S P I R I U M

b i o d e s i g n e d ,
s y m b i o t i c ,
space habitat.

May, 2020

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SPIRIUM: A Symbiotic Space Habitat, Biodesigned.

A multi-sensory installation, depicting a speculative future of symbiotic space exploration habitats, created with biology.

THESIS REPORT

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vita

Sara Nejad is an interdisciplinary artist and designer, born in Tehran, Iran. In 2012, she graduated Cum Laude from California State University Northridge with a Bachelor of Science in Marketing. After graduating, she pursued a career in digital marketing and design. In 2015, she co-founded a fashion technology startup, where she applied her skills as a product designer. She then transitioned to an independent UX/UI designer, working with various startups and design agencies.

In 2018, she enrolled in the Integrated Digital Media graduate program at New York University, where she explored the convergence of design, biology and engineering. In September of 2019, she began her Master's thesis project, investigating the intersection of biodesign and space exploration. She received guidance from her internal advisor, Ahmed Ansari, PhD; external advisor and industry expert, Chester Dols; and lastly, her mentor, Elizabeth Hénaff, PhD.

Her goal with her thesis project is to integrate her passion for sustainability, biodesign and multi-sensory experience design to imagine, speculate and create the future of food and agriscience.

abstract

The fantasy of long-duration space exploration and settlement may become a reality as early as 2035. Whether we embark on this journey to explore new frontiers, or to escape an inhabitable Earth, we will face a plethora of unprecedented challenges. Given the inevitability and urgency of this future, we need to actively and collectively create a manifesto and design technologies that allow us to thrive as a multi planetary species.

Deep space habitation systems rely on life support systems: a system of regenerative life support hardware that provides clean air and water for the astronauts through artificial means.[1] However, astronauts remain heavily dependent on continuous shipment of essential supplies, such as food, from Earth.

SPIRIUM is a multi-sensory installation that aims to illustrate a different imagined future for space habitation design: one that is organic, bioregenerative, and in symbiosis with companion species cultivated in space. A biodesigned and self-sustaining life support system.

This installation engages the imagination, and generates curiosity to promote discussion around the subject of sustainability in the context of space exploration. It invites the audience to see this moment in history as a novel opportunity to imagine and design future technologies that could also improve life on Earth, now. It aims to leave the audience pondering: how can we leverage biology, design and technology to create regenerative solutions for life on Earth and beyond?

1 Mohon, “ECLSS.”

content

introduction

Humanity has been fascinated with the stars and the infinite night sky for thousands of years. We stargaze and imagine what else is out there in the unknown. We are explorers by nature. Our curiosity has been the driving force behind many of the discoveries we have made throughout our existence. Discoveries that have benefited our society in various ways. Human space exploration helps us to discover more about our place in the universe, the history of our solar system, and the cosmos. In this global effort, through addressing the challenges that are associated with long duration space exploration, we collectively advance science and technology. Moreover, “given the fragility of our planet, we also believe that it is vital that we not only preserve the biosphere of earth using the resources of space, but that we expand that biosphere, taking life to worlds now dead.”[1]

"THE EARTH IS THE CRADLE OF MANKIND, BUT ONE CANNOT LIVE IN THE CRADLE FOREVER."

Konstantin E. Tsiolkovsky

1 Tumlinson, Shull, and Venkatesan, “Cosmological Effects of the First Stars.”

Whether inspired by our species' ever-explorative nature, or due to apprehension of our inevitable demise as a single-planet civilization, long duration space exploration involves multiple unprecedented challenges affecting astronauts that we need to resolve prior the first human mission to Mars and beyond.

Deep space exploration exposes the astronauts to a series of environmental and psychological stressors, including altered gravity, higher levels of cosmic radiation, and prolonged isolation and confinement in a hostile closed environment.[1] Yet, this hostile closed environment is precisely the habitat that protects and sustains the astronauts throughout their mission. Deep space habitation systems rely on life support systems. The Environmental Control and Life Support System (ECLSS), for instance, is a system of regenerative life support hardware that provides clean air and water to the International Space Station (ISS) through artificial means.[2] Although the ECLSS is a regenerative system, the ISS is by no means self-sufficient and relies on continuous shipment of supplies from Earth. Currently, the ISS is re-supplied every few months by rockets from Earth, containing essential 'consumable' supplies such as food and water, oxygen as well as nitrogen and carbon-dioxide filters to keep the atmosphere breathable.[3] However, space voyages into deep space will not be able to rely on deliveries from Earth. Therefore, it is crucial to plan ahead and design self-sufficient closed loop life support systems to sustain explorers during long duration space travel.

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1 Perez, "The Human Body in Space."
2 Mohon, "ECLSS."
3 Walker and Granjou, "MELiSSA the Minimal Biosphere."

Long duration human exploration missions beyond low-Earth orbit will require life support systems that maximize recycling of essential resources such as water and oxygen; therefore, replacing open-loop systems that treat these resources as ‘consumables’.[1] Researchers at different space organizations, including The National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) have been working on developing closed loop life support systems that would enable space explorers to venture into longer missions, farther into space. Current research explores a multitude of possible technologies, including bioregenerative system design to create a fully self-sustaining closed loop life support system.

Bioregenerative life support systems are designed to have closed nutrient and gas loops, making them a self-sustaining system that continuously provides astronauts with breathable air and fresh food. Several ecological model systems with different levels of complexity have already been developed and tested here on Earth as well as on shorter space flights. These systems leverage photosynthetic organisms such as cyanobacteria, flagellates or higher plants to take up carbon dioxide from the environment, produce oxygen, and grow biomass that could be used for food, fuel or material. These systems also utilize bacteria to detoxify urea and ammonia.[2]

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1 “Next Generation Life Support (NGLS) | Space Technology.”

