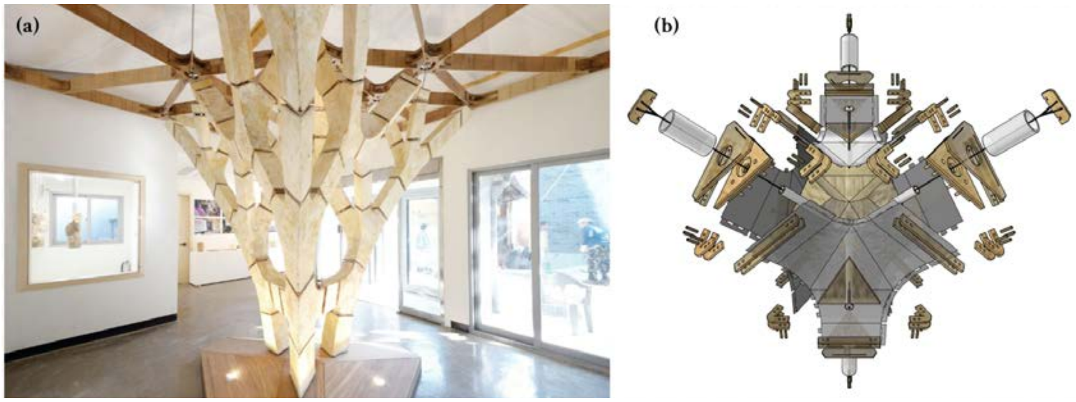

Figure 2: **(a)** MycoTree branching structure at the 2017 Seoul Biennale. **(b)** Explosion drawing of mold construction[3].

While the MycoTree uses a comparably soft material (roots produced by the mycelium fungus) to fill predefined brick-like volumes, the overall construction of the branching structure demonstrates what can be achieved by using computational design approaches in conjunction with bio-based material formulation and sourcing. The question remains—can variability be achieved in shape without requiring construction of a new set of molds? Could a more fine-grained direction of fungi spores at the core of the material production redefine, or even skip, the entire process of mold-making?

In his artworks, beekeeper and artist Ren Ri explores another concept[4]. Working with honey bee hives, he creates cubic or polyhedral spaces from transparent acrylic, which are added to common Langstroth hives. The beehive subsequently takes on ownership of the additional space and builds wax combs onto a thin wooden structure that is positioned in the acrylic compartment and which sets one of the initial conditions. Over several weeks or months, the compartment is rotated. Since the hive continuously attempts to follow gravitational forces while building the combs, this results in a change of direction of the comb structure into a multi-directional hive architecture.

Here, the environmental conditions are set both as constants (wooden structure) and as variables (multi-directional shape of the acrylic container, rotation). The resulting structure is the creation of both the beehive and the human (Fig. 3). Most notably in this example, the bees, as pollinators, are a crucial part of the local ecology and therefore not separated from nature.

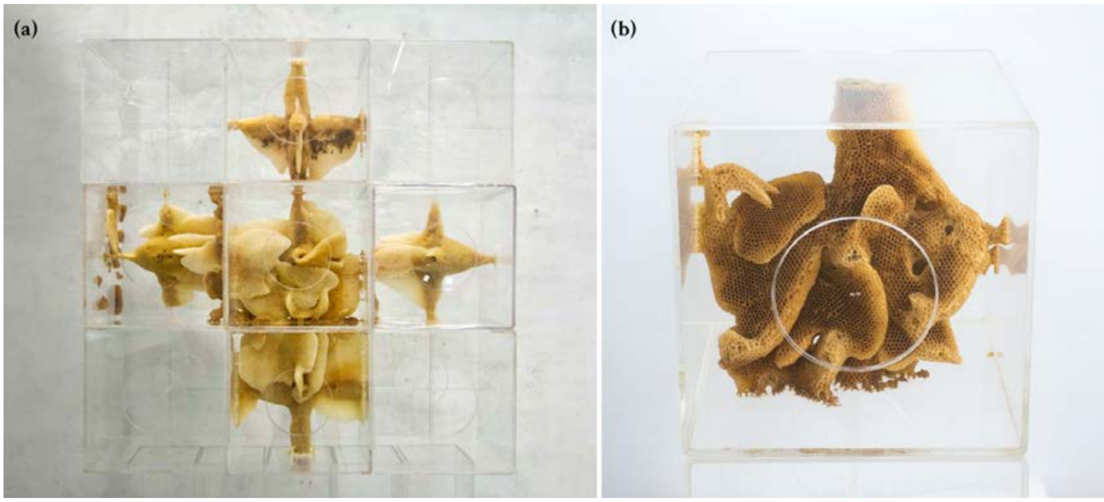

Figure 3: **(a)** Yuansu Series II[4] arrangement of multiple modules **(b)** Single module from Yuansu Series II • works and images by Ren Ri

In 2016, the Mediated Matter Group, led by Neri Oxman at the MIT Media Lab, presented *Silk Pavilion*, a dome structure made of 26 polygonal panels (Fig. 4 (a)). Each panel consisted of a scaffold mesh of one continuous robotically deposited thread. The structure was populated with 6500 silkworms that deposited natural silk directly onto the base scaffold, connecting the robotically spun thread into a membrane. A Parametric model of the impact of daylight was used to develop a strategy to inform the spinning phase of the silkworms (Fig. 4 (b)). In common forms of silk production, silk cocoons, including the silkworm pupae inside, are dried and reeled to produce about one kilometer of continuous thread. The approach of the Mediated Matter Group focuses on keeping the silkworms alive, with their natural metamorphosis intact, while the larvae spin flat silk patches instead of cocoons.

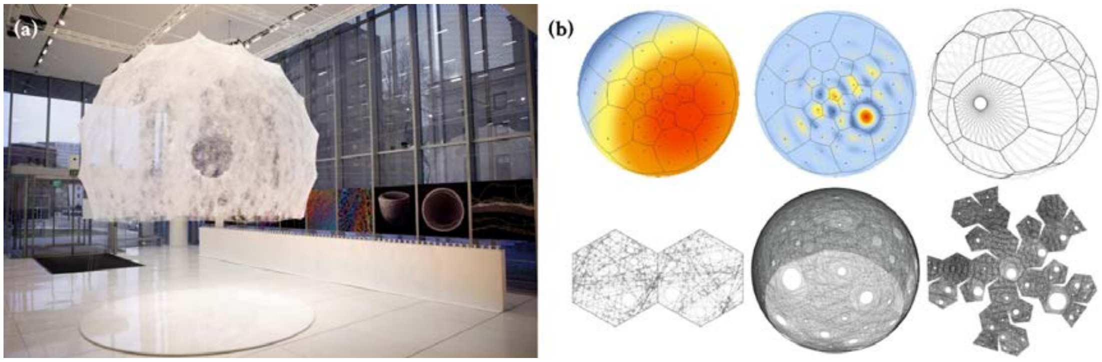

Figure 4: **(a)** Silk Pavilion, Mediated Matter Group **(b)** “Sun-diagram” outlining the potential of templating strategy focusing on light as a source of heat to inform the spinning phase of the organisms. • Images and diagrams by (Markus Kayser and Jorge Duro-Royo), 2016

This project demonstrates how an architectural-scale pavilion can be achieved through a computer numerically controlled (CNC) process in conjunction with the modification of environmental (boundary) conditions supplied to a swarm of organisms. It is limited in that once the virtual model of the structure is developed, the density and distribution of the silk membrane are not tunable during the process of production. *Silk Pavilion* forms the basis for *Silk II*, which is presented as part of this thesis.

1.2 Mutualism

Mutual relationships in natural ecologies are usually examined by weighing benefits and detriments to any of the participants in a system or process. In the case of *Silk Pavilion*, it is important to note that in addition to the fitness of the organisms used in a co-fabrication process, there is the question of long-term benefits as a result of the system design. If, for example, the genetic diversity of silkworms can be maintained better through the use of a silk fabrication platform that preserves the metamorphosis of the larvae, then it could be argued that there is a net benefit both for the human (who is harvesting silk) and for the silkworm as a species (genetically). Of course, it remains challenging, if possible at all, to determine what constitutes a *benefit*, especially when looking at highly domesticated species.

Studies of mutualism in nature have relied on graphical tools to visualize the relationship between partners in a mutual relationship. One of the earliest representations is the interaction grid by Edward Haskell (Fig. 5).

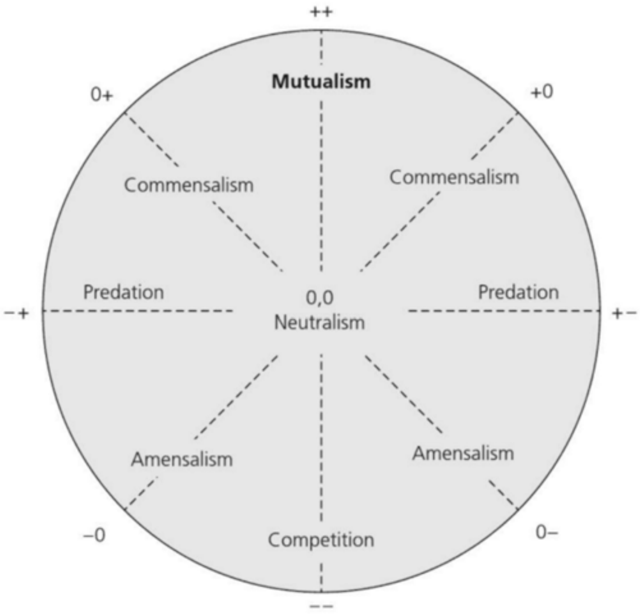

Figure 5: Haskell Interactions Grid[5] classifies interactions by defining relationships according to neutral (0), beneficial (+), and detrimental (-) effects.

Research led by Judith L. Bronstein, Distinguished Professor of Ecology and Evolutionary Biology at University of Arizona, examines mutually beneficial relationships in nature. According to Bronstein's review "Mutualism"[6], there are conceptual problems with the Haskell Interactions Grid, mainly because there is no distinction made between the interactions themselves and their effects. Furthermore, it remains unclear what the symbols '+' and '-' represent and if the benefits or detriments are qualitative or quantitative.

The Symbiotic Relationships Diagram by Ian Alexander is another representation widely used to describe mutual or symbiotic relationships (Fig. 6).

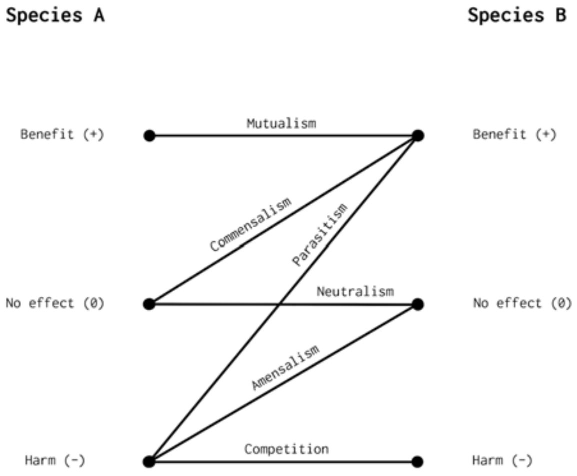

Figure 6: Symbiotic Relationships Diagram based on diagram by Ian Alexander[7]

While the diagram gives a good overview of different types of interactions, like in the case of the Haskell Interactions Grid, the causal mechanism of interspecific interactions and their effects is not represented enough to use it as a tool for the assessment of a specific fabrication process.

Since this thesis features a strong emphasis on material synthesis and architectural shape construction, it is important to acknowledge the factor of goods or materials exchanged between species. In **Conclusions**, this factor is considered in order to develop a new interactions grid adapted for this specific field. RC Connor describes interspecific relationships in terms of "by-products", "investments", and "purloins"[8] and treats these like assets that are traded between species interacting with each other. Some even describe interspecific mutualistic relationships in nature in terms of "markets," comparing them to human trading behavior[9].

This thesis includes aspects of *commodities* exchanged as part of the fabrication system. Higher-level discussions such as whether the actions performed as part of the experiments warrant the use of terms such as *supply, demand,* or *marketplace* are not included as they would require a larger ecosystem including many other factors and would exceed the scope of this thesis.

2. Motivation

2.1 The State of Cutting-Edge Fabrication

The field of robot-assisted fabrication has made tremendous leaps over the last decades. With robotic automation, goods could be produced at a rapid pace with customized setups implemented for the production of large quantities of identical goods. Recently, a high degree of customizable production workflows has led to an era of mass customization[10]. However, despite constantly changing, fabrication technology persists as a collection of processes that generate an enormous environmental burden, starting when a material or an amount of energy is taken out of a natural flow or system and used to make or build something. The process of isolation, extraction, and refinement of materials and resources is often not the goal but rather a necessary means that allows for the discrete handling of components and ingredients needed to fabricate products. Hence, products are created by a human-made process in which little of the used energy is fed back into the environment since neither byproducts nor used products can be reused by the environment. The most prominent example of this is, of course, the vast amounts (an estimated 8.3 billion metric tons) of plastics produced to date, just 9% of which we are currently able to recycle[11]. Since the 1970s, initiatives to apply the principle of *circular economy* and *industrial symbiosis* to architecture and product life cycles have been underway[12,13]. These follow the notion that in industrial and architectural complexes, just like in natural ecologies, there should be a zero waste policy as all excess products of any organism are used by other organisms in the ecosystem.

With these principles in mind and focusing on robotic fabrication systems, the question motivating the work of this thesis is: How can we use the robotic technologies we have developed to interact with natural systems during the process of fabrication?

Over the last decade in robotics, there has been a movement away from devices that simply execute position scripts towards collaborative systems[14]. In these systems, the human is the subject in collaboration with the robot. Interface components like force sensors, LiDAR rangefinders, motor control chips, etc., are configured to allow for safe human-machine interaction. In a synergetic, collaborative co-fabrication process with other species, however, these organism-machine interfaces may need to look different. They may not be fully human-centric but instead aimed at connecting fabricating organisms like insects to the machine and the human.

2.2 Fabrication Relationships

Literature suggests that mutualism has a substantial impact in natural environments ecosystems[15,16] . Judith L. Bronstein describes a system with low degrees of mutualistic relationships as one in which there is a low amount of diversity as well as a divide between highly specialized individual organisms and “incompetent generalists”[6]. In this scenario, she concludes, there would be a high degree of competition among successful participants of an ecosystem, and at the same time, these participants would be spending more of their available resources on competing against others than they would in the case of a mutualistic environment.

Parallels are apparent between this system and the status quo in production industries for goods and architecture. Currently, a majority of materials used in fabrication and building processes are manufactured in a subtractive fashion. Material is sourced, refined and processed, cut to size, assembled into products, cataloged, stored, transported, and installed or sold. Various forms of emissions are created throughout the entire operation. In contrast to natural processes, these byproducts and emissions often cannot be used by the ecosystem or by other species unless altered via complex extraction processes.

In this thesis, I examine if and how a mutualistic approach to fabrication can be leveraged in order to reconnect artificial and natural systems.

3. Problem Statement

As part of this thesis, two problems are identified.

A. Many of the common fabrication and building systems still focus on exploitative extraction-refinement-assembly processes that do not generally over feedback on energy flows, nutrients exchanges, or other desirable emissions back into the natural environment.

B. When interacting or indeed co-designing with living organisms to establish a co-fabrication process, there is almost always a limit in scale, which does not allow for large architectural designs.

I hypothesize that kinetic organism-machine interfaces enable us to connect natural and artificial fabrication into architectural-scale mutualistic co-fabrication.

4. Definitions

4.1 Interface (Kinetic Interface, Organism-Machine Interface)

Kinetic interfaces are usually referred to in the field of human-computer interaction(HCI). In this thesis, however, the term *interface* describes an actuated, physical hardware architecture—a machine—that enables an interaction or physical exchange between two or more species. The term *Organism-Machine Interface* relates to a non-human-centric approach, including other (fabricating) organisms, their needs, and their physiologies, while placing the human as a stakeholder at the periphery of the interaction process. Arguably, anything engineered or designed will inherently be human-centered to a certain degree, as it lives up to a set of expectations formulated by humans. Including and treating living organisms like participants (stakeholders), however, changes the focus and effects of our designs. Where previously there was only a manufacturing process and a rare material, there could be an organism with a natural habitat, which is not treated based on the scarcity of one of its products (in economic terms) but regarded as an active entity with benefits or detriments and with a lifespan.

4.2 Mutualism

In this thesis, *mutualism* is defined as:

> "all mutually beneficial, interspecific interactions, regardless of their specificity, intimacy, or evolutionary history."[6]

Bronstein suggests a further categorization of different types of mutualism into groups[6] according to factors such as:

- Degree of dependency
- Degree of specificity
- Degree of physical interaction (Symbiosis)
- Shared evolutionary history
- Nature of the exchanged benefits

In **Conclusions**, these categories will be referenced to define an additional category directly relating to the effects and outcomes of a mutualistic relationship geared toward fabrication.

4.3 Symbiosis

According to Bronstein's review of various works of the past, *symbiosis* is a relationship directly tied to close physical contact of the species involved. The emphasis here is on an intimate physical co-evolution which doesn't necessarily encompass mutualistic aspects of a relationship. The term is also used in cases where the exact interspecific exchange remains unclear.

4.4 Domestication

As the projects described in this thesis focus on two domesticated species, *Apis mellifera* and *Bombyx mori*, it is useful to define the relationship between *domestication* and *mutualism*. For this thesis, *domestication* is defined by a permanent mutualistic relationship such that:

> "Domestication is a sustained multigenerational, mutualistic relationship in which one organism assumes a significant degree of influence over the reproduction and care of another organism in order to secure a more predictable supply of a resource of interest, and through which the partner organism gains an advantage over individuals that remain outside this relationship, thereby benefiting and often increasing the fitness of both the domesticator and the target domesticate."[17]

Due to the impacts of domestication, *Bombyx mori*, in contrast to *Apis mellifera*, are fundamentally not independent of the human in procreating and in maintaining a diverse gene pool throughout several generations.