2 Häder, Braun, and Hemmersbach, “Bioregenerative Life Support Systems in Space Research.”

Researchers developing the next generation of life support systems within the European space life sciences program have taken a modular approach to learn how the different species in ecological life support systems interact with each other.[1] To optimize the efficacy of bioregenerative systems, researchers need to investigate the specific needs of each organism, and create the precise physico-chemical conditions controlled by automatic systems.Moreover, it is critical to consider ample backup, in case one or more modules fail in the system. Since such systems are 'alive' and reliant on biological organisms to function, they also require careful control of potential contaminants and protection from unpredictable parasites such as viruses, bacteria, and fungi.[2] Such systems would operate best, if designed holistically and with the goal to promote symbiotic relationships among all living organisms within them. Hence, it is sensible to employ a design approach informed by natural processes that have evolved over millions of years. Leveraging biomimicry, biotechnology and biodesign could therefore be essential in developing technologies for future human space travel exploring the solar system and beyond.

Historically, humankind has been inspired by nature's genius to design and develop a wide range of technologies. Through biomimicry, we have modeled technologies after forms and functions found in nature. Prior to the Industrial Revolution, we built majestic architectural marvels such as the Buddhist temples and shrines that were actually carved into caves and mountain sides 6000 BCE; or the more known Pyramids of Giza that were designed after mountains.

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1 Pathak et al., "Cyanobacterial Farming for Environment Friendly Sustainable Agriculture Practices."
2 Häder, "On the Way to Mars—Flagellated Algae in Bioregenerative Life Support Systems Under Microgravity Conditions."

Nature inspired design and engineering became even more prominent after the Industrial Revolution in different industries, such as transportation, aviation, material science and energy.[1] In space exploration, researchers investigate applying biomimicry to develop hardware solutions and design principles, including interconnected networks, multi-function components and extensive control networks.[2]

Similar to biomimicry, biotechnology has been a powerful tool that our species has used to advance civilization for thousands of years. Biology related technologies encompass an extensive scope of procedures for modifying living organisms to serve our purposes, including domestication of animals and cultivation of plants in agriculture, as well as making “improvements” to these organisms through selective breeding. Today, however, the term biotechnology mainly refers to genetic engineering as well as cell and tissue culture technologies. While biotechnology has medicinal, agricultural and industrial applications, scientists at space agencies such as NASA examine how it could help develop advanced technologies to sustain life in space, and explore how bioengineered organisms can enable long duration human spaceflight by providing essential resources such as food, clean air and water, as well as biofuels.[3]

1 “Biomimicry: A History | EHISTORY.”
2 Kundrot, “NASA Mission and Applications of Biomimicry.”
3 Kovo, “About Space Biosciences - Bringing Life Into Space.”

Despite its hostile nature and numerous challenges, exploring the galaxies remains one of humanity's most ambitious collective dreams. To travel farther into the cosmos, however, it is vital to think, design and innovate radically. Human space exploration and settlement will require leaps forward in life support for environmental management. Life support structures for long-term space travel must be closed loop systems that efficiently use nonrenewable resources packed from Earth, while increasingly transitioning to regenerative resources, grown onboard spacecraft or, locally, on other planets. Human-designed solutions are rudimentary, additive and inefficient in use of material and energy. In contrast, natural processes rely on unique geometries and material properties, resulting in more efficient systems.[1]

Therefore, nature's unique expertise in designing closed-loop ecosystems makes it the ultimate blueprint for developing bioregenerative life support systems to sustain multispecies beyond Earth.

The currently unresolved challenges inherent in long-duration space exploration provide scientists, engineers, artists and designers with an exhilarating opportunity for collaboration. Moreover, the exponential growth in computing power, current advances in biotechnology, and the collective effort of the public and private sector in the field of space exploration offer a unique possibility to speculate nonconventional solutions, and push the boundaries to pioneer space exploration bio-technologies for the future of human space exploration.

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1 "Nature Does It Better."

In this design fiction project we will speculate the future of space exploration technologies beyond biomimetic design and engineering. We will explore the possibilities of integrating biodesign to create a biological life support system inspired by closed loop sybiomes in nature. We will depict a future, in which space explorers can design, program and grow anything, including ecological life support systems to sustain multi-organism habitats in deep space.

literature review

Life Support Systems (LSS) are an essential part of a deep space habitation capability. Habitation systems will provide a safe place for humans in space, and life support is key to sustaining life inside a deep space habitat. LSS functions include monitoring atmospheric pressure, oxygen levels, waste management, and water supply. Although LSS technologies have advanced a great deal in the last 40 years, they remain heavily dependent on Earth.[1]

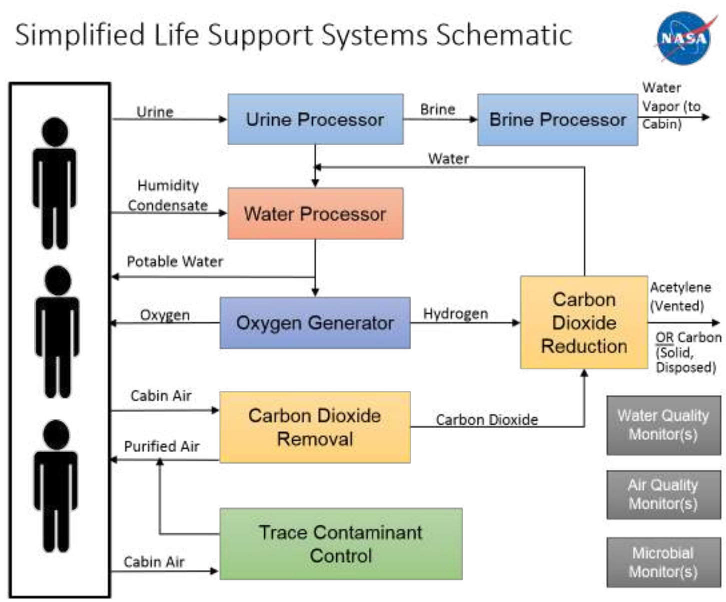

Fig 1. The Simplified Life Support Systems Schematic (Credits: NASA)

1 Jackson, "Life Support Systems."

Presently, both air and water get recycled aboard the ISS. The process of water purification and the recovery of oxygen from exhaled carbon dioxide is performed via physico-chemical processes.[1] The drinking water is processed from urine, condensation and other sources, yet the system still needs regular refills and fresh filters.[2] The researchers at NASA have been investigating different materials to determine which would be most effective for use in filters for carbon dioxide removal on long-duration missions.[3] However, even the most durable material will eventually deteriorate and need to be replaced, unless it is derived from a regenerative source.