5. Methods

5.1 Seasonality and Climate

All research presented in this thesis was conducted between September 2018 and March 2020. Due to the seasonal nature of work with insects, the timing of each project depended on geolocation and local climate. For example, most research work regarding *Silk II* was set up and conducted in collaboration with the CREA AA Sericulture laboratory in Padova (Veneto) in Italy in Summer 2019. The *Maiden Flight* experiment was conducted in West Texas in Spring 2019. Each experiment included a thorough investigation of the local climate and adaptation strategies to ensure the appropriate and ethical treatment of the organisms involved.

5.2 Research Approach

While the primary research objective was to identify interfaces to interact with organisms, some of the prototypes focus on data acquisition and basic research first, before diving into possible applications in a fabrication environment. Because of the reciprocal and long-term nature of this work, short-term scientific goals are less dominant. Studying the fertility of honey queen bees, for example, often requires sacrificial methods in which the individual organism needs to be dissected to gather data. However, our transport vehicle for bees to travel into space and back was designed to keep the queens and their retinues alive and healthy. In such a conflicting case, a life-preserving approach to data collection, and therefore a validation of the capsule design, was preferred over any sacrificial method.

The species chosen to interact with these prototypical environments were *Bombyx mori* (silkworms) and *Apis mellifera* (honey bees). While both species are fundamentally different in behaviors and metabolisms, they both modify their environments over the course of different stages of their lives. Both insect species additively construct very distinct forms of architectural structures that offer a host of functions such as protection from predators, climate regulation (Fig. 7a), food storage (Fig. 7b), and brood bearing. Because of their natural display of additive manufacturing, they lend themselves well to the study of co-fabrication interfaces.

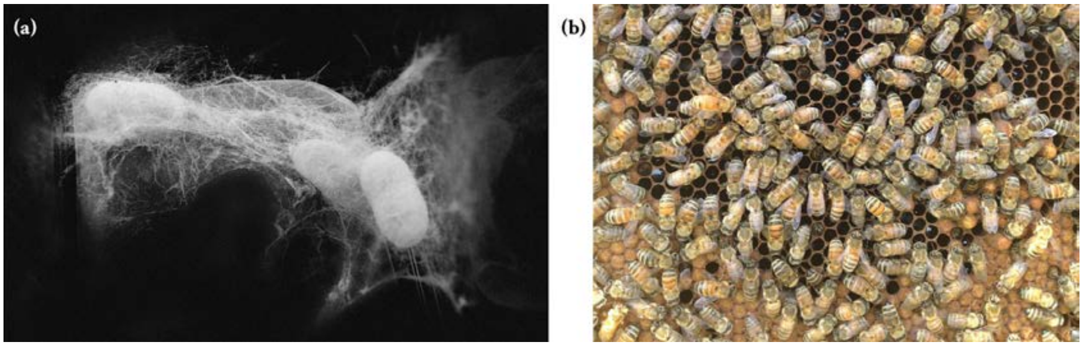

Figure 7: (a) Silk cocoons and surrounding thread structure, produced at the beginning of the spinning phase. Image by João P. Costa **(b)** Worker bees maintaining a partially capped (closed) honeycomb. • Image by The Mediated Matter Group

The research in this thesis is part of a wider range of works by the Mediated Matter Group at the MIT Media Lab. As such, it references and builds upon previous work of the group. One example is the notion of *environmental templating*—the design through environmental conditions that inform the outcome of a natural fabrication process.

5.3 Variables

Each of the presented projects examines a range of *variables* (environmental factors) that may represent a key to the modification of the behavior and metabolism of an organism. The following variables are most notable as they are examined in each case:

- Gravity (strength, direction)
- Space (surface shapes)
- Time (rate of change)

The following enabling factors were crucial throughout, although not directly as variables used to shape co-fabrication:

- Nutrition
- Climate (temperature, humidity)
- Visible Light
- Surface Features

6. Organisms

6.1 Silkworm (*Bombyx mori*, Non-Eusocial)

Sericulture, or the production of silk, relies on the larvae of the domesticated *Bombyx mori* (silkworms), a member of the *Bombycidae* family in the order of the *Lepidoptera*. Silkworms only consume one type of nutrition, the leaf of mulberry trees (*Morus alba* among others)[18]. They experience five distinct larval periods (instars), including four molting events (Fig. 8). At the end of the fifth instar, the larvae pupate, emerge from their cocoons, and develop into moths. The silk moths live for five to ten days[18]. Due to a high degree of domestication that has resulted in a loss of sensory functions[19] and loss of the ability to fly, females and males need to be mated in a procedure manually facilitated by humans. The female silk moth produces 450 to 550 eggs.[18]

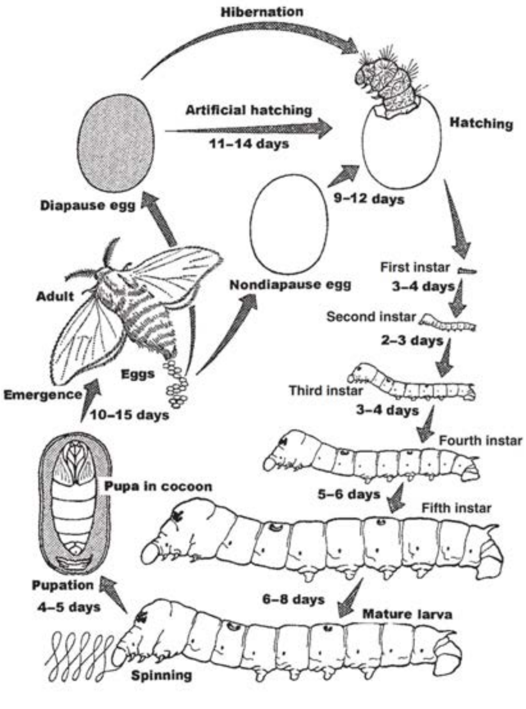

Figure 8: Life Cycle of *Bombyx mori* Silkworms[18]

In industrial silk production, a silkworm larva produces a continuous silk thread of about 1,000-1,500 m in length[20] on average and constructs a cocoon from it in preparation for pupation. The silk consists of a protein-based fiber core (fibroin) with a thin sericin coating, the latter of which can be dissolved using warm water.

If left for too long, the pupa (which is in the metamorphic stage following a cocoon spinning by larvae) develops into a moth; emerging from the cocoon it damages the thread and destroys its continuity. The cocoon is therefore usually dried when silkworms are at their pupal stage and soaked in soap water in order to reel the silk thread, avoiding moth emergence.

The relationship between humans and silkworms is closely tied by the process of domestication. In this relationship, the organism cannot live without the host (human) and the organism needs to genetically benefit from the host's interventions. Silkworm rearing laboratories such as the CREA-AA Sericulture Laboratory (Padova, Italy) play a key role in conserving the biodiversity of the species by maintaining Europe's largest genetic pool of silkworm strains.

Until now, humans could only profit from silk production if a majority of the individual organisms were sacrificed. The practices described in this thesis focus on situating silkworms and humans in a dynamic balance in which the human guides the organisms to produce silk without interrupting the silkworm's metamorphosis by sacrificing it.

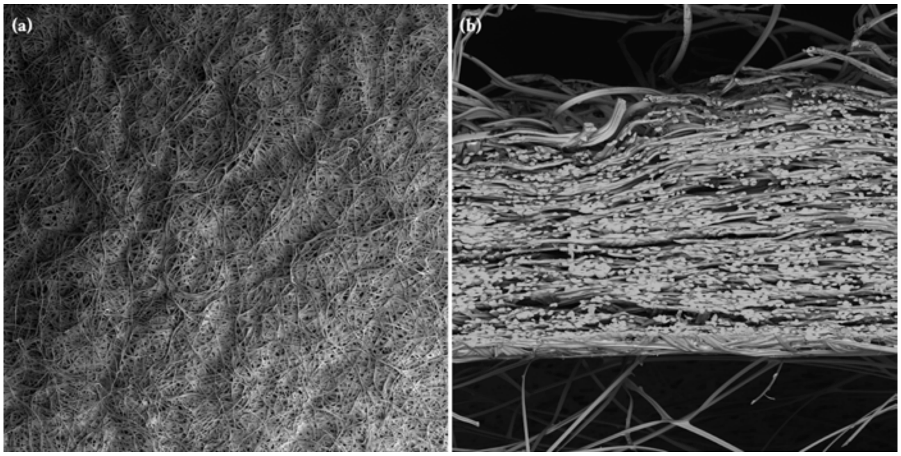

Figure 9: **(a)** Scanning electron microscope(SEM) image of silk-layering on the surface of a cocoon **(b)** Section through the shell of a silk cocoon. • Microscopy by James Weaver.

Recent work of the Mediated Matter Group has shown that several factors affect how the silkworm spins, at what rate, and resulting in what shape. If given only flat surfaces as terrain, it will spin patches without constructing a cocoon. Environment temperature and light were found to have a significant influence on where the silkworm spins on any given surface.

One of the most consistent behaviors observed in worms in the fifth instar is the extreme desire to move upwards, as high as possible. The vertical migration suggests that worms can sense the effects of gravity, and change their behavior accordingly. It is thought that silkworms, like many other insects, have gravity sensing cells or tissues, such as Johnston's Organ, which help detect mechanical signals[21].

Silkworms have been thought to not exhibit social or collective behavior. Wild moth and butterfly caterpillars like the Oak Processionary (*Thaumetopoea processionea*) or the Madrone Butterfly (*Eucheira socialis*) clearly show clustering, communal nest building, and other communal activities including thermoregulation and group defense against predators. If *Bombyx mori* does, in fact, demonstrate collective behavior, it could provide new opportunities in fabrication.

Research conducted by the Mediated Matter Group (Sunanda Sharma, Sarah Wilson) as part of the *Silk II* project has revealed collective behavioral traits such as clustering and recurring physical contacts between pairs or small groups of individuals (Fig. 10).

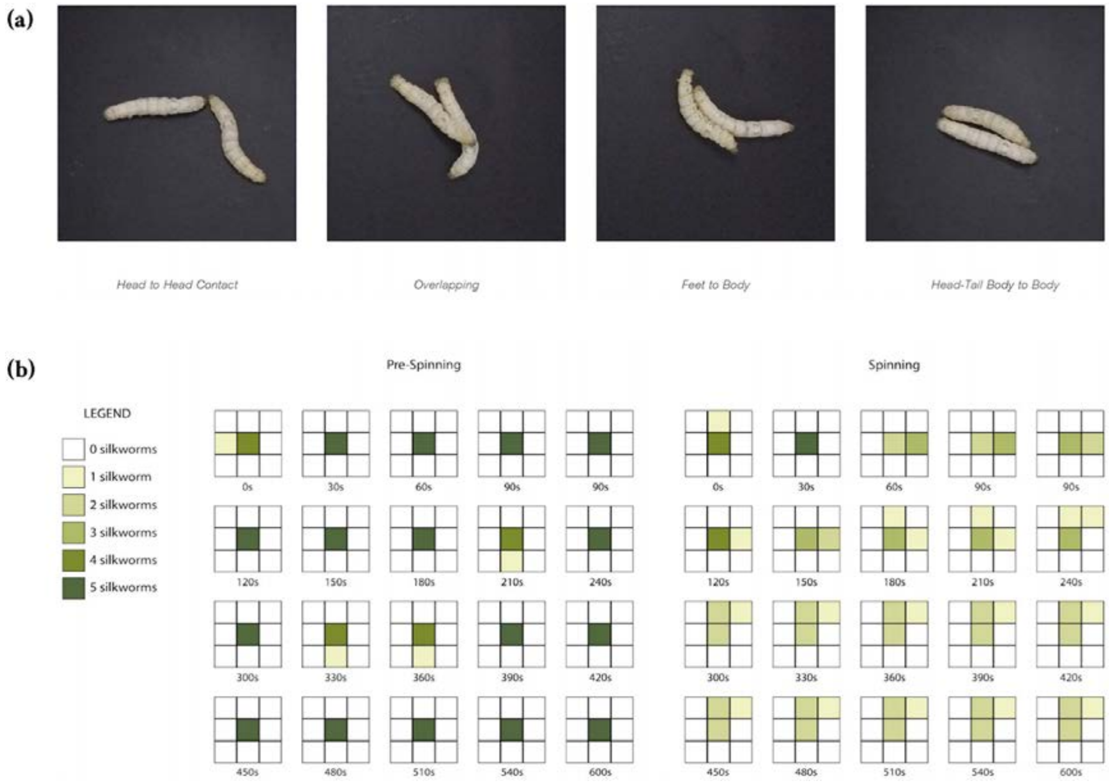

Figure 10: Research by The Mediated Matter Group shows that some social behavior is present in silkworms in the form of **(a)** types of frequently recurring physical contacts, determined by manual tracking. **(b)** Density maps show clumping behavior before and during the spinning phase. • Images and analysis by Sunanda Sharma and Sarah Wilson.

While the social interactions of *Bombyx mori* are subtle, the results of this study indicate that in some stages of development, collective behavior is present. The question of whether this behavior can be triggered through environmental conditions or human interventions remains open for future developments of the projects presented in this thesis.

6.2 Honey Bee (*Apis mellifera*, Eusocial)

Apis mellifera (western honey bee), belongs to the *Apidae* family from the order *Hymenoptera.* It is the most common honey-producing and, next to wild bees, the second most important plant-pollinating insect in the world[22]. Honey bees live in colonies of tens of thousands of individuals. Colonies are structured into different castes (queens, workers, and drones) with various responsibilities, including scouting, foraging, brood-bearing, and nest building, among others. At most times, there are multiple generations of bees actively pursuing these activities across generations at the same time, which makes *Apis mellifera* a eusocial species.

The central reproductive node of a honey bee hive is the queen. She is surrounded by female workers that groom her, feed her, and attend to her thermoregulation (Fig. 11). The queen bee produces eggs and deposits them in cells of the comb structure, which is produced and maintained by worker bees.

Figure 11: Image of a queen being surrounded by her nurse bees. • Image by Ren Ri.

The wax comb structure inside a beehive serves as a storage unit both for honey, which worker bees produce out of nectar, and for larvae hatching from eggs inside the cells[23]. The specific hexagonal shape and precision of the comb structure are believed to result in part because of the physical properties of the wax and in part because of the building skills of the worker bees[24]. It has been observed that at the beginning of the building process, the cells are actually cylindrical and only later become hexagonal[25]. Combs are built on frame structures provided in human-made Langstroth hive models and always include a double-sided hexagonal structure of cavities (cells). If no structure is provided, the workers of a hive will start to form “wild” wax combs downward from the ceiling of the space they inhabit[26]. If the hive runs out of comb surface area, additional combs are added, usually in parallel to the existing ones.

As can be seen in works by the artist Ren Ri and more recently in research by the Mediated Matter Group (Fig. 12), the shape of a honeycomb can change during the building process, for example when the direction of the gravitational forces change, either due to a modification in the orientation of the hive housing or due to a change in orientation of the base material structure.

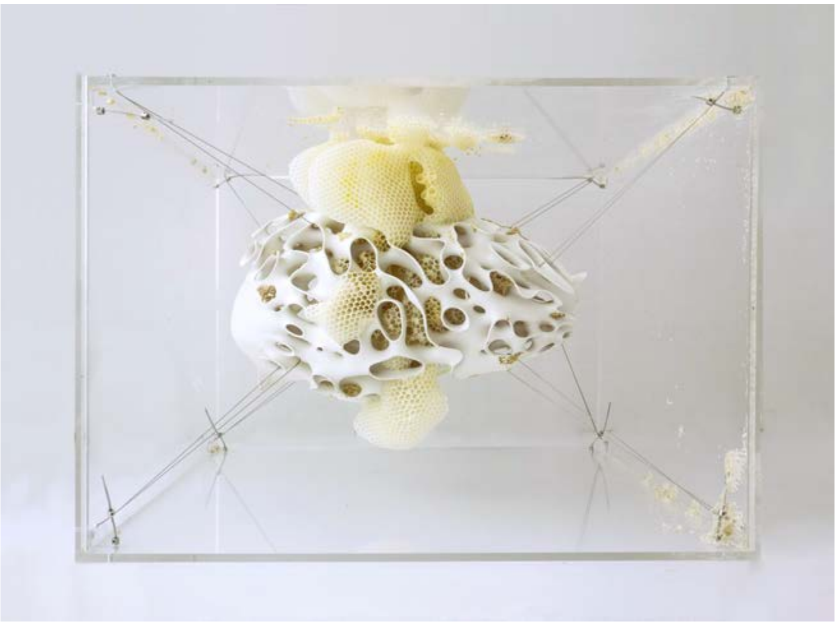

Figure 12: Pneuma by Ren Ri and The Mediated Matter Group. • Image by João Costa.

As insects which additively build and modify wax architecture in their immediate environments, bees are a promising subject. Not only has previous work shown that a modification in the direction of gravitational forces may reflect in the comb structures built by hives, working with bees also adds a behavioural component as any constructional effort happening in the hive is executed collaboratively by many individuals.

In order to lay the ground for future co-fabrication systems incorporating *Apis mellifera*, the Maiden Flight study (**Environments**) was conducted .

7. Environments

7.1 Maiden Flight

Maiden Flight is an autonomous payload module ("Nanolab") built for studying the behavior of honey queen bees and their retinue in the context of space travel. The conducting of experiments with living organisms in a spacecraft is in this case both a physically challenging and an aspirational field of scientific inquiry. On one hand, this environment provides the opportunity to study the impact of fluctuating (high and low) gravitational forces on bees as additively fabricating organism. On the other hand this extreme environment may give insight into what modifications could be made to the environment in order to protect and to strengthen hives on earth.

Two Nanolabs were produced and successfully sent on the 11th unmanned Blue Origin *New Shepard* flight in early 2019 in West Texas, performed with a reused vehicle, the *New Shepard III.* Another two experiment control Nanolabs remained on the ground.