Energy

The ISS is fully powered by solar energy, using solar arrays that convert energy to electricity. These solar arrays consist of thousands of solar cells, made from purified chunks of the element silicon. These cells directly convert light to electricity using a process called photovoltaics. Only 40 percent of the electricity generated by the solar arrays is used to power station systems and experiments when the station is in the sun, and the remaining 60 percent of the electricity is used to charge the station's batteries. The batteries then power the station when it is not in the sun.[4] However, the farther we get from the Earth, the less abundant sunlight becomes. Therefore, in addition to developing more efficient solar technologies for the journey to Mars, we need to investigate sun-independent energy sources for long-duration missions.

1 Walker and Granjou, "MELiSSA the Minimal Biosphere."
2 "Life Support."
3 Rainey, "Clearing the Air in Space."
4 Garcia, "International Space Station Solar Arrays."

Food

Stored food represents the largest expected non-propulsion consumable mass for human spaceflight. The food aboard the ISS is prepared here on Earth and designed to supply the crew members with all the Recommended Dietary Allowances (RDA) of vitamins and minerals necessary to perform in the environment of space. The astronauts are supplied with three balanced meals and snacks per day, and have a wide variety of food items to choose from; yet, their options are limited to dehydrated and prepackaged foods.[1] Long-duration missions will require unique solutions to provide the astronauts with their dietary needs. The Human Research Program at NASA, for instance, is developing methods of formulating, processing, packaging and preserving food, to ensure nutrients maintain their integrity and stability for the first manned mission to Mars.[2] Sustaining space explorers on journeys beyond Moon or Mars, however, will demand a completely novel framework to design self-sustaining food production systems in situ. Such systems would not only eliminate reliance on Earth-produced supplies, they would also provide the astronauts with fresh fruits and vegetables that currently lack in their dietary regimen. This improvement in diet could potentially help to boost the astronaut’s immune system, and alleviate the effects of space-induced health issues.

1 MSFC, “Food for Space Flight.”
2 Perez, “The 5 Hazards of Human Spaceflight.”

General effects of space exploration on health

Deep space exposes the astronauts to a series of environmental and psychological stressors that impact their mental and physical health. In a recent experiment, NASA performed a year long study to examine the effects of long-duration spaceflight on the astronauts overall health. In this undertaking, a pair of male monozygotic twins were studied for 340 days, during which one of the twins aboard the International Space Station (ISS), while his identical twin remained on Earth. Throughout the study, the researchers collected physiological, telomeric, transcriptomic, epigenetic, proteomic, metabolomic, immune, microbiomic, cardiovascular, vision-related and cognitive data, as well as stool, urine, and whole blood samples from both subjects. The results of this study suggested that long term spaceflight could increase the risk of astronauts suffering from mitochondrial dysfunction, immunological stress, vascular changes and fluid shifts, and cognitive performance decline, as well as alterations in telomere length, gene regulation and genome integrity.[1]

1 Garrett-Bakelman et al., “The NASA Twins Study.”

Effects on the astronaut's microbiome and immune system

In addition to NASA's twin study, extensive past and current research in the area of asto-microbiology indicate that the environmental and psychological stressors in space travel combined with astronauts' restricted diet of prepackaged food affect the composition and functions in their gastrointestinal microbiome.[1] The research suggests that during spaceflight the astronauts' microbiome loses multiple beneficial bacteria that are imperative to the overall gut microbiome health and could result in a compromised immune system that makes the astronauts more vulnerable to infections and diseases, especially during longer missions.[2] Therefore, it is critical to explore preventative measures, such as incorporating prebiotics and probiotics to maintain and improve astronauts' gastrointestinal microbiota, and therefore their immune strength. Diet based therapies, such as incorporating fresh fruits and vegetables, is one of the countermeasures that could help regulate the gastrointestinal microbiota of the astronauts, by providing them with fiber-rich food to promote the growth of healthy butyrate-producing bacteria in the gut. Researchers in different organizations, including NASA, are currently examining the feasibility and best practices for space farming, as well as the effects of space stressors on different plants and microorganisms.[3]

1 Voorhies and Lorenzi, "The Challenge of Maintaining a Healthy Microbiome during Long-Duration Space Missions."
2 Voorhies et al., "Study of the Impact of Long-Duration Space Missions at the International Space Station on the Astronaut Microbiome."
3 Voorhies and Lorenzi, "The Challenge of Maintaining a Healthy Microbiome during Long-Duration Space Missions."

Effects on the astronaut's psychological well being

In addition to the potential physical risks, long term exposure to deep space stressors along with prolonged confinement could also result in maladjusted psychological reactions among crew members. Currently crew members are carefully selected and spend ample time training together under simulated stressful conditions to prepare for a mission, but even the most qualified humans are prone to adaptation problems in unpredictable situations, especially in extreme environments and during longer journeys. In fact, adverse psychological response among astronauts is one of the most harmful effects of long term space travel.[1] These psychological risks include decline in mood, cognition, morale and interpersonal relationships. These maladaptive responses could result in team miscommunication that could be detrimental to the mission. It is notable that consistent lack of access to fresh food may also contribute to these negative psychological effects.[2]

Food production systems in situ would not only eliminate the crew's reliance on Earth for supplies during long-duration journeys, they would also provide astronauts with fresh fruits and vegetables that could help improve their psychological well being, and strengthen their immune system. However, farming in space is much different than growing produce on Earth. Therefore, the effects of deep space stressors on plants and the conditions in which plants thrive onboard spacecraft should be carefully examined in order to design such systems.