Previous experiments conducted by NASA in 1984 focused on a comparison between the shapes and properties of honeycomb constructed by *Apis mellifera* in a zero gravity environment and under regular conditions on the ground. Findings concluded that bees adapted to the environment and built regular honey combs with the exception that downward orientation of the overall comb structure was not as pronounced when built in a zero g environment. Once reintegrated into hives on earth, the eggs laid by queens in these experiments, however, did not turn out to be viable.[27]

The Nanolab presented here supplies nutrition (sugar fondant), regulates temperature, and records humidity measurements as well as video footage of the queens during a ten-minute parabolic flight to suborbital space. The design specifically takes into account the anatomy and biology of bees while enabling the collection of data and video of the insects in a microgravity environment.

Two objectives were pursued in the experiment presented here:

- To record the reaction of the queen bees (and of their retinue) to changes in g-forces.
- To develop a viable autonomous environment for unsupervised space travel of honey bees.

Payload designs for space missions have conventionally been constructed using a "frame" or "housing" approach[28], in which the contents of the experiment must be individually affixed to a machined or 3D printed frame. Utilizing a novel design philosophy, a lightweight foam (*General Plastics FR7100*) was used to consume all available space (Fig. 13), and a design process to subtract the physical and functional footprints of all functional parts of the experiment (camera, sample, sensors, battery, connectors, etc.) from the volume, thus securing them multi-directionally.

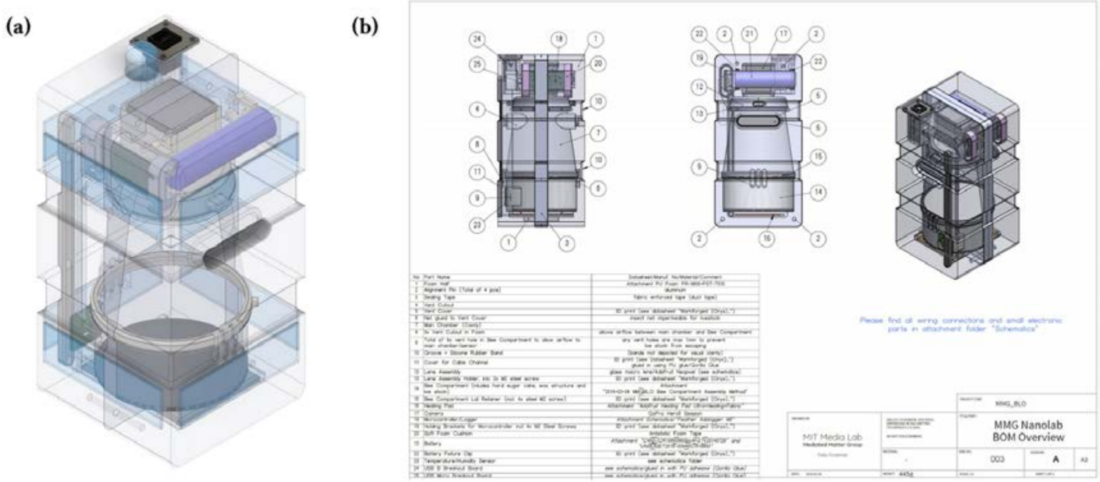

Figure 13: **(a)** Nanolab 3D CAD wireframe drawing **(b)** Nanolab bill of materials drawing.

The two-part lightweight foam chassis (Fig. 14a) simultaneously serves as a shock-absorber, thermal and electric insulator, fire-retardant, and multidirectional fixture. The interior of the bee compartment inside the Nanolab was constructed in a joint process of classic prototyping using tubular acrylic and an augmentation procedure in which the compartment was placed inside a beehive previous to the flight. Within the hive, the bee compartment was laid out and coated with wax deposited by worker bees. This process prepared the interior of the bee compartment for the flight (Fig. 15).

Figure 14: **(a)** Two-part foam design, two identical autonomous Nanolabs (A and B) were produced for the flight. Controls were performed in separate settings using foam parts of the same type and color. **(b)** All parts of the Nanolabs.

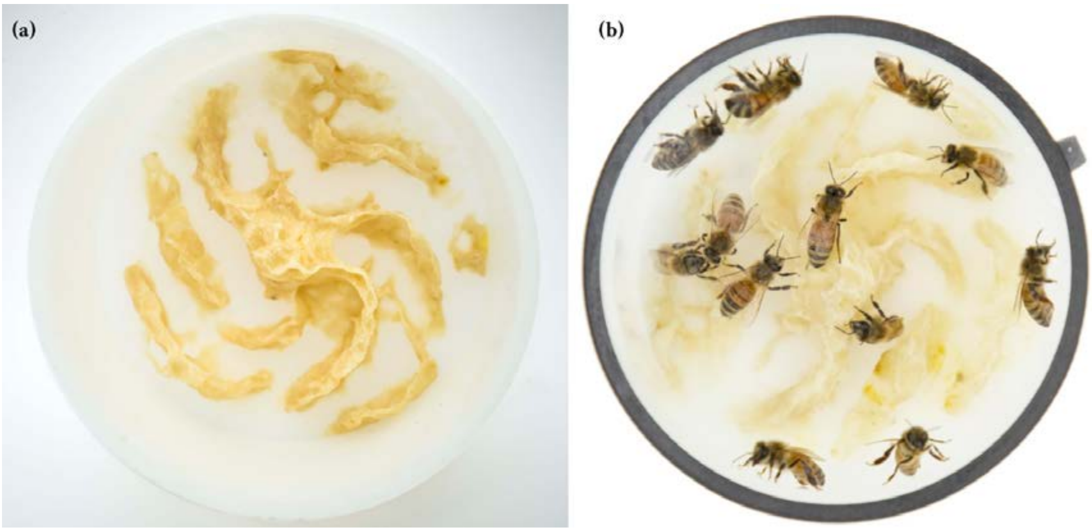

Figure 15: **(a)** Wax lining inside the bee compartment after preparation by a hive. Foundation (~15%) of the wax pattern laid out by Ren Ri and subsequently completed by a regular size hive in Cambridge in late Summer 2018 • Image by Ren Ri **(b)** Bee compartment including lid, ready for integration into a Nanolab.

The Nanolabs were prepared on the day before the launch and the queens, each accompanied by 15–20 nurse bees, were integrated into the vehicle capsules at ~10 p.m. local time. Final integration of the Nanolabs into the vehicle capsule took place at ~1 a.m. local time on launch day. After integration into the vehicle, a period of ~7 hours followed in which vehicle preparations were performed by Blue Origin ahead of the start. The vehicle liftoff took place on May 2, 2019 at 8:30 a.m. local time at the West Texas launch site.

7.1.1 System Structure

The *Maiden Flight* capsule system is divided into two circuits (Fig. 16, marked in blue and orange). To ensure continuous operation of logging functions, temperature measurement, heating function, and camera launch function, a 9V battery is included in the module. All devices and functions connected to the controller circuit (orange) remain operational, even when vehicle power systems are cycled after integration into the vehicle and prior to liftoff. Vehicle USB provided by the *New Shepard's* system is split into 5V and Data. Power for macro lighting (circular LED array) is connected to the USB 5V supply and therefore dependent on vehicle power. Ground is shared via the microcontroller. The vehicle data stream providing live information from vehicle systems is received by the microcontroller.

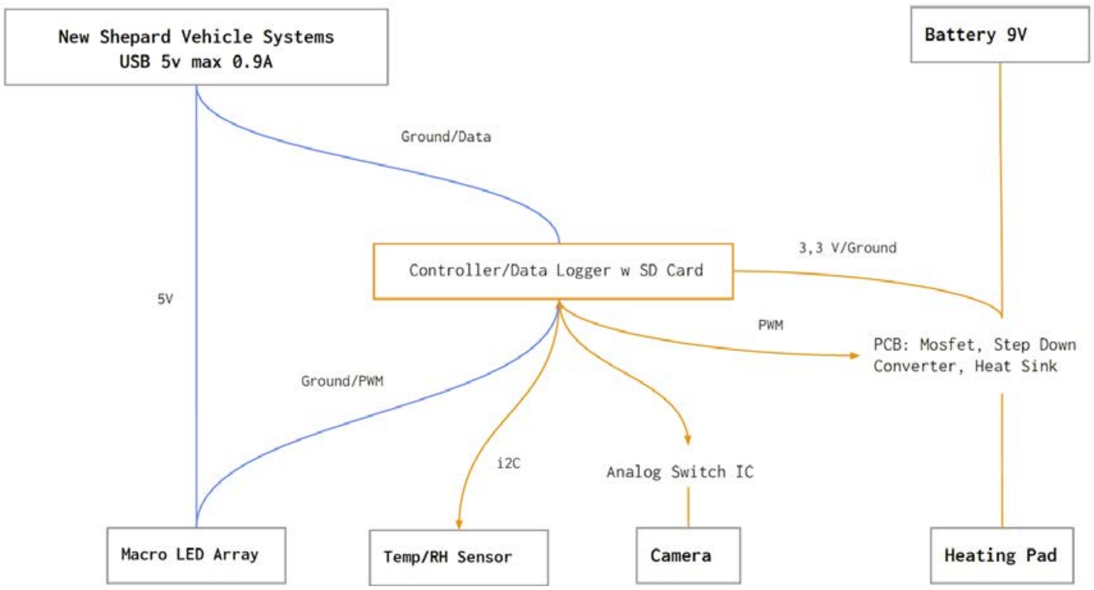

Figure 16: *Maiden Flight* Nanolab system diagram showing all connected devices and circuit structure (blue and orange).

In order to achieve the most efficient and high-quality recording inside the capsule, a GoPro Session Hero 5 camera is modified and connected to an analog switch, which enables triggering of the video recording programmatically, from the microcontroller.

Temperature of the bee compartment can be monitored continuously, and the heating pad switched on if necessary. (During the actual experiment, heating was not required and therefore was not triggered). Upon receipt of the "liftoff imminent" vehicle signal, the module's camera capture is triggered.

7.1.2 Flight

Fig. 17 shows the combined measurements retrieved from onboard systems and each one of the *Maiden Flight* modules. Temperature and humidity remained effectively constant during the flight. The crew capsule reached apogee at 240 seconds after liftoff and returned to ground, decelerated by two parachute stages (changes in acceleration can be clearly discerned and correlated with upward velocity, altitude, and acceleration at 120 sec, 360 sec, 480 sec, and landing at 600 sec from liftoff). The entire flight duration was ten minutes. Approximately 2.5 hours after the flight, the modules were retrieved from the locker inside the crew capsule.

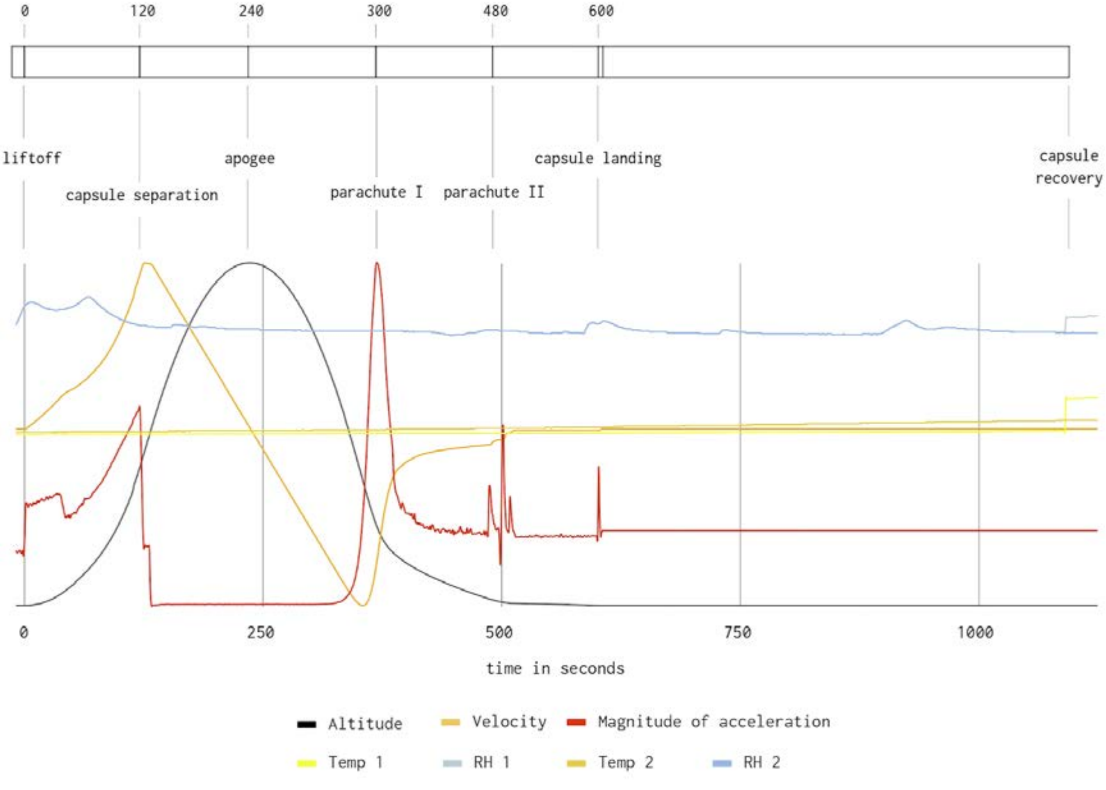

Figure 17: Graph overlay of vehicle data and *Maiden Flight* capsule data. Values are scaled and plotted without units to allow for comparability. Peak values: altitude 135326.64 m (above sea level), velocity 1289.36 m/s, magnitude of acceleration 63.82 m/s^2 (equals 6.507829 g). Capsule temperature ranges: 19.32–23.42 °C, capsule relative humidity ranges 30.74–34.17 %.

Figure 18: In-flight shot at apogee (approx. 240 sec after liftoff) with corresponding data obtained from Nanolab camera and vehicle systems. • Image assembly by Miana Smith.

7.1.3 Tracking

All queens taking part in the experiment were marked using a colored dot on the thorax. Footage collected inside the module during flight as well as inside the control capsules was analyzed (Fig. 19) using color separation, OpenCV object tracking and image foreground accumulation.

7.1.4 Findings

All bees inside both the main experiment modules and the controls on the ground survived the experiment and were subsequently transferred to Boston, MA for observation and re-integration into larger hives. During this period, one of the two queens perished due to the inaccessibility of nutrients, unrelated to transport or to the event of the flight itself.

After reintegration into hives, the remaining queen successfully laid fertile eggs and produced one generation of healthy offspring within the hive in summer 2019. This suggests that the event of the flight had no detrimental effects on the health and fertility of the remaining queen.

In order to examine if there were any hints of adverse behavioral effects of the bees during the flight, the video footage of the flight was processed and consulted.

Due to a difficulty in timing the Nanolabs video captures in relation to the autonomous liftoff controlled by the New Shepard vehicle system, the video footage collected during the flight starts one minute after liftoff. Therefore the tracking dataset (Fig. 19) starts one minute into the flight time as well and needs to be regarded as incomplete. All other data collection captured the entire experiment from time of integration into the vehicle until retrieval. Nonetheless, certain observations can be made: The probability distribution in both the flight setting (Fig. 19a, 19c) and the control (Fig. 20a) shows that the nurse bees attended to the queens by staying with them in close proximity. The queen path analysis shows that in both flight settings (Fig. 19b, 19d), the queens moved more within the compartments compared to the control (Fig. 20b). In both flight settings, the activity (Fig. 19e, 19f) of the queen increased for a duration of several minutes, upon landing of the vehicle.

Overall, the wax interior of the experiment capsules was observed to have facilitated placement of the bees (their ability to hold onto the surface) and seemed to significantly lower stress symptoms (racing, fanning) in the queens and their nurse bees during transportation as well as during the flight, compared to test capsules which were not lined with a wax interior.

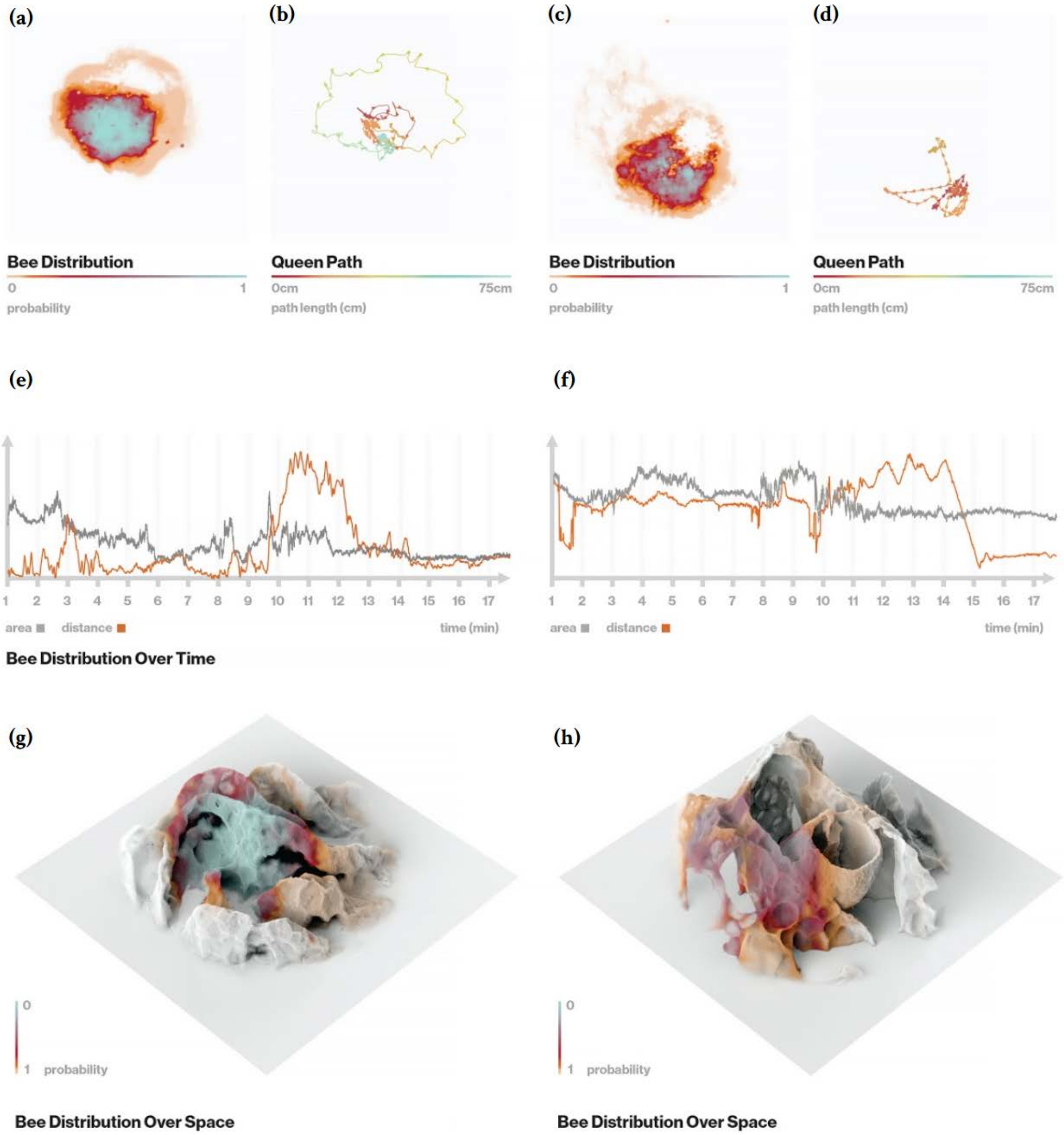

Figure 19: (Video recording, and therefore tracking, starts one minute into flight time) **(a)** Nanolab A: Probability distribution encoding the likelihood of a bee at a location in the 2D plane. **(b)** Nanolab A: Path of the queen. **(c)** Nanolab B: Probability distribution. **(d)** Nanolab B: Path of the queen. **(e)** Nanolab A: Average area of the bee cluster in grey. Orange line shows the distance from the bee cluster centroid to the queen. **(f)** Nanolab B: Average area of the bee cluster Nanolab B. **(g)** Nanolab A: CT data of the wax lining with a color overlay of the heatmap from the previous diagram. **(h)** Nanolab B: CT data of the wax lining with color overlay of the heatmap from the previous diagram. • Tracking and graphical composition by Christoph Bader, CT scans by James Weaver.

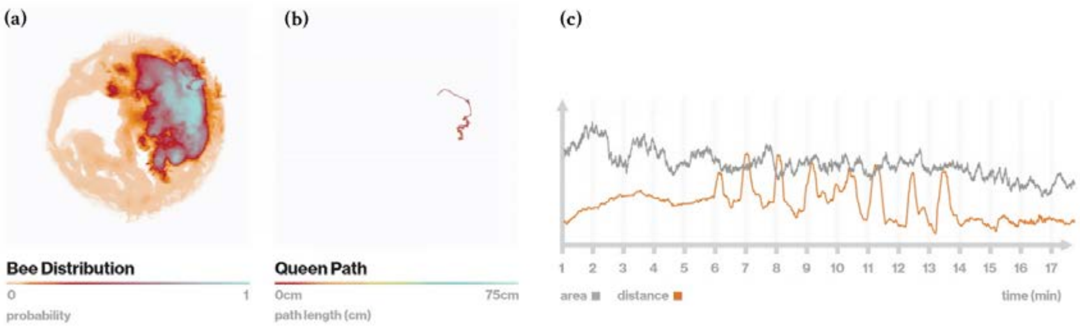

Figure 20: **(a)** Control: Probability distribution encoding the likelihood of a bee at a location in the 2D plane. **(b)** Control: Path of the queen. **(c)** Control: Average area of the bee cluster in grey. The orange line shows the distance from the bee cluster centroid to the queen. • Tracking and graphical composition by Christoph Bader

7.1.5 Future Maiden Flight Development

Maiden Flight examined the behavior of queen bees in microgravity while laying the foundation for further experiments due to its entirely integrated capsule design. This approach could be applied to experiments with a different set of goals, requirements, or sensor types.

While the presented experiment gave insight into some of the behavior of honey queen bees in a microgravity environment, the follow-up *Maiden Flight II* will focus on metabolism. A redesign of the capsule's sensor system and on-board controller platform incorporates a radiometric Flir Lepton 3 module in combination with an OpenMV H7 single board python camera to record thermal footage during the flight and to perform any necessary OpenCV-based tracking at experiment time. An additional change in sensor equipment is planned to allow for the recording of carbon dioxide levels. Both thermal footage and respiration levels (CO_2) are anticipated to give insight into the levels of exertion the bees go through during a flight.

7.2 Silk

7.2.1 ZG Stardust

Project *ZG Stardust* is a custom designed, miniature insect imaging module (100 mm ∅), suitable to be carried by individuals (Fig. 22) during a parabolic flight. It is designed to enable video and still photo coverage of insects during a period of microgravity. The module was carried as part of a parabolic flight on August 15, 2019. A *Bombyx mori* silkworm in the fifth instar (spinning phase) and a silk moth were carried within the compartment. The research associated with the project looks at the impact of changing gravitational forces during and after the productive spinning phase as well as during the entire lifespan of the insect.

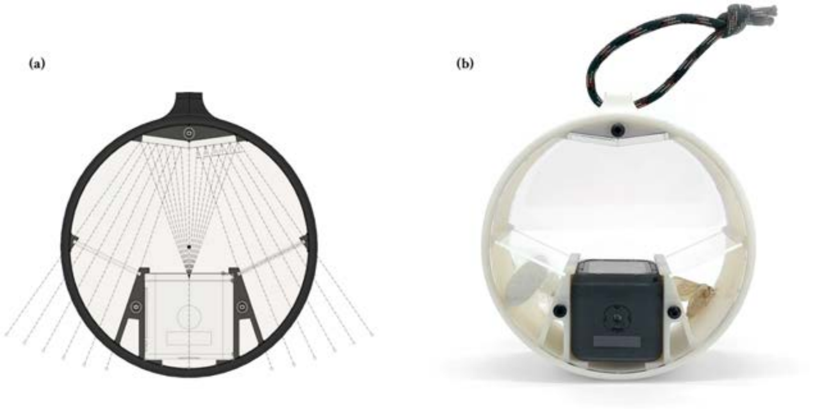

Figure 21: **(a)** CAD drawing of ZG stardust imaging module, showing the optical path planning for the integrated camera. Use of mirrors (top part) allows for use of minimal focus distance within limited module footprint. **(b)** *ZG Stardust* miniature insect compartment.

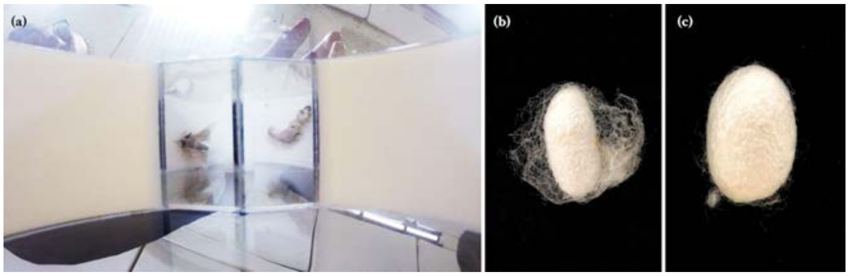

Figure 22: **(a)** In-flight shot captured by the module, showing a silkworm in the fifth instar (spinning phase) as well as a silk moth via a mirror construction. The module is worn on the wrist of one of the participants (Harpreet Sareen) during the parabolic flight. **(b)** Cocoon spun during parabolic flights (25.7 mm x 11.53 mm x 11.43 mm). **(c)** Control cocoon spun in 1 g (29.2 mm x 18.7 mm x 18.8 mm). • Images (b), (c) by Sunanda Sharma.

The cocoon spun during the experiment exhibited a smaller overall footprint and a more densely-packed fiber mesh. Consulting SEM imaging of the cocoon confirmed this observation. The silkworm survived the flight, successfully went through pupation, and emerged from the cocoon.

Other experiments conducted during the flight found similar results. Spinning under changing gravitational influences was possible for the worms, with a majority (90%) of moths successfully emerging from the cocoons. Individuals in the moth stage carried during the flight survived but were not able to mate afterwards. However, this may not be representative as the experiment was only conducted with one pair.

Overall, it was concluded that the design of the imaging compartment worked as planned, hinting at possible future versions of the compartment for the purpose of studying insects in an environment with low availability of rack or floor space.

7.2.2 Preliminary Prototyping

The following kinetic prototypes build upon an approach explored by the Mediated Matter Group whereby silkworms in the fifth instar are provided a surface to spin on. The absence of suitable geometry to spin a cocoon results in deposition of the silk in flat patches. Upon completion of the spinning phase, pupating worms remain on the surface and can be gathered to continue their metamorphosis.

The approach in Fig. 23 was demonstrated and evaluated by members of the Mediated Matter Group in 2016/2017 on a series of flat platforms on to which silkworms were placed on. Each platform included a cylinder with a height ranging from 3 to 30 mm. The results showed that when provided a geometry >23 mm, the worms succeeded in constructing a basic web of threads at the center of which a cocoon enclosure started to grow. If provided less height as a basis for a cocoon base structure, attempts to build circular patches are visible, but the overall geometry of the silk construction remains 2-dimensional.

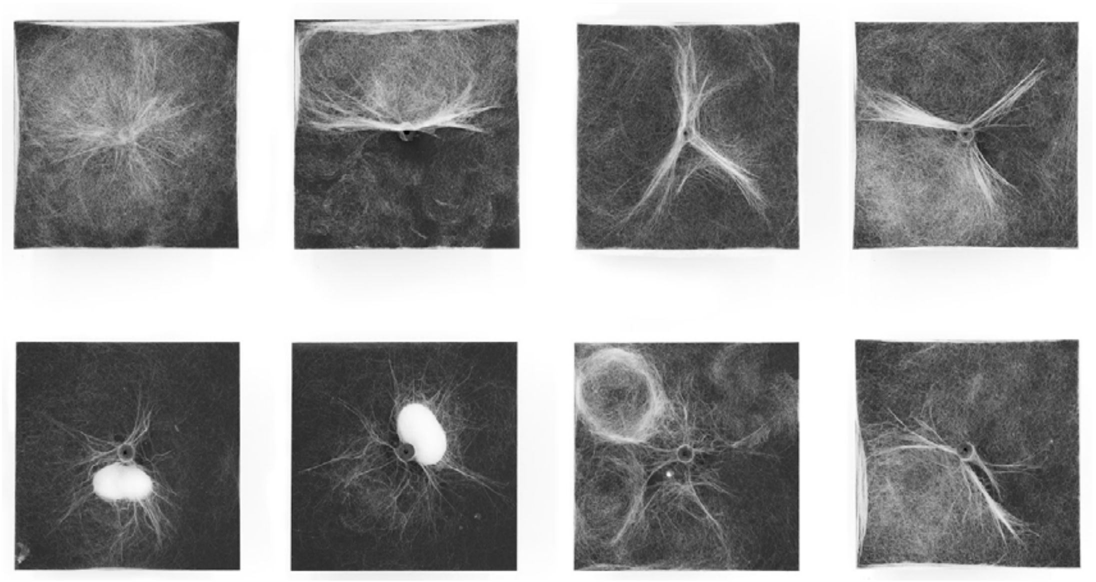

Figure 23: Research conducted by the Mediated Matter Group, showing a series of platforms (top view) with cylinders in different heights. Silkworms were placed on the platforms for the durations of the spinning phase, producing flat silk patches (when provided low geometry to attach silk to) and cocoons (when provided cylinders > 23mm). • Image and composition by João Costa.

The "Swivel" prototype (Fig. 24) explored the idea of actuating the spinning surface. Silkworms generally tend to migrate to any higher point or plane. Actuated using a stepper motor, the platform can be tilted, and by repeating the tilting motion, the average height of the extremes of the platform can be modulated. As an early prototype, it allows us to gauge the silkworm's responsiveness to a kinetic change of the surface angle. The setup was populated with ten silkworms.

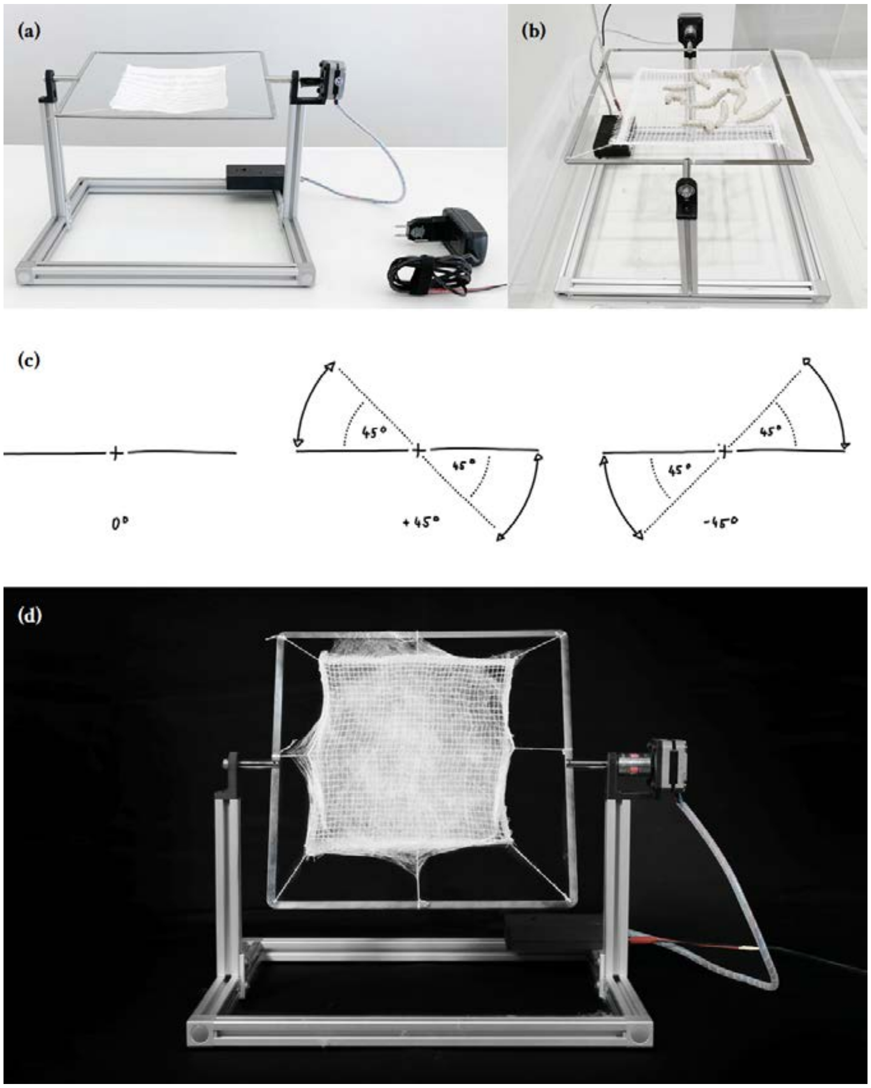

Figure 24: **(a)** "Swivel" Prototype with a 250 mm x 250 mm symmetric platform attached to a stepper motor. • Image by Susan Williams **(b)** "Swivel" system, populated with silkworms **(c)** Succession of programmatically defined system positions **(d)** "Swivel" with resulting silk surface after prototyping sessions. • Image by João P. Costa

The system was run with two different interval settings:

A. → pos +45° → pos -90° → pos +45° in 1 minute (angular velocity 0.0524 Radians/second)

B. → pos +45° → pos -90° → pos +45° in 20 minutes (angular velocity 0.0003 Radians/second)

Each interval was run twice, each time continuously for five hours. In Setting A, there was no apparent migration of the silkworms between the center of the platform and the two outer edges. This was suspected to be due to the interval speed. In Setting B, a clear migration towards the outer two edges of the platform was visible during tilting angles with more than approximately ±20°. Overall, silk distribution on the surface remained even.

Iterating on the "Swivel" prototype design, a cylindrical (hyperboloid) spinning surface, “Mini Hyperboloid,” was created (Fig. 25). The base for this surface was a pair of aluminum wheels, each 150 mm diameter, mounted on a central axis, 435 mm apart. A set of ten steel wire ropes was tensioned between the wheels, each wire crossing two other wires. After tensioning the cables, a stretchable knitwork was applied, resulting in a hyperboloid surface A of approximately 2403 cm^2.

Wrapping the spinning surface into a hyperboloid resulted in a continuous surface and introduced new possibilities for kinetic intervention using an actuator. The axis of the construction was mounted at either end, using a ball bearing to allow for rotation. To allow for control of the movement of the mandrel, a pulley was fabricated, adapted to the end of the axis and connected to a DC motor via an elastic belt. Speed and absolute position of the mandrel were measured and controlled using an absolute rotary encoder (*CUI AMT203*), attached to the axis, and a DC motor controller (*Roboteq SDC2160*).

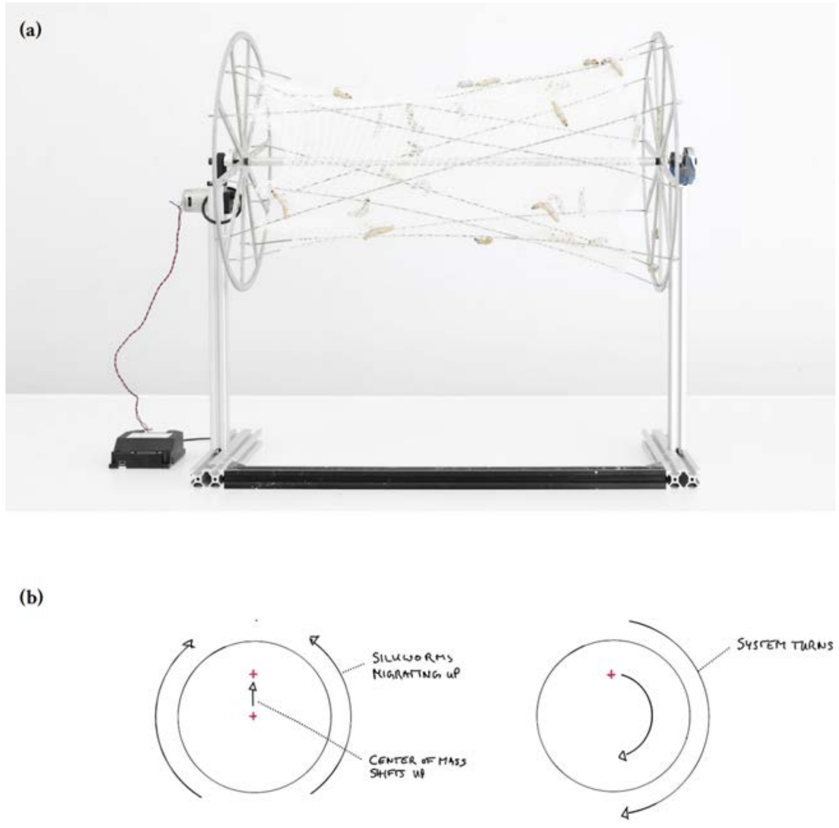

Figure 25: **(a)** “Mini Hyperboloid”. • Image by Susan Williams **(b)** Observation of system behavior.