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1 Alfano et al., "Long-Duration Space Exploration and Emotional Health."
2 Perez, "The 5 Hazards of Human Spaceflight."

farming in space

According to pioneering astronauts, fresh plants on the ISS are tokens from Earth that create a more beautiful atmosphere and improve the psychological well-being of the crew in space. Moreover, fresh produce will be critical for keeping astronauts healthy on long-duration missions, since the vitamins in prepackaged form will break down over time. Hence, researchers at different agencies, including NASA are investigating different solutions to provide astronauts with nutrients in a long-lasting, easily absorbed form: freshly grown fruits and vegetables. The challenge with farming in space is growing produce in a closed environment without sunlight or Earth's gravity. Results from plant growth on the space station have come from experiments designed for developing bioregenerative food production systems for the space station and for future long-duration exploration missions.

Fig 2. ISS-30 Zucchini plant in the Destiny lab (Credits: NASA)

One of NASA’s ongoing experiments, the Vegetable Production System, known as Veggie, is a space garden residing on the space station. The purpose of this project is to study plant growth in microgravity, while adding fresh food to the astronauts’ diet and enhancing happiness and well-being.

Veggie is a hydroponic system, in which each plant grows in a “pillow” filled with porous clay substrate with controlled release fertilizer to deliver water, nutrients and oxygen to the plant roots. Since liquids behave differently in space and form bubbles, the pillows are important to help distribute water, nutrients and air in a healthy balance around the roots. The system also includes light emitting diodes (LEDs) above the plants that produce a spectrum of light suited for the plants’ growth. In the absence of gravity, plants use other environmental factors, such as light, to orient and guide growth.

To date, this system has grown a variety of plants, including three types of lettuce, Chinese cabbage, mizuna mustard, red Russian kale and zinnia flowers. Some of the harvest samples were returned to Earth to be analyzed for harmful microbes growing on the produce. However, no harmful contamination has been detected, and the food has been safe to eat. Moreover, astronauts described the experience of eating freshly harvested produce enjoyable. The team plans to continue experimentation by growing other plants such as tomatoes and peppers, as well as antioxidant-rich foods like berries and certain beans that could provide some space radiation protection for crew members.[1]

1 Heiney, “Growing Plants in Space.”

The Advanced Plant Habitat (APH),has a similar system structure to Veggie. But unlike Veggie, it is enclosed and equipped with automated water recovery and distribution, atmosphere content, moisture levels and temperature. Plus, it consists of cameras and more than 180 sensors that are in constant interactive contact with a team on the ground, so it doesn't need much maintenance and day-to-day care from the crew. The APH team is interested in what happens to plants in space at the gene, protein and metabolite level, and what changes occur and why.[1]

The Biological Research in Canisters (BRIC) studies the effects of space on microorganisms, such as yeast and microbes. BRIC-LED is the latest version, that includes light-emitting diodes (LEDs) to support organisms such as plants, mosses, algae and cyanobacteria that need light to photosynthesize. This project investigates changes in the organism's gene expression in space, such as alteration in genes associated with gravity, and changes in the plants' immune system, which may compromise plants' ability to fight off infections.[2]

Fig 3. Astronaut Shane Kimbrough, Veggie experiment on board the International Space Station. (Credit: NASA)

1 Heiney.
2 Heiney.

Other experiments have also yielded interesting findings about plant growth in space. For instance, scientists observed that altered gravity does not impact plant growth substantially. Another series of experiments performed on the space station showed that the development cycle of plants, their genetic status, morphological and biometric indicators, and basic processes (i.e., photosynthesis, gas exchange, formation of generative organs) do not depend on the spaceflight conditions. Moreover, it was concluded that higher plants' seeds formed in microgravity were biologically complete, and the plants grown from these seeds did not differ from ordinary plants, grown on Earth. Results also indicated that at least four successive generations of higher plants can grow and develop in spaceflight conditions. Therefore, developing technology for cultivation of higher plants will offer the possibility of introducing greenhouses as natural human life support systems during long-duration human exploration missions.[1]

1 Johnson, "Plant Biology and Bioregenerative Life Support."

Bioregenerative Life Support System (BLiSS)

Bioregenerative systems go beyond sustainability. They are artificial ecosystems consisting of complex symbiotic relationships among multiple species, including humans, higher plants and microorganisms. Bioregenerative systems intend to replenish, restore and preserve the ecosystem's integrity. These systems look at every ecosystem interdependent on other ecosystems, and operate on the principle that for one ecosystem to thrive, it needs to make sure other ecosystems are thriving as well. In a balanced BLiSS ecosystem, microorganisms, plants, insects and animals establish symbiotic relationships.[1]

An example of a bioregenerative system designed for space exploration is European Space Agency's (ESA) Micro-Ecological Life Support System Alternative programme (MELiSSA), which is a self-sustaining closed loop life support system that by finely tuning how microbiological cells, chemicals, catalysts, algae, bacteria and plants interact could process waste to supply astronauts with the oxygen, water and food they require throughout long-duration spaceflight.[2]

1 "Regeneration and Regenerative Systems."
2 Walker and Granjou, "MELiSSA the Minimal Biosphere."