The system was run intermittently in various configurations and speeds, with the goal of gauging the behavior of the silkworms on the surface. A total of 25 silkworms were placed on the surface for a timeframe of 48 hours. The actuator was controlled manually via the controller driver software, switching between the following speeds:

A. Fast (~0.6109 Radians/second)
B. Middle (~0.3393 Radians/second)
C. Slow (~0.2443 Radians/second)

A continuous velocity lower than Setting C could not be achieved due to imbalances in the system (see **Prototyping Findings**). In parallel to prototyping efforts conducted with actuated surfaces, a large-scale double hyperboloid structure with an approximate surface area of 6.2 m^2 was created and tested in Padova, Italy (Fig. 26). This allowed for scaling up the number of silkworms spinning on the structure.

Figure 26: "Double-Hyperboloid" structure produced in Padova, Italy (2.5 m length). • Image by Susan Williams.

7.2.3 Prototyping Findings

In all three of the above prototypes, a migration of the silkworms towards higher terrain was observed. The surface area (625 cm^2) of the flat "Swivel" platform was too small to show differentiation in silk distribution but resulted in an even layer of silk of 2–6 mm thickness on top of the knitwork.

In "Mini Hyperboloid" (Fig. 25), as a result of the silkworm's simultaneous upward migration,

- a change of the center of mass of the system (imbalance) was observed.
- When run on a "slow" setting (<0.24 Radians/second, supplying ~0.4 V to the motor), the motor stalled whenever there was a higher density (~65%) of silkworms on the lower half of the surface.
- Once most of the silkworms consequently migrated upwards, the system started to move again.
- When the motor control was set to remain in one position (position control) for more than 10–15 minutes, a higher density of silkworms could be observed on top of the hyperboloid surface.

- A subsequent pause of the control system, or a movement in either direction resulted in a fast spinning motion with the center of mass (estimated) orienting towards the lowest possible point.

Once the silkworms approached the end of their spinning phase (fifth instar), their rate of movement visibly reduced. While entering pupation phase, their ability to hold onto the structure reduced and they dropped onto a cloth provided below the structure. From there, the worms could be collected and stored for the duration of the pupation phase and kept for rearing.

In the larger "Double-Hyperboloid" structure (Fig. 26), which didn't contain any machine-side actuation, a reoccurring rotational movement of the barrel was observed. This was thought to be the case due to a rebalancing of the system, as outlined in Fig. 25b.

It was concluded that the "dialog" between the natural instinct of the silkworms to move to higher ground and the intervention using a kinetic, actuated system may be a viable method to interact with silkworms in order to construct membranes. The aspect of *organism-driven actuation* of the hyperboloid system seemed especially notable and worth pursuing. Moreover, even though differential density in silk distribution could not directly be observed (due to a lack of surface area), a change in density of silkworms hinted towards position control as a means to control fiber density at large scale.

7.2.4 Development of a Soluble Substrate

In the above prototypes and platforms, it became apparent not only that the functional mechanical design of the system played a crucial role in creating an interactive fabrication procedure, but also that the tactile properties of surface structures needed to be designed and planned in order to live up to the requirements of silkworm migration and serve as a substrate for the spun thread.

Observations regarding surface properties of different materials (acrylic, smooth and rough surfaces, textiles etc.) showed that meshes could be used to provide silkworms with a structure as long as the density of the mesh was high enough (not containing holes larger than 30 mm in diameter). At the same time, the sericin covering the core fibroin of the silk thread should bond well with the mesh. A durable textile-like substrate would have become part of any membrane produced and would have therefore altered the balance of the resulting material, rendering the silk component an added feature.

Therefore, extensive prototyping and development of custom knitworks were undertaken by the Mediated Matter Group (Susan Williams). Knit meshes made of polyvinyl alcohol (PVA,

$[CH_2CH(OH)]_n$) thread were found to supply a sufficiently tactile yet ephemeral quality as a silk spinning substrate. Thread made of PVA dissolves when brought in contact with water, which serves as a plasticiser. PVA is known to be biodegradable[29]. Supplying a knitwork of PVA thread to silkworms, showed that it could be used as a substrate and could be dissolved by uric excretions of the worm during the spinning phase (Fig. 27d) as well as by manual application of water after the spinning procedure (Fig. 27b).

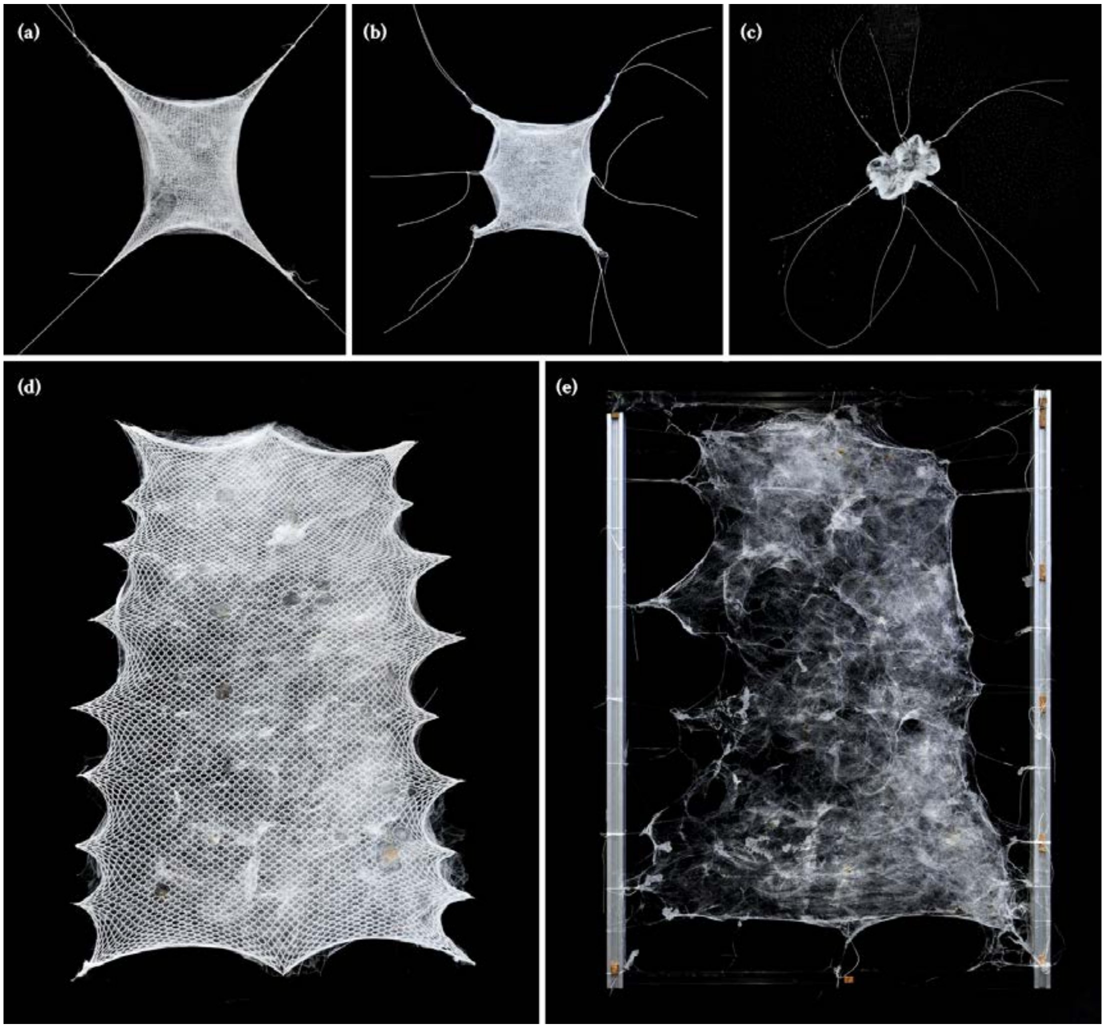

Figure 27: Soluble PVA substrate 150 mm x 150 mm with silk in three phases: **(a)** dry, **(b)** wet and **(c)** after submersion in water. The change in plasticity leads to contraction of about 75% size. Soluble PVA substrate 400 mm x 550 mm with silk shown in two phases: **(d)** dry, with small holes formed by excretions of the spinning silk worms and **(e)** after submersion in water using six threads of mono-filament to tension and stabilize membrane structure. Only silk and mono-filament remained. • Images by Susan Williams.

7.2.5 Main Experiment Introduction

The above explorations of material and hardware interfaces for the fabrication of membranes in co-fabrication with silkworms showed that such an approach was promising and could be demonstrated as part of a larger, more comprehensive design of a fabrication platform combining observational aspects (senor technology) and material synthesis. In order to tie exploration back to the issues outlined in **Problem Statement,** the following factors were identified as central for a successful demonstration as an architecturally relevant fabrication process:

- **Scale.** A demonstration of the capabilities of co-fabrication at an architectural scale should consist of a surface area of at least 30 m^2, spanning an area under which a group of people should be able to stand upright. It should span a base diameter of at least 5 m.
- **Parametrics**. The system should have the functionality to parametrically change aspects of the shape and size of a resulting architectural element. This aspect should provide the potential for future functional and aesthetic tunability.
- **Synthesis**. The resulting material should be the product of a synthesis between machine-made and naturally-produced fibers, combining advantages of both and in line with the aim of designing in a technically symbiotic relationship with a natural process.

7.2.6 Silk Platform Design

The following describes a custom-built hardware platform created in 2019 for research into the production of large-scale membranes that take the above aspects into account. The platform was designed by the Mediated Matter Group, fabricated by Bodino Srl in Italy, and operated in collaboration with a demonstration sericultural farm (in Abano Terme, Padova, Italy) the activity of which is supervised by the CREA AA Sericulture Laboratory.

A five-step process was designed to outline and to anticipate the steps involved, illustrated in Fig. 28:

1. **Setup**. Install and tension a web of stainless-steel wire ropes to a set of adjustable connection points on a large mandrel.
2. **Knit application and modification**. Apply and tension stretchable PVA knit (as described in **Development of a Soluble Substrate**) over the stainless-steel scaffold wires. Where the membrane needs to reflect architecturally crucial passages or visual

connectivity, water mist can be sprayed onto the knit, resulting in removal of local patches of material.

3. **Fiber organization and silk deposition**. Populate the resulting hybrid steel wire and PVA knit with silkworms. During the first day of the spinning phase, silkworms secrete uric acid, introducing further, smaller, holes in the PVA knit, which help to make the inside of the membrane structure available as a spinning surface for the worms. These smaller (< 50 mm diameter) breakthroughs in the membrane are later covered with silk by the silkworms. During the last quarter of the spinning phase, pupating silkworms fall off the structure onto a textile canopy and are collected and stored for pupation.

4. **Release**. Release the resulting membrane structure, consisting of natural silk with a core scaffold of steel wire and PVA knit, from the steel wire rope connection points and remove from the platform. Turn by 90° and install upright.

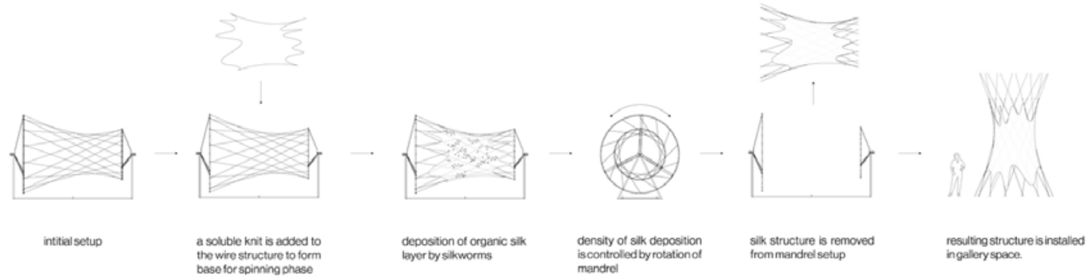

Figure 28: Diagram showing the steps involved in the kinetic production process of the hybrid silk, steel, and PVA membrane.

The hardware platform was constructed according to the above process requirements. It consisted of two large wheels, one with a span of 3.5 m, the other with a span of 5.1 m. Both were held apart by a central axis mounted on a metal framework using ball bearings on either end of the mandrel.

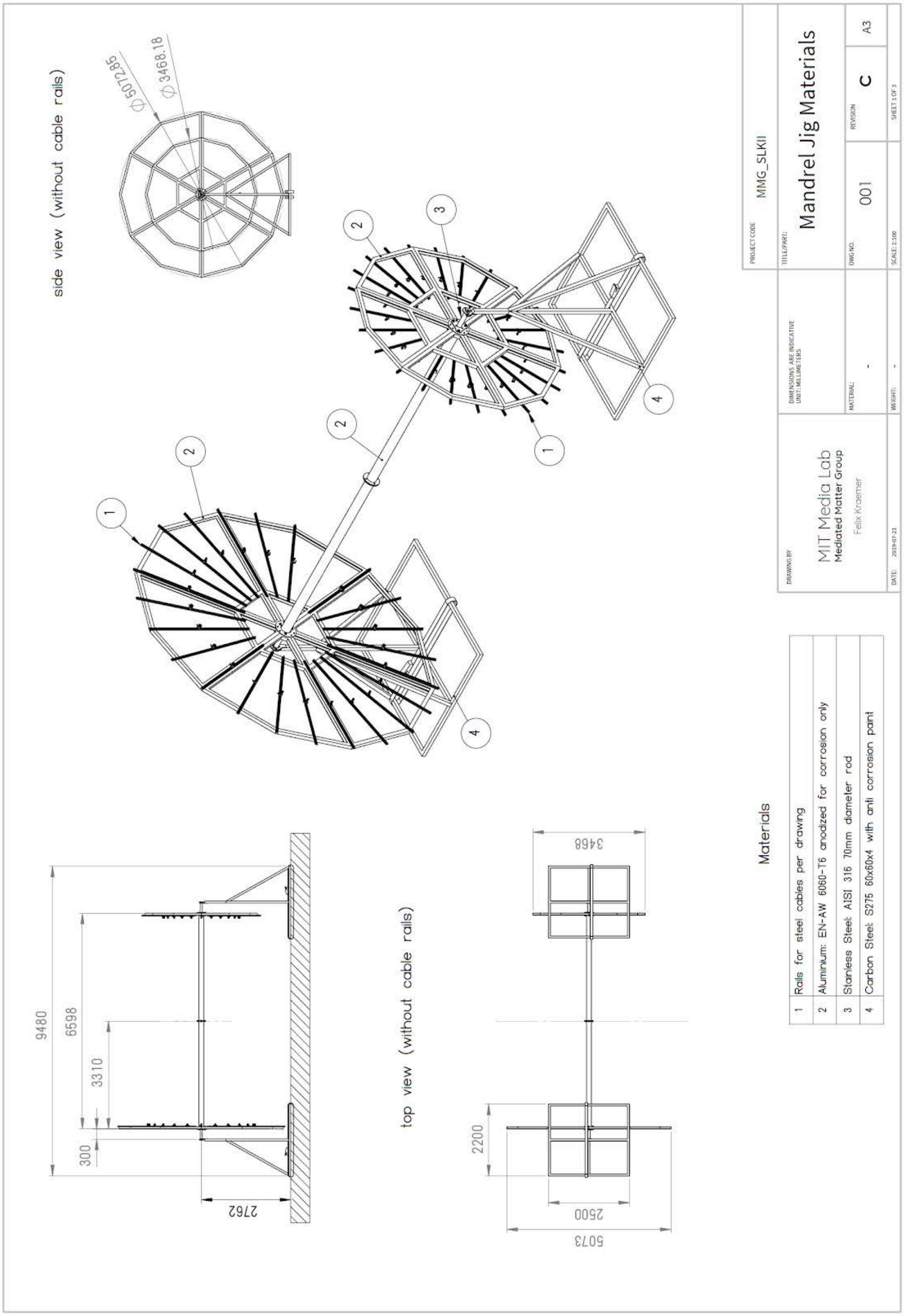

Figure 29: **(a)** Overview CAD Drawing of Platform: Overview

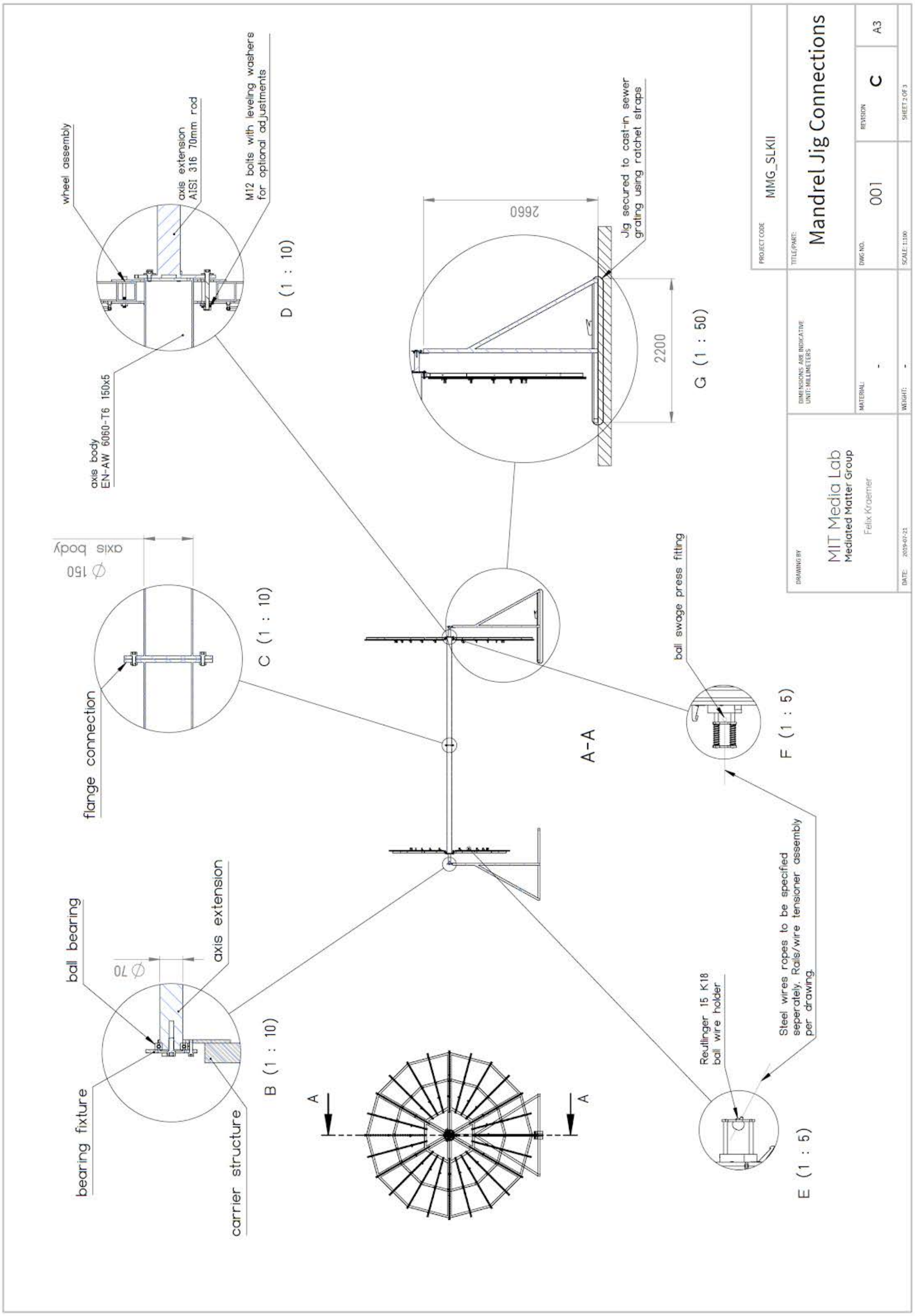

Figure 29: **(b)** Overview CAD Drawing of Platform: Connection Details

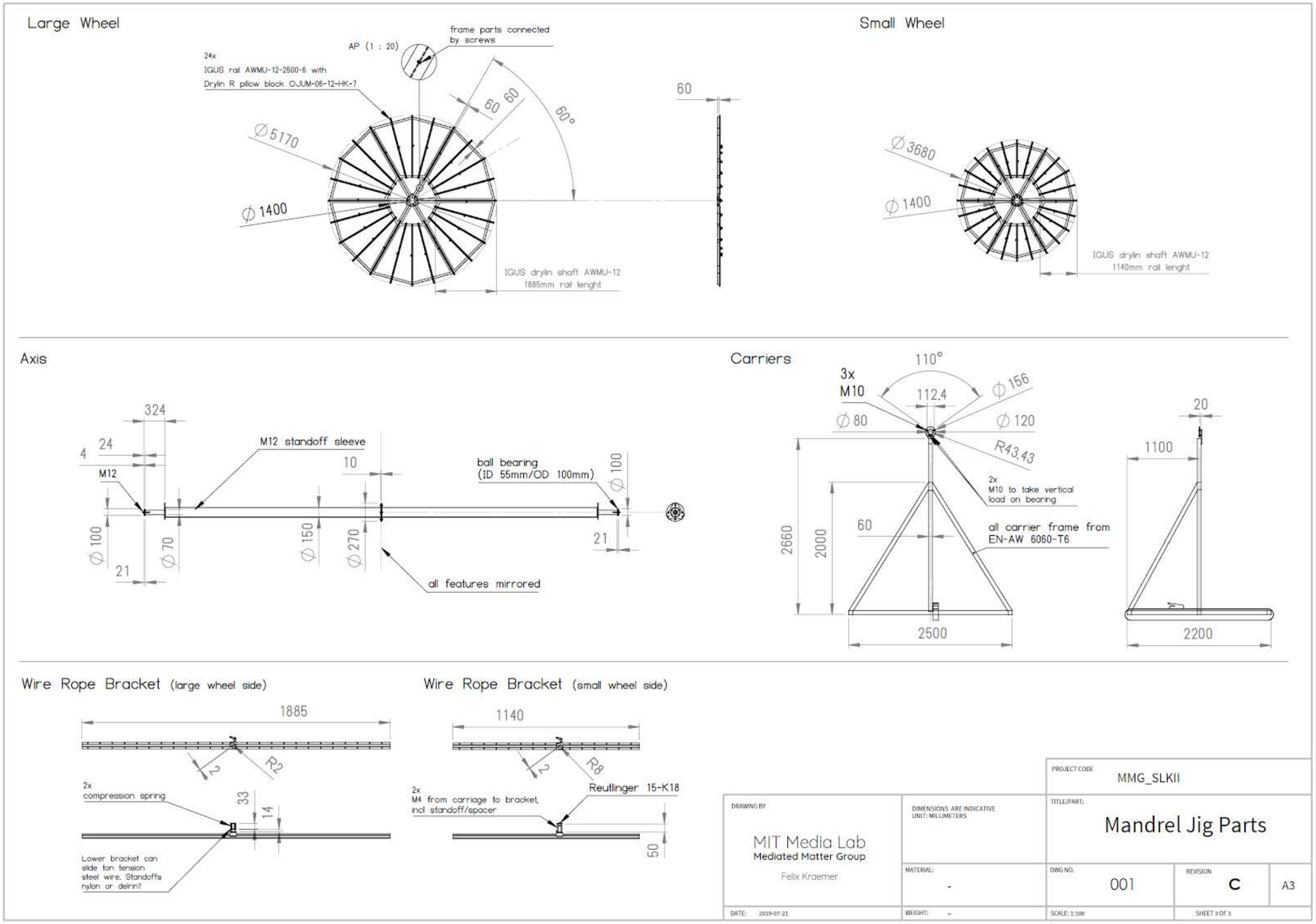

Figure 29: **(c)** Overview CAD Drawing of Platform: Part Details

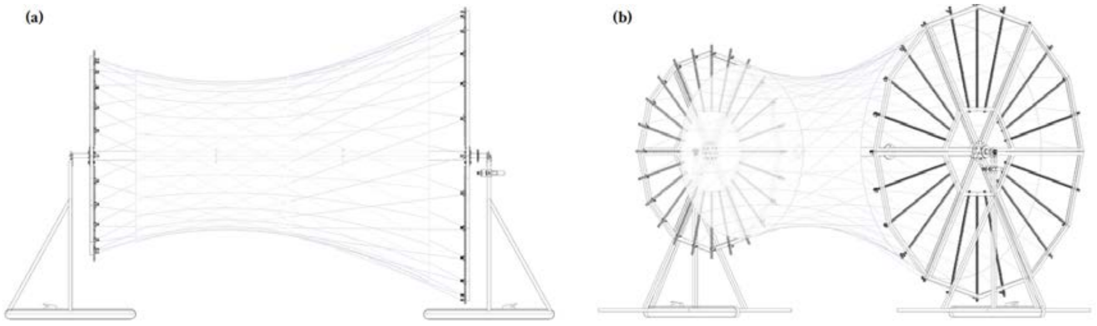

Figure 30: CAD Model of the final prototype platform, 5 m x 5 m x 9.5 m **(a)** 45° view **(b)** side view.

7.2.7 Adjustability

All anchor points (24 on each of the two wheels) for wires were adjustable in position along rails, effectively allowing for a stepless change in diameter ranging from 1415–3645 mm on the smaller wheel and 1415–5140 mm on the larger wheel. Any of the anchor points within the two radial grids could be connected, which meant that *wire distribution*, *twist*, *diameters* (top and bottom) and potentially (with some modification of the platform) *tilt* of the membrane's main framework could be modified (computation of different variations, Fig. 31).   .

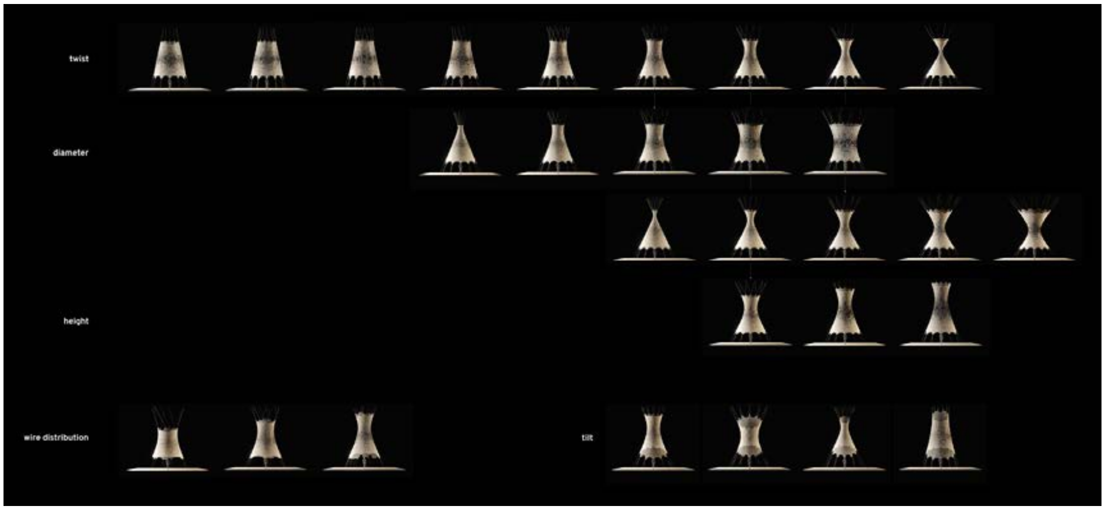

Figure 31: Details of adjustable anchor point rails and resulting variety of membrane shapes. • Computational analysis and renders by Christoph Bader.

Wire tension was adjustable via a ratcheted wire-holding mechanism (spherical part in Fig. 32a) on the non-terminated side of each cable, as well as through a compression spring-based mechanism on the terminated end of each wire (Fig. 32b). In the first setup step of the experiment, six wires were used and each one was tensioned to ~78 N.

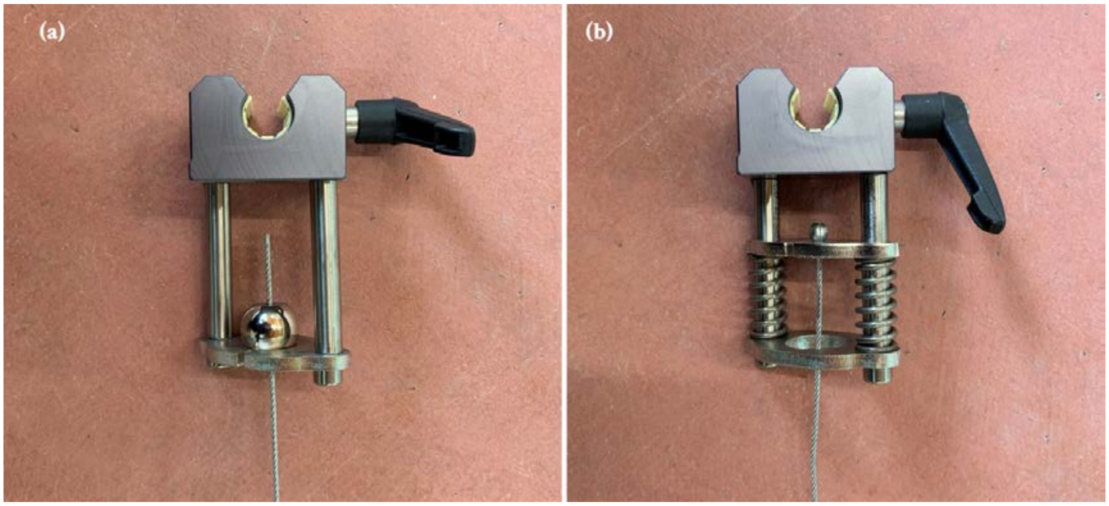

Figure 32: **(a)** Ratcheting mechanism inside a spherical wire rope holder, mounted on a clamping pillow block. **(b)** Compression spring mechanism mounted on clamping pillow block. The springs allow for tensioning up to ~98 N.

7.2.8 Textile Application

In order to provide a continuous surface for the start of the silk spinning procedure, a custom-sized, stretchable PVA knit was developed, based on knit density tested in prototyping (see **Development of a Soluble Substrate**). Extremities of the knit were first attached along the steel wire rope using a custom CNC-cut part, developed to mechanically attach the soft PVA knit on 1/16 in steel wire in a non-destructive fashion (Fig. 33).

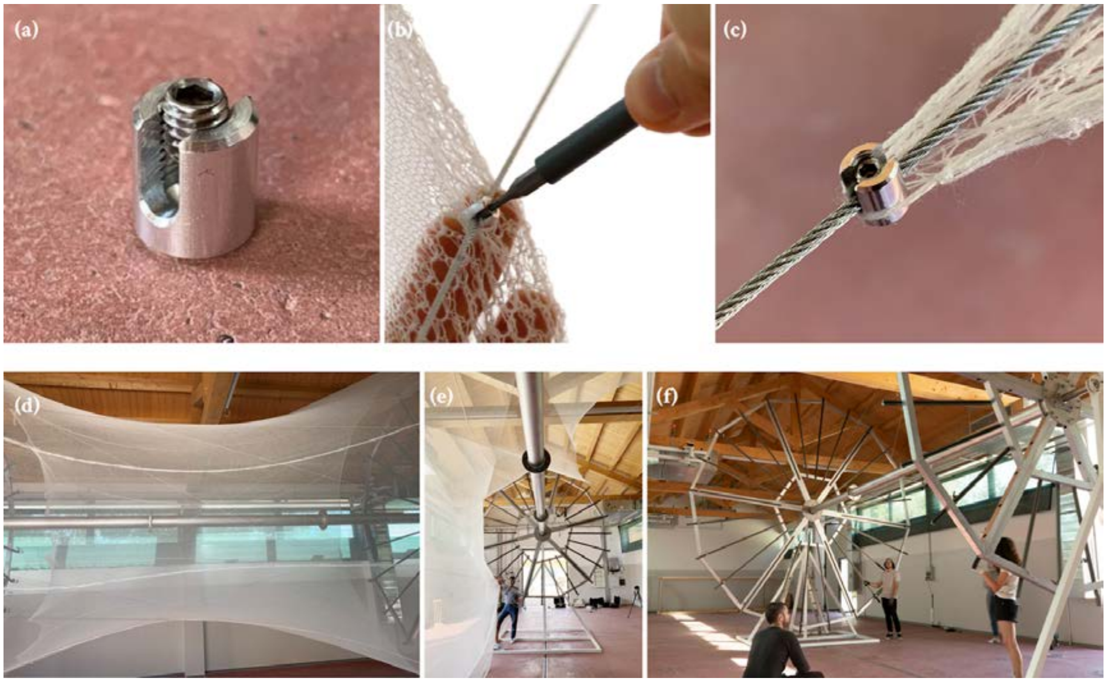

Figure 33: **(a–c)** wire rope to knit connectors. Custom-developed CNC-cut part from 6061 aluminum, using a partial thread and a stainless-steel set screw to allow for re-adjustment of the clamping position **(d–f)** Application of PVA knit.

The PVA knit was installed and tensioned, closing the wire structure into a continuous surface. Another six steel wires were added from the outside of the membrane, each crossing two to three existing steel wires, going to anchor points in the opposite direction. Using thin nylon monofilament, any remaining gaps between the steel wire and the knit were closed manually. To allow silkworms to migrate to the inside of the structure and to connect the steel wire with the soluble knit, holes were introduced using a water dispenser at all intersections of two steel wires (Fig. 34).