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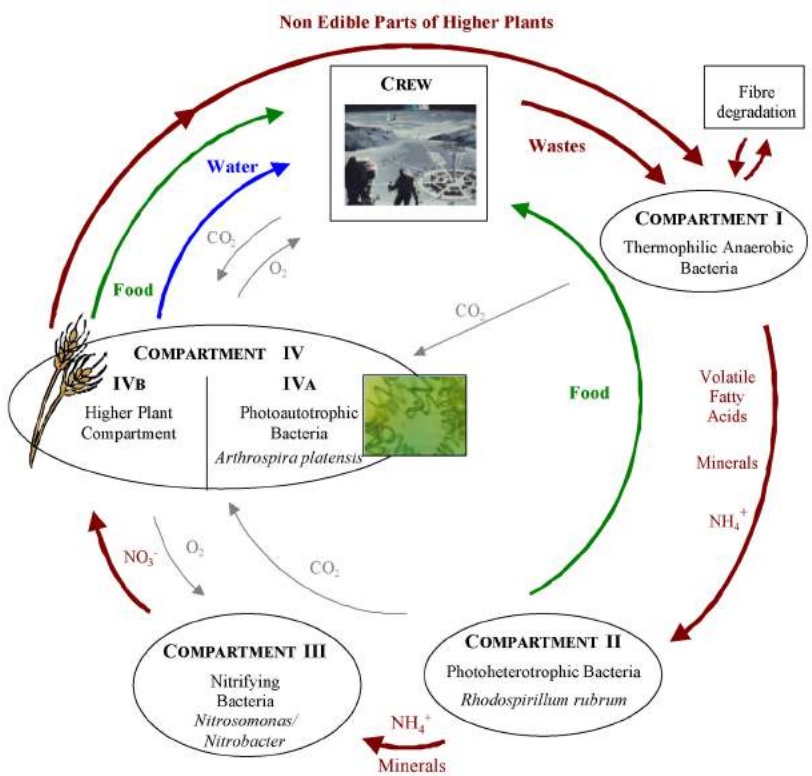

Fig 4. The MELISSA loop. (Credit: Christophe Lasseur/ESA)©

MELiSSA proves our vital dependence on a multispecies biosphere. This biomimetic closed-loop system is modeled after aquatic ecosystems and aims to engineer the minimal biosphere that promotes a symbiotic relationship between humans and microbes and is capable of reliably sustaining human life. MELiSSA minimizes biodiversity, reducing its biosphere to the most basic of the microbiological processes that sustain global ecological functions. It consists of five compartments populated respectively by microbiota and edible plants, interconnected by tubes that circulate elements between microenvironments. These compartments are designed specifically for the species inhabiting them. Some of the compartments contain bacteria that break down human and plant waste into nutrients for the higher plants that are housed in a growth chamber and supply astronauts with food. Another chamber contains cyanobacteria of the genus Arthrospira ('spirulina') that take carbon-dioxide and water and turn it into oxygen and edible biomass. Eventually, the system will become self-sustained so that astronauts on long-duration missions can reduce their dependence on costly supplies from Earth.[1]

Plant growth systems are a critical component of a comprehensive Bioregenerative Life Support System (BLiSS) for long-duration human space exploration missions. In addition to providing astronauts with food, higher plants, through the biological processes of photosynthesis and transpiration, can also contribute to atmosphere revitalization and water recycling.[2] Previous BLiSS technology development and crop selection have primarily focused on optimizing edible biomass and caloric content. However, a holistic approach to designing plant growth systems and crop selection for human exploration missions must consider long-term crew health, morale, and performance through multiple modalities.

1 Walker and Granjou.
2 "Next Generation Life Support (NGLS) | Space Technology."

SIRONA: Sustainable Integration of Regenerative Outer-space Nature and Agriculture is a more complex example of BLiSS. SIRONA uses an innovative multispecies design approach to integrate: astronauts, plants, animals and microbes. It is a food production, preparation, and preservation facility that includes: Integrated Multi-Trophic Aquaponics (IMTA), Controlled Environment Agriculture (CEA) systems, automation technologies, food preparation/preservation concepts as well as integration of crew recreation, access to nature, and horticulture therapy. This system could produce a wide variety of food sources including land crops, algae, aquatic crops and aquatic animals, while providing additional psychological health benefits for the crew.[1]

Despite recent advances in Bioregenerative Life Support System technology, many technological issues still need to be tackled to provide the consumables required to sustain crews. Using biological systems to produce resources in situ is an enticing approach. However, all organisms we currently know have evolved on Earth and not the deep space environment. The main challenges include keeping organisms alive in a metabolically active state with minimal maintenance, while relying only on recycled resources or those found locally. Moreover, during space flight, another challenge is to frequently produce enough to feed the crew, given the limitations in space and resources. The tools and methods recently developed within the field of biodesign and synthetic biology can greatly accelerate the development of human space exploration.[2]

1 Hava et al., "SIRONA."
2 Verseux et al., "Synthetic Biology for Space Exploration."

biodesign

Biodesign goes beyond biology-inspired approaches to design and fabrication. In contrast to biomimicry, biodesign is the design of, with, or from biology; A practice that integrates living organisms as essential components in design, to enhance form and function. Biodesign dissolves the boundaries between biology and engineering and makes it possible to synthesize new hybrid objects and architecture. Most importantly, it enables us to harness nature’s self-replicating manufacturing systems that could replace industrial or mechanical systems with biological processes.[1] Biodesign encompasses a wide scope of disciplines, including biomedical engineering, biotechnology, design and synthetic biology. In space exploration, most research thus far has been focused on biomedical applications, such as investigating the effect of spaceflight on the genetic responses and disease-causing potential of microbial pathogens.[2] Several projects, however, explore other potential applications of biodesign in space exploration, including food production and preservation, biomaterial[3] and fabrication[4], as well as synthetic biology.

Biodesign could help solve many challenges involved in space exploration, because life can replicate and repair itself, and perform a wide variety of chemical reactions including making food, fuel and materials. Growing organisms as feedstock and additive manufacturing through bioprinting will enable space explorers to make bespoke tools, food, smart fabrics and even replacement organs on demand.[5]

1 Myers and Antonelli, Bio Design.

2 Rainey, “Spark 101.”

3 Rothschild, “Biomaterials Out of Thin Air.”

4 Snyder et al., “A Makerspace for Life Support Systems in Space.”

5 Rothschild, “Synthetic Biology as an Enabling Technology for Space Exploration.”

Food

Precision biotechnological methods have opened new possibilities in agriculture, nutrition, and other areas of the food industry. Instead of crossbreeding different organisms across generations, researchers are speeding up the process of gene transfer with precise biotechnological tools like DNA recombination and CRISPR. This technology enables scientists to produce modified crops that are more resistant to disease and environmental conditions of deep space. These qualities can increase crop yields or stabilize production throughout the mission. Additionally, gene modification could improve the nutrient profile of organisms for optimal fat, protein or vitamin content. Moreover, we can create modified bacteria that, through fermentation, use excess carbohydrates to directly synthesize supplement molecules.[1]

For instance, NASA is engineering a bacterial strain that can manufacture a crucial nutrient called Zeaxanthin -an antioxidant critical for eye health for astronauts- during space travel missions. Bacteria engineered to produce Zeaxanthin can be dehydrated and packed into tiny capsules, ready to be reanimated when needed.[2]

1 "Synthetic Biology for Sustainable Food | Twist Bioscience."
2 Sims, "BioNutrients-1 (BN-1) Payload Overview."

Biomaterial and Fabrication

In addition to providing the astronauts with oxygen and edible biomass, using photosynthesis in combination with physico-chemical systems, bioreactors could synthesize natural substrates for biomaterials for long duration human missions.[1] Fungi, algae and bacteria are among dexterous organisms with compelling properties that make them suitable for cultivation during long duration space exploration.

"The future of design is a future where anything material in the environment — whether it's wearables, cars, buildings — can be designed with this variation of properties and relationship with the environment that can take part in the natural ecology. Hopefully it points towards a shift that goes beyond the age of assembly into the age of a new kind of organism."

—Neri Oxman

1 Kolodziejczyk and Summerer, "Bioreactors and Biomaterials in Space Architecture."

Fungi and Mycomaterial

Fungi can become important cell factories for life in space. First, it is one of the most robust and efficient production systems used in industrial biotechnology. Second, it is a multipurpose cell factory that produces a diverse range of organic acids, proteins, enzymes and natural products. Therefore, making it an ideal source of food, enzymes and antibiotics. Furthermore, its vegetative part, mycelium, is a versatile source for biomaterial that could be utilized in space travel.[1]

Fungi are one of the most versatile organisms used to produce a variety of biomaterials, such as mycelium-based foams, textiles and construction materials. Mycelia are the root-like structures of fungi. They have a fine and thread-like structure, but they are strong and have a number of surprising capabilities. The material could be used dry, wet, frozen with water or as part of a self-produced composite.

Mycomaterials are naturally fire-retardant, a critical component in sealed, pressurized, oxygen-rich habitats. They are also excellent insulators that could help protect the astronauts against the extremely freezing temperatures in deep space. Moreover, melanin-rich fungi are able to absorb radioactivity and could potentially create radiation-blocking structures. As mycelia normally excrete enzymes, it should be possible to bioengineer them to secrete other materials on demand such as bioplastics or latex to form a biocomposite.

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1 Cortesão et al., "Fungal Biotechnology in Space."

Most importantly, this material is self-replicating and self-repairing. A mycotectural structure will require minimal energy for building, because in the presence of food stock and water it would grow itself, and it can generate additional structures, using feedstock of mission-produced organic waste streams. Mycomaterial can have a long life, but at the end of its life cycle the material could be used as fertilizer for mission farming.[1]

building material. Not long ago, using mycomaterial was explored mainly by artists and designers. Today, however, there are several companies such as Ecovative Design, MycoWorks and Mogu that produce and sell consumer mycomaterial; therefore, proving the material's ability to scale and meet growing demand.

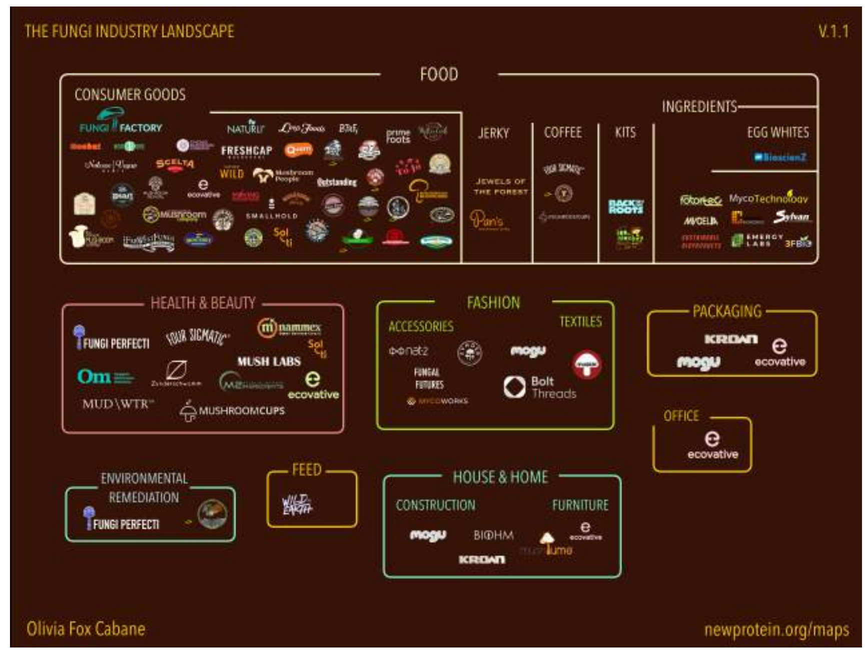

Fig 5. The Fungi Industry Landscape.
(Credit: newprotein.org)

1 Rothschild, "Myco-Architecture off Planet."

Ecovative Design

Ecovative Design is a New York based startup that uses mycelium and fine-tunes the structure to account for porosity, texture, strength, resilience, fiber orientation and more. They have developed mycelium based products such as MycoFlex and MycoComposite.[1]

MycoFlex is a high-performance, pure mycelium foam that can be tailored into applications such as textile.[2]

Fig 6. MycoFlex. A flexible mycelium-based material. (Credit: Ecovative Design)

1 "Ecovative Design."
2 "MycoFlexTM."