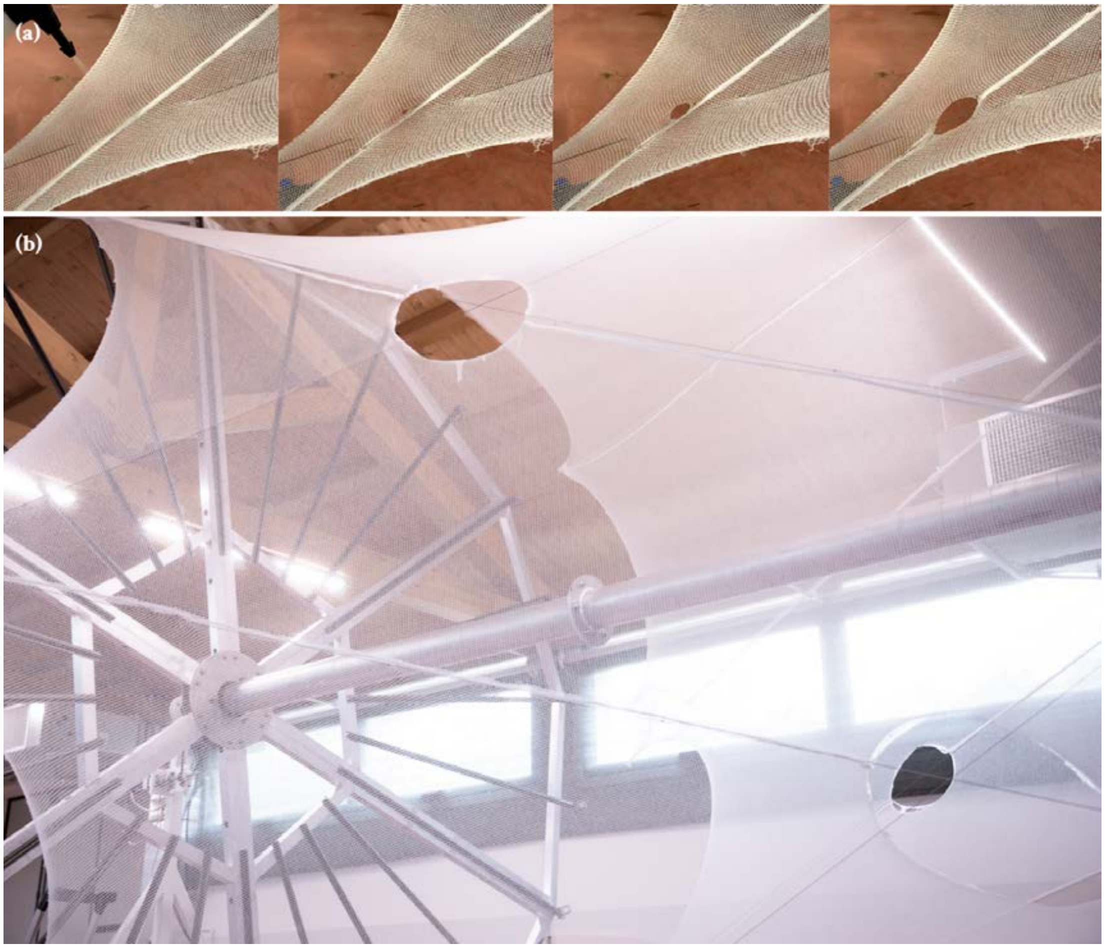

Figure 34: **(a)** Modification of base membrane using a water dispenser (series of four images taken in interval of 5 sec). **(b)** PVA base membrane after modification with water.

7.2.9 Actuation and Operation

For machine-side actuation, a motor and belt drive were installed, attaching to the main axis (Fig. 35). Locating the motor on the outside perimeter of one of the wheels was evaluated as an option, as it would have vastly improved gear ratio and allowed down-scaling of the motor. However, due to fabrication and timeline constraints, this approach was not possible for the presented system.

A servo motor (60 V DC NEMA23) was used in combination with a 10:1 gearbox and torque was applied to the main mandrel using a V-belt with custom pulleys, resulting in a 3.76:1 gear ratio. To allow for position control, an absolute rotary encoder was used with a resolution of 20 bit and a nominal resolution of ±0.01°. In this configuration, position control under real-world conditions (with steel wire and PVA fabric setup but without silkworms) could be performed with a precision of ±1°. Readout in continuous motion was achieved with a precision of ±0.7°. Data from the encoder and a LiDAR rangefinder were used for 3D image acquisition (See **Point Cloud Imaging**).

Figure 35: Motor and belt drive system.

Motor control, encoder data, and LiDAR data stream were handled through USB serial connections using a single-board (*Raspberry Pi 3*) Linux computer mounted on the platform.

The platform was run in two sessions, producing one preliminary test membrane and one refined membrane for demonstration. For clarity, this section refers only to the second membrane, which, after the experiment was used as a demonstration exhibit.

After setup of the hybrid base textile on the platform, the structure was populated with an average of 1750 silkworms per day for ten days. During this time, room temperature remained at 21–23°C and relative humidity at 71–78%. After the initial gauging of the silkworm's impact on the balance of the system, the mandrel was actuated with an interval of 30° rotation in the same direction every five minutes, repeated continuously.

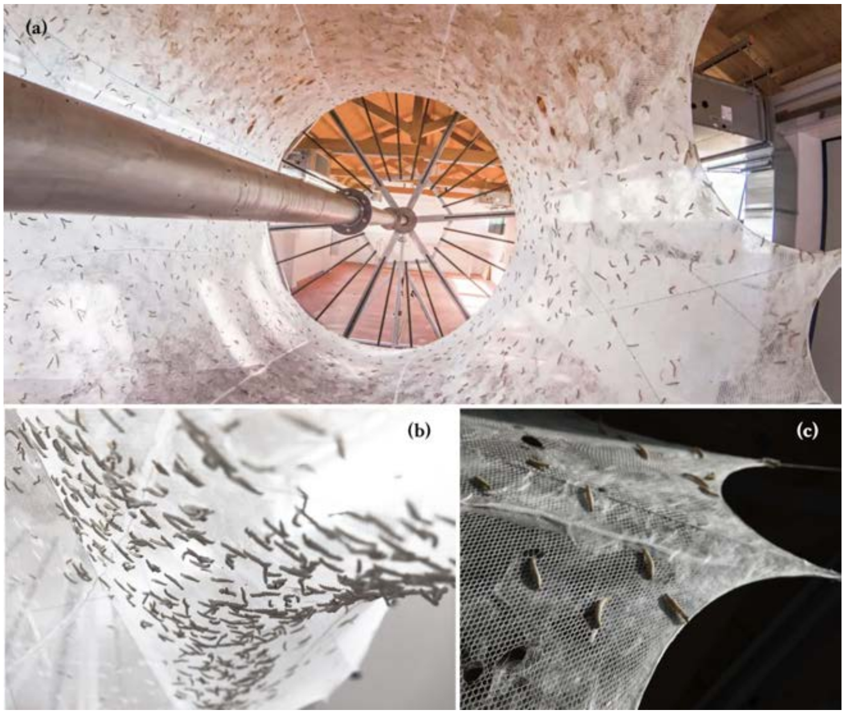

Figure 36: Hybrid textile made of steel wire rope and PVA, populated with silkworms. **(a)** View along central system axis. **(b)** PVA textile with silkworms and completed silk patches on surface. **(c)** Silkworm grouping after actuation pause. • Images by Lilium Sound Art

Any silkworms approaching the end of the spinning phase, entering pupation, fell onto the canopy structure installed under the mandrel or were collected manually.

To remove the resulting membrane, wooden transport boards were mounted onto both wheels. All steel wire ends were then released from their anchor points and transferred onto the transport boards. The middle section of the main axis of the platform was removed, while both wheels were secured to their carrier frameworks. Subsequently, the transport boards holding the membrane were removed from the platform and slid into a crate (Fig. 37e).

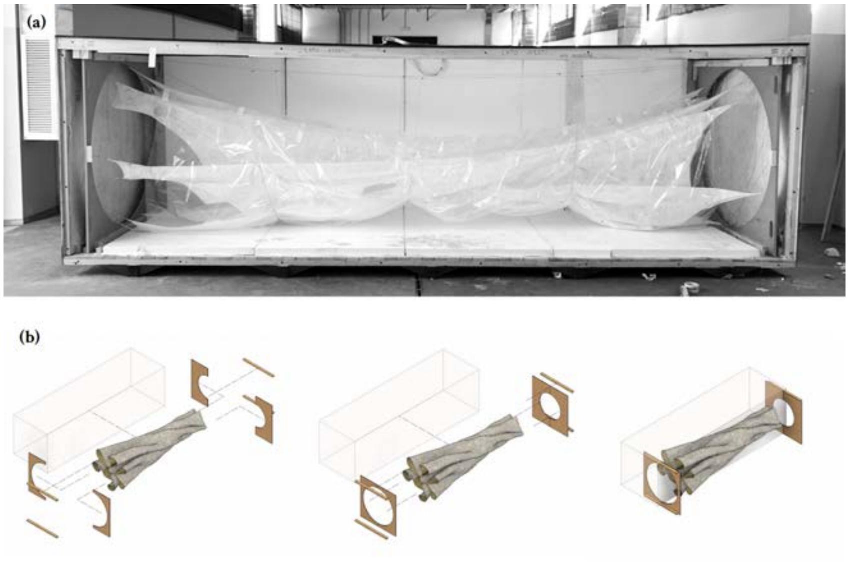

Figure 37: **(a–c)** Release of the membrane **(d)** Storage in crate for shipping. **(e)** Crate sliding mechanism.

7.2.10 Point Cloud Imaging

As a means to evaluate changes in the physical product of the platform at production time, a 3D point cloud acquisition system was designed and implemented. This system is based on the combination of two data streams; one from the rotary encoder described in the previous section, the other from a LiDAR laser rangefinder (*Hokuyo UBG-04LX-F01*), pointing at the membrane at a fixed angle and distance (Fig. 38).

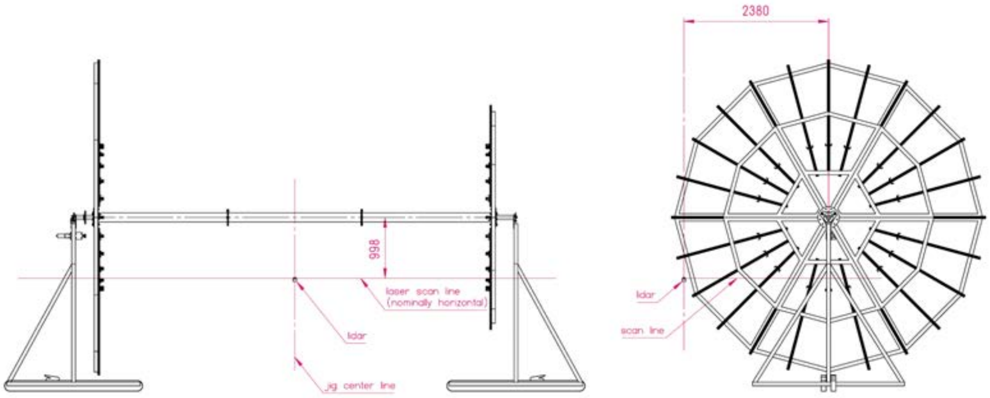

Figure 38: LiDAR rangefinder setup specifications developed for 3D point cloud imaging purposes.

A custom application was developed (João P. Costa) to control the motor for scanning procedures and to acquire raw point cloud data. Each scan consists of a csv file containing lists of (polar) distance values from the LiDAR rangefinder and simultaneous position values from the encoder.

When a scan is triggered, the following procedure is executed:

A

1. A new csv file is created
2. Encoder value is reset

B

1. Platform motor is set in motion, rotating at a continuous speed
2. Current encoder value is received, current LiDAR list of distance values is received
3. Both values are logged in a single line, within the csv file.
4. Part B is repeated until an entire revolution of the mandrel is registered

The collected scans were processed in a 3D computer-aided design (CAD) environment. For every line contained in the file, the polar distance values were converted to cartesian values. Then, a transformation matrix was applied to rotate the obtained set of points around the x-axis by a factor defined by the encoder value. The resulting list of points was post-processed to exclude any errors caused by depth registered beyond the possible surface of the membrane. Each full scan contains around 1,000 scanlines with a total of 1 million points.

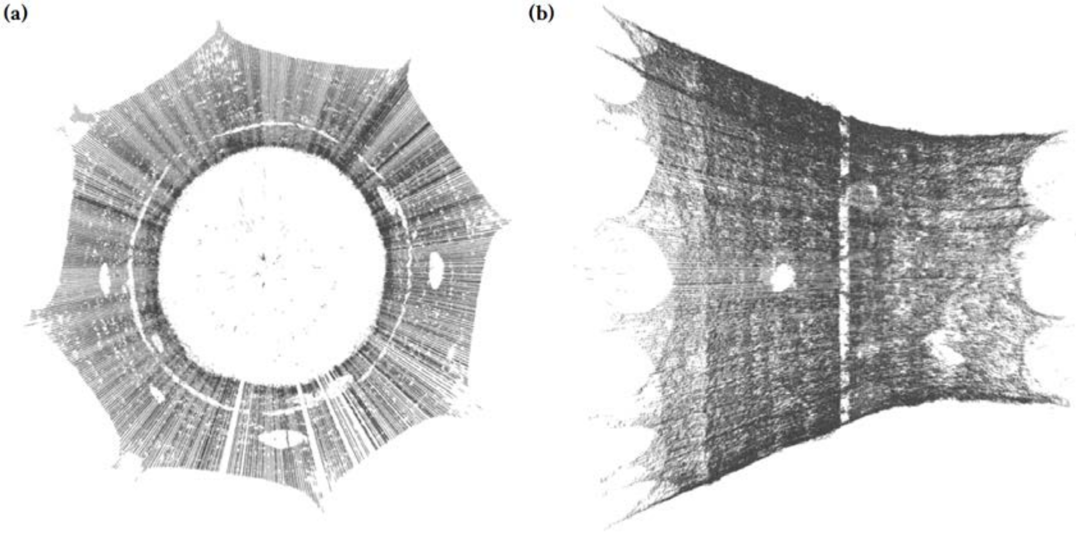

Figure 39: 3D point cloud scan early in the spinning process. Each full scan contains around 1000 scanlines with a total of approximately one million points. **(a)** View along system axis **(b)** Side view. • Computational processing and analysis by Christoph Bader.

Scans were performed in the beginning and at the end of the spinning process, capturing deformation of the membrane. In addition, the capture of 3D data contributed to the next step, the architectural installation for demonstration purposes. A full 3D CAD model of the membrane was based on a fusion of point cloud data and nominal construction geometry.

7.2.11 Findings

At least 90% individual silkworms involved in the process survived the spinning phase and were collected, stored for pupation and remained at CREA AA Sericulture Laboratory for further scientific use.

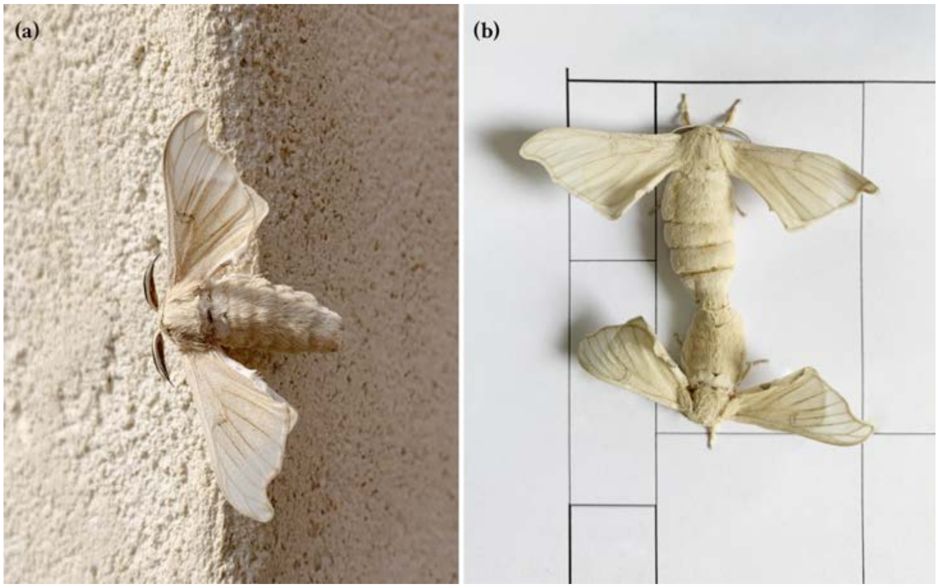

Figure 40: **(a)** Female silk moth after fabrication process and pupation. **(b)** Male and female silk moth mating after the fabrication process.

A percentage approximately 10% of the worms raised to spin on the platform suffered from nuclear polyhedrosis virus (NPV), which is a common issue in sericulture. Using a fresh diet with low levels of pesticides, dynamic climate control, and separation of healthy worms from diseased ones, the effects of the virus could largely be mitigated.

When initially populating the membrane with batches of 200 silkworms, upward migration of approximately 90% of the worms could be observed over the course of 15 minutes with the majority of the worms reaching the top of the membrane shape in a matter of 30–40 minutes.

For initial tests, the platform remained unactuated, with the belt disconnected and without any component blocking the rotation of the mandrel. It was observed that a total of 200–250 silkworms was sufficient to move the mandrel, if added on one side of the membrane. With an average of 2.9 g per silkworm (determined in a separate experiment on site) at the beginning of the spinning stage, this equals a total weight of approximately 650 g necessary to set the system in motion. Of course this value is dependent on the location of the batch (center of membrane or fringes; bottom or side of membrane) as it vastly changes the leverage applied on the system, and is therefore only indicative of the general functionality of the rotational mechanism.

Generally, a clear movement pattern towards height could be observed, with silkworms gathering on elevated sections of the topology of the membrane, for example on ridges made up by the underlying steel wire (Fig. 41a). The following movement patterns on the overall shape were observed:

Work Coordinate System:

x = along main axis, **y** = perpendicular to main axis (horizontal), **z** = vertical axis

Location	**Movement direction**
Bottom center:	→ y (+ or -)
Bottom edge:	→ center
Half height (axis level) center:	→ z +
Half height (axis level) edge:	→ z +
Top center:	→ x (+ or -)
Top edges:	Move off the membrane (via steel wire rope)

This pattern shows that a majority of silkworms which are located on the top (edge) of the membrane (attempting to move off the membrane) turn around and move towards the center of the membrane if the system is rotated by 180°. However, the steep angle of the outside sections of the membrane, compared to the relatively moderate to shallow surface angle towards the center of the membrane, meant that over time, silkworms tended to gather on the outside fringes, causing the outside parts of the membrane to exhibit a thicker silk layering (Fig. 41b–c).

All holes in the PVA knit with ø < 180 mm were first lightly spun over and finally covered entirely by the silkworm’s spinning activity (Fig. 41d–e).