MycoCoposit is a patented biomaterials platform that utilizes mycelium as a self-assembling biological binder for agricultural byproducts. The product is licenced to several packaging producers around the world. In addition, ready to grow kits of MycoComposit are available to consumers. These grow kits are used by designers, artists and regular people to create their own designs.[1]

Fig 7. MycoComposit. A mycelium-based material used in packaging. (Credit: Paradise Packaging)

1 “MycoCompositeTM.”

MycoWorks

MycoWorks is a San Francisco-based startup which produces sustainable products and apparels from fungi. They produce weatherproof material using the fungi “Ganoderma lucidum” and “Pleurotus ostreatus”. Their mycomaterial is utilized to make furniture, bricks, footwear and leather.

Mogu

Mogu is an Italian startup that develops mycomaterials and products that have remarkable technical properties and innovative aesthetics. They use fungal mycelium and upcycled textile residues to make their products, including a collection of acoustic panels and floor tiles which consist of a mycelium composite core, coated with a proprietary formulation of 90% bio-based resins.[1]

Fig 8. Decorative acoustic panels. (Credit:Mogu)

1 muvobit, “Mogu | Radical by Nature.”

Algae and algal polymer

Similar to fungi, algae is a polyvalent organism that has proven promising as an integral part of a BLiSS in space exploration. They grow and replicate fast, contain a variety of unique value added material, and have high bioenergy feedstock potential. Moreover, they do not compete with food resources.
Algae could be used to take carbon dioxide from the habitat and produce oxygen for the astronauts. Moreover, via photosynthesis, it produces biomass that could be used for food, feedstock, biofuel and biomaterial. It could also be utilized for water purification and waste treatment.

Algae could be cultivated as a multi-purpose organism, and used as feedstock for biopolymer production on long-duration missions. Algae derived biopolymers are classified into three types. First type includes natural polymers, such as polysaccharides, lipids, extracellular polymeric substances. Polysaccharides from algae such as alginate and agar are well known for their biotechnological applications. Second type is polyhydroxyalkanoates (PHA) which accumulate in only cyanobacteria. Third type is bio-based polymers polymerized from algae derived monomers that could have the same characteristics as conventional synthetic polymers.[1]

1 Yıldız Technical University, Faculty of Chemical and Metallurgical Engineering, Bioengineering Department, Esenler 34201, Istanbul, Turkey et al., "A Review on Algal Biopolymers."

Biomaterial in space habitats

Myco-architecture off planet: growing surface structures at destination, is a design proposal for growing habitats, using mycelium on Mars and beyond. Fungal mycelia is a lifeform that needs oxygen and nutrients. That's where cyanobacteria comes in. This photosynthetic bacterium can use energy from the Sun to convert water and carbon dioxide into oxygen and food for the fungi.

These two organisms form an elegant habitat concept with a three-layered dome. The outer layer is made up of frozen water ice and serves as a protection layer from radiation. The second layer is made up of cyanobacteria that can take water from the outer layer and photosynthesise to produce oxygen for astronauts and nutrients for the final layer of mycelia. That last layer of mycelia organically grows into a robust habitat.[1]

"If successful in developing a biocomposite material that can grow itself, NASA will have a radically new, cheaper, faster lighter material for designing habitats for extended duration lunar missions, Mars missions, and mobile habitats as well as furniture and other structures."[2]

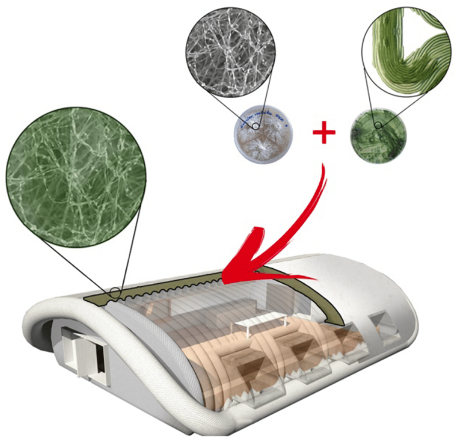

Fig 9. Myco-architecture off planet. (Credit: NASA)

1 Tavares, "Could Future Homes on the Moon and Mars Be Made of Fungi?"
2 Hall, "Myco-architecture off planet."

primary research

To gain more insight on how biodesign could be integrated in space exploration research to create more advanced bioregenerative systems, I performed a series of primary research. My methodology in this phase of the exploratory process falls into three main categories: observation, expert interviews and experiments.

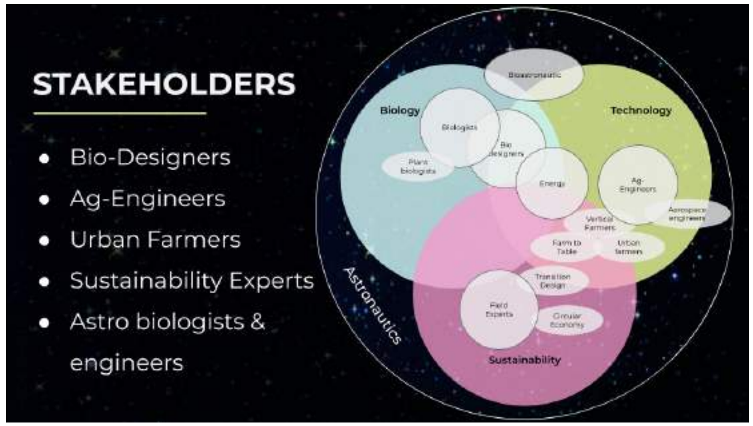

Fig 10. Stakeholders Map

observarions

I visited multiple urban farming facilities in New York to learn more about indoor farming techniques. I collected notes as well as photograph and video documentation of each site. I also conducted short interviews with the facility managers. I was especially interested in indoor farms with controlled environment technology, since my literature review indicated it to be the preferred farming method to grow different organisms onboard the ISS or for future human missions to Mars and beyond.

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Square Roots

Location: Square Roots Urban Farming Campus Brooklyn, NY
Date: 10/19/2019

Description: Square Roots is a seed-to sales urban farm that grows fresh herbs and distributes them in the same communities as their farms.