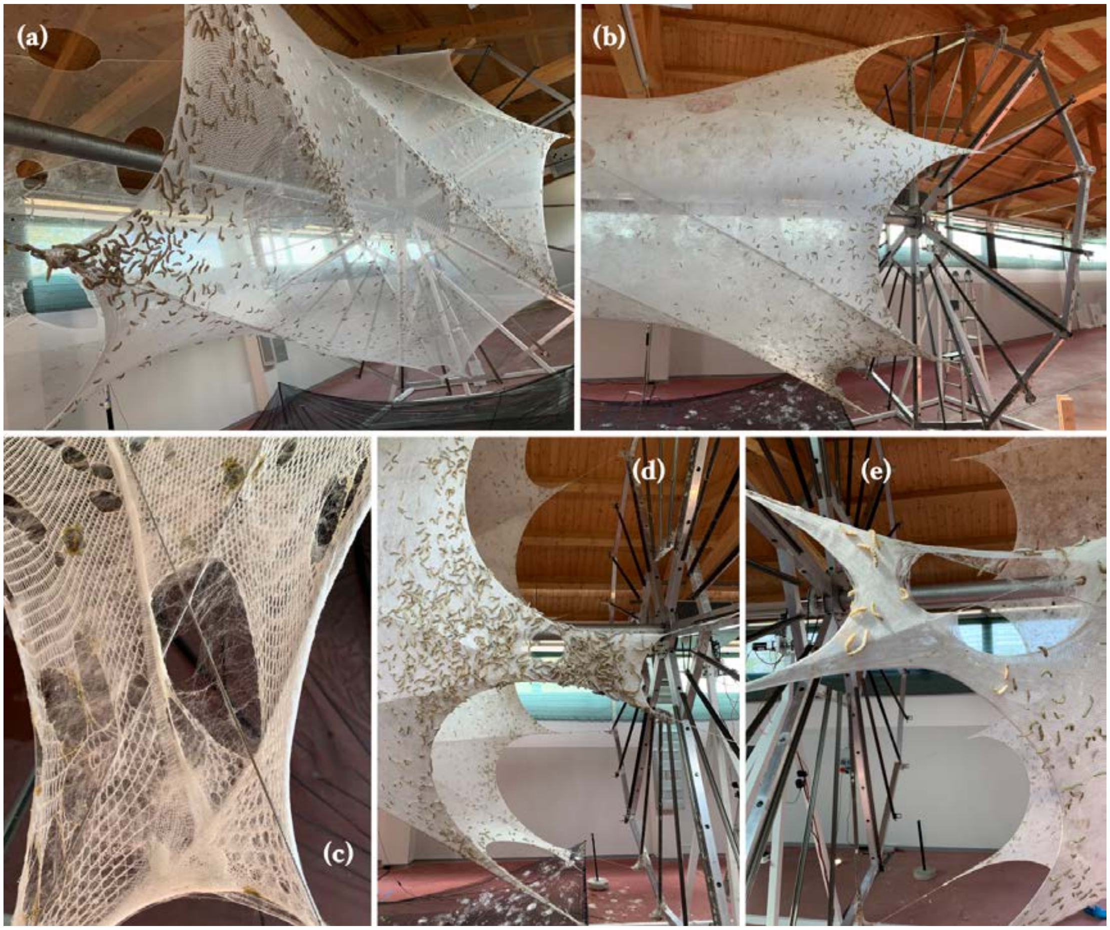

Figure 41: **(a, b)** Silkworm grouping along elevated terrain, **(c, e)** covering of holes, **(d)** migration to sides (height).

After population of the membrane with 17,500 silkworms over the course of ten days (an estimated total of 16,000–17,500 km of silk added to the surface), the center section exhibited a layered silk membrane thickness of 4 mm and the outer sections a thickness of 8–13 mm.

Analysis of the point cloud, as seen in Fig. 42, indicates that the silk deposition caused a shrinkage of the middle section of the membrane of about 8%, with the edges remaining largely unaffected. This is remarkable due to the fact that the amount of silk deposited towards the outside of the membrane was higher compared to the center. The state (98% compressed) of the springs on the wire tensioning mechanisms at the end of the production phase (compared to approximately 92% compression in the beginning) supported the observation of an apparent shrinkage of the membrane over the course of the production process. Contraction of the structure due to silk deposition therefore seems avoidable by use of a rigid support scaffold. In future projects using continuous silk surfaces, the factor of shrinkage should be taken into account.

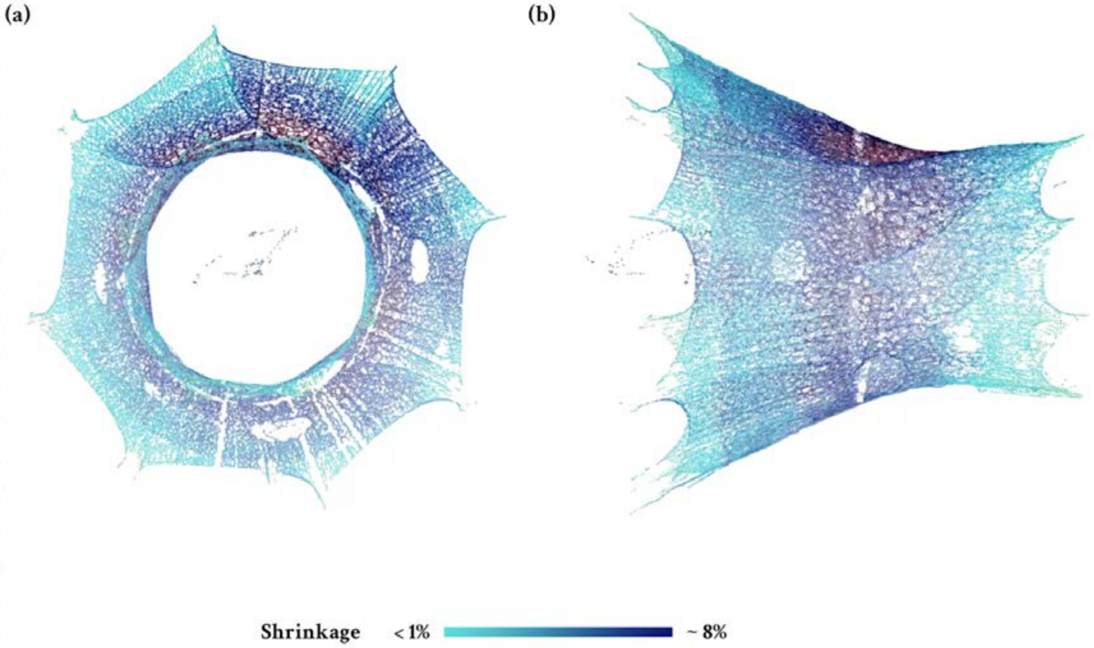

Figure 42: Computational analysis of membrane shrinkage over the course of the production process. **(a)** View along system axis. **(b)** Side view. • Computational processing by Christoph Bader.

7.2.12 Demonstration

The resulting membrane was installed as a pavilion structure (*Silk II*) and presented as part of the *Neri Oxman – Material Ecology* exhibition at MoMA New York in February 2020 (Fig. 43), demonstrating the architectural dimension and viability of the procedure. In order to anchor the pavilion within the space, steel wire ropes making up the structural core of the fabric, were attached to the floor and ceiling using jointed wire holders with tensioning mechanisms on the ceiling and custom-developed wire-to-wood connectors on the floor. With the lower (floor) diameter of the pavilion spanning 5.8 m, and a total height of 9.1 m to the ceiling, it is to date the largest structure produced in a collaborative, kinetic fabrication process with silkworms.

Figure 43: Views inside MoMA New York exhibition space, featuring *Silk II*, including prototypes, early 2020.

In this gallery setting, the *Silk II* membrane serves a demonstrational as well as artistic purpose, embodying engineering efforts, scientific endeavour and design exploration in the form of an architectural piece. It is embedded in a range of works by Neri Oxman and the Mediated Matter Group, which explore the connections that can be designed and engineered between artificial and natural systems.

8. Conclusions

8.1 Outcomes

While the primary research objective of all works presented here was to identify interfaces for the purpose of fabrication, **Maiden Flight** focuses on data acquisition and basic research first. Kinetic fabrication systems involving bees may be on the horizon but behavioural and biologic precursors are studied first in order to find entry points for interactions with the species. As an experiment and form of demonstration, **Silk** is therefore not different regarding its goals but more developed in terms of tangible outcomes. It shows that architectural-scale fabrication can be achieved through the use of a kinetic organism-machine interface, connecting both artificial and natural systems. This suggests a confirmation of the hypothesis of this thesis. Future research into interactions with fabricating organisms of other species may give an insight into the range of material formulations this approach enables.

8.2 Unifying Properties

In order to describe the approach of a hardware platform meant to connect species, I propose a coordinate system in which the two axes represent activity (autonomy in the extreme) on one hand and kinetic motion on the other. One may compare these factors to terms from a machining environment such as toolpathing and feedback loops for axis A and actuation on axis B. Going a step further, the projects presented in this chapter may be mapped in this field according to their properties (Fig. 44).

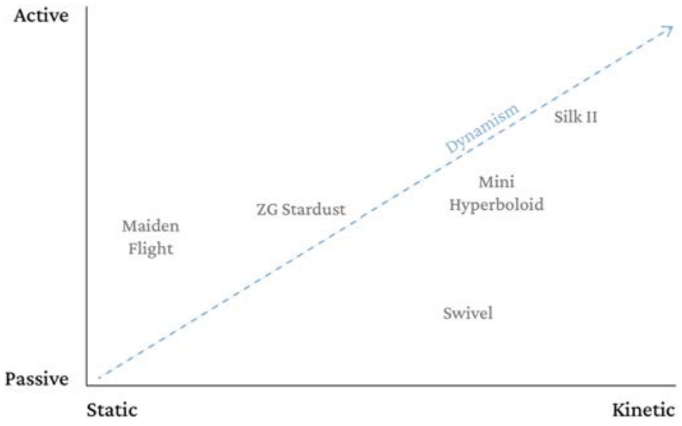

Figure 44: Contributions of this thesis can be mapped in a space describing the dimension of dynamics/dynamism of each project. While earlier prototypical environments show a lower amount of kinetic actuation (motion) and are not active (electronically autonomous) in collecting data, more evolved environments show higher degrees of dynamic responsiveness to the environment and to the process they enable.

The following unifying factors, dictating each one of the range of projects presented, were observed:

- The influence of seasonality on the experiment and production timeline was central and could not be bypassed. The biology of both honey bees and silkworms is dependent on climate, daylight rhythms, and nutrition. To provide all of these without the support of naturally-occurring seasons greatly increases costs, adds many complications in handling the organism, and potentially causes catastrophic effects on the population.
- Environmental influences such as viruses (i.e. NPV) or predators (i.e. mites) need to be factored into project timelines and setups. The use of fresh, high quality nutrition for the organisms and provision and monitoring of the climate is therefore paramount and should not be an option but a basic part of the fabrication process.
- Just like in the case of other fabrication processes, before any new fabrication is set up, tests need to be performed. In the case of co-fabrication with living organisms, this means that custom setups for studying and learning from the organisms (*Maiden Flight, ZG Stardust*) need to be designed first and foremost with the goal of focussing on certain aspects of the organism (like *metabolism*, *behavior* or *reactions*).

- The aspect of infrastructure and logistical arrangements made to provide appropriate care for the organism constitutes an estimated 60–80% of the process, be it observational (Fig. 45c) or preparation or fabrication (Fig. 45a–b).

- When working with living organisms, prototyping and engineering efforts need to reflect the changes that organisms undergo. Therefore, a high amount of adjustability and flexibility needs to be built into co-fabrication systems. Dimensioning a system for such a type of fabrication, for example, means to use driver systems which allow for scaling of actuator sizes or are adaptable to different pulley sizes to allow for a change in gear ratio. Even central goals such as anticipated fiber distribution of a system may change once the system is built and in use.

Figure 45: **(a)** Mulberry branches collected to provide silkworms with nutrition. **(b)** Silkworms feeding on mulberry leaves. **(c)** Check-up of a beehive performed by Ren Ri.

8.3 Interactions, Causality

To be able to inform the design of the Fabrication Interactions Grid, some of the causal relationships between activities performed by humans and their effects on organisms are worth mentioning.

Breeding → Genetic Diversity

Responsible breeding practices, as mentioned in **Organisms**, have a great impact on genetic diversity and, especially in the case of domesticated species, could be seen as an obligation to avoid the destructive effects inbreeding has on organisms.

Nutrition → Health, Material Synthesis

The quality of nutrition supplied to organisms can have an impact on both their health and on the material synthesis that happens as part of the life of the organism.

Substrate Design → Material Deposition

Design of the basic conditions that lay the groundwork for material fabrication in collaboration with organisms is crucial. Tactile structures (such as wax lining in the case of *Maiden Flight* or PVA knit in the case of *Silk*) enable material deposition and well-being of the organism.

Actuation → Migration, Movement

Machine-side actuation of substrate surfaces was shown to result in migration, movement of the organisms and therefore in a change in material deposition and material fusion (ie. acrylic to wax in the case of *Maiden Flight* or steel wire to natural silk in the case of *Silk*).

Protection (from predators, climate) → Domestication

Protection from predators, climate control, and supply of nutrients all—separately or combined—lead to domestication and therefore a loss in capability of the organism to function in the wild.

While some of these effects may be desirable (judged by whether they contribute to a balanced overall relationship), others may not easily be assessed as having positive or negative results. This thesis does not attempt to evaluate whether domestication is in itself a beneficial or a detrimental development.

8.4 Fabrication Interactions Grid

To propose a graphical representation, the Fabrication Interactions Grid, I would like to focus on causality (like the ones described above) as a unit in a larger system. Assuming that the *organism-machine interface* is the connection between human and organism, and enables the interaction between them, we arrive at a triangular, directional representation (Fig. 46) in which both participants provide something (sometimes multiple commodities). There are effects on either of the providers which are valued with (+) or (-) and a resulting property, which is a part of the final product. For example, nutrition provided by humans in combination with material synthesis provided by organisms results in material formulation, with the side effects of a cost (labour) for humans and health benefits for the producing organism.

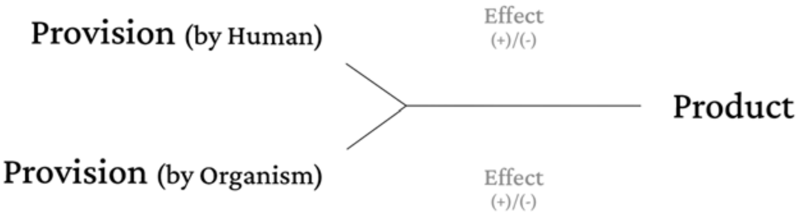

Figure 46: Main component of the proposed Fabrication Interactions Grid.

Translating this idea into a grid with different categories of provisions and the corresponding effects leads to a circular grid of multiple units, as shown in Fig. 47.

Figure 47: Proposed Fabrication Interactions Grid with example nodes resulting in product properties *Scale*, *Material Formulation,* and *Material Distribution.*

Bundling each *provision*, *effects*, and resulting *properties*, allows for a quick overview of the potential costs, benefits, and effects of the system on both the human and the producing organism. The addition of further nodes is imaginable if a system requires other more specific product properties such as *precision* or *autonomy.*

Adding to the term *industrial symbiosis* referenced in **Motivation** and Judith L. Bronstein's categorization of mutualistic relationships, I propose to describe the systems presented in this thesis as *fabrication mutualism*. In this relationship, the overarching goal is to produce a material or structure. However, this is only possible through a mutual provision of various commodities (nutrition, climate, protection, material synthesis, etc.). The overarching goal might not be mutual per se, since it follows human interest, but the system, when set up correctly, benefits the producing organism, the human, and the ecologies around us.

8.5 Research Limitations

When discussing human-organism relationships, it is important to note the potential moral implications of terms such as *mutualism* or *interaction*. Whether organisms like bees or silkworms choose to *interact* or whether they are manipulated to do so is unknowable. This in itself does not constitute a problem for the design of co-fabrication systems, but it indicates that any evaluation of a relationship is a direct product of the human perspective. In the case of mutualism (as it is outlined in **Definitions**), the validity of the term depends on its implementation in each given context. If a fabrication environment is only beneficial for the human and not for the organism, then the use of the term may not be warranted. A system may even be set up to align with the goal of fabrication mutualism, but if a net benefit for the fabricating organism is not maintained throughout the project, then the mutual quality may be lost so that the system becomes exploitative. Additionally, beneficial effects on the organism (such as health, genetic diversity, etc.) are fundamentally identified from a human perspective. The scope of the research presented here is limited in that it does not investigate in depth how benefits are identified and evaluated.

9. Future Work

The projects and approaches presented in this thesis are a step towards a framework for a new kind of interaction design—one that focuses on the relationships and effects between ecosystems, machines, and humans with the underlying goal of changing the fabric of how we design and construct. For me, the potential of this field lies in the new questions introduced by the experimental work presented:

1. What other shapes could be achieved by use of a silk production platform like the one presented; or by one on a different, much smaller scale, perhaps that of the human body?

2. How can the field of (collaborative) robotics be challenged and pushed towards incorporating living organisms, perhaps beyond the scope of end-effector design?

3. What other species would be suitable to collaborate with and how do they compare to bees and silkworms in the Fabrication Interactions Grid?

Beyond these practical fields, other questions remain:

5. When applying the Fabrication Interactions Grid to a range of future projects, can it become a tool to evaluate processes and to detect potential issues arising from interface designs ahead of time?

6. Does the Fabrication Interactions Grid hold true even in the case of collaborations with more complex species and settings?

The future of industry, design, and fabrication is tightly interwoven with the life of other species and ecologies. By better understanding the relationships and interaction between these realms, we may hold the keys to our most important innovations.

Contributions

Projects, Papers:

- *Heat Bonding End Effector* (design and fabrication of hot air-based thread depositing nozzle)
- *Adaptable Meshes* Conference Paper (2nd co-author, imaging contributions)
- *Totems* (design/engineering of interface between mechanical parts and bio-reaction)
- *Maiden Flight* (Nanolab design/engineering, Nanolab code, fabrication, assembly)
- *Silk II* (design/engineering of platform, design of 3D point cloud acquisition system)
- *ZG Stardust* (design/engineering and fabrication of mirror-based capsule)
- *Radiofunghi* - ISS Payload (consultation regarding design of imaging setup)

In Progress :

- Silkworm Social Behavior Paper (co-author)
- *Maiden Flight II* (Nanolab design/engineering)
- Bee Interfaces (bio-controlled interface to augment thermal self-regulation in a beehive)
- *Maiden Flight* Paper (imaging, edits)
- *Maiden Flight* Module Patent

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