Method: I attended the Square Roots farms open house tour, where I had the opportunity to tour the facility, see the farm modules and learn more about the company and how the farms work from the CEO and co-founder, Tobias Peggs. I also interviewed one of the farm managers to inquire more about the technology they use in their farms. Finally, I got to taste some herbs from the farm, which were, in fact, quite flavorful.

Key Findings:

The facility consists of multiple modular and scalable controlled environment units, housing hydroponic systems that grow vegetables all year round. Each module is equipped with several sensors to collect data to harness the collective knowledge of every farm in their network. Some sensors control the humidity and temperature of the environment to create ideal growth conditions, while others measure nutrient, ph level and mineral content in the water.

The modules are made from shipping containers, with vertical flow hydroponic systems, and only red and blue LED lights to optimize energy efficiency. The system uses 150 kilowatts of energy per day. The water circulates constantly in the system, which means each module only uses approximately eight gallons of water per day. Water is replaced every three months.

Each module produces the equivalent of a two acre farm land, with the end produce containing 80 percent edible mass. It can grow 120 different varieties of crops, including herbs, greens, tomatoes and strawberries. The nutrient blend is tailored to grow plants with enhanced taste and texture.

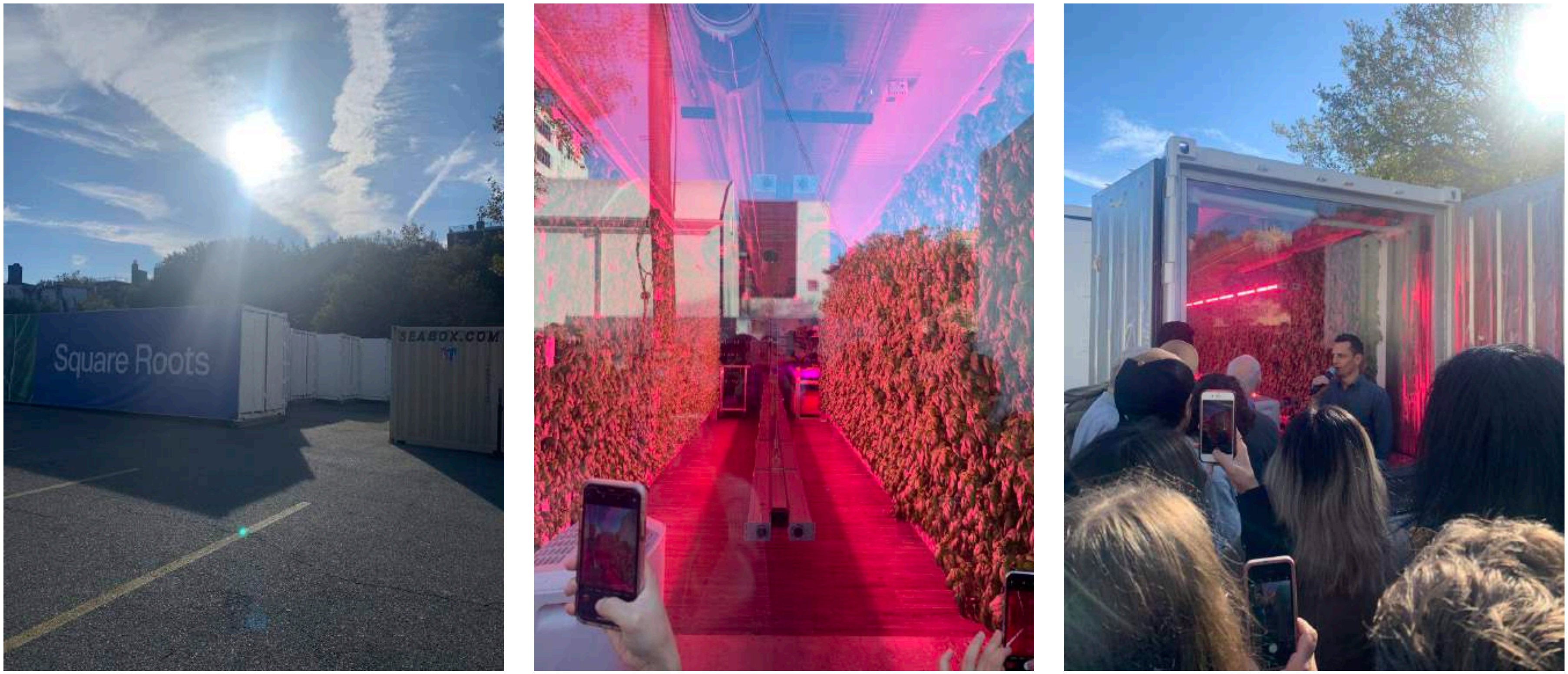

Fig 11. Square Roots Farms, Open NYC Tour

NYU Urban Food Lab

Location: NYU Tandon MakerSpace 6 MetroTech Center, Brooklyn, NY
Date: Multiple visits during 10/2019 - 2/2020

Description: The Urban Food Lab is a vertical urban farm and research laboratory. The indoor farming lab at NYU Tandon was started by NYU graduate and PhD students, researching indoor vertical farming technologies to grow algae, plants and fish sustainably. The farm and program is managed by PhD candidate, Omar Gowayed. Omar's students learn about aquaponics and project design by developing projects to apply their respective fields to the farm while simultaneously working on the farm.

Method: I got a tour of the facility and interviewed Omar to learn more about their controlled environment and aquaponic system. Later, I volunteered at the farm multiple times to learn how the system is maintained.

Key Findings:

Vertical farming allows produce to be grown in urban areas in a controlled environment, allowing for year-round growing without the environmentally costly effects of conventional farming.

The system integrates either blue and red or full spectrum LED grow lights, depending on the type of plant and the stage of growth they are in.
The aquaponics system aims to create a symbiotic closed-loop system, in which the water is circulated between the aquarium and the vertical garden. In this set up, fish waste provides nutrients for the plants to grow. The plants produce edible biomass for food consumption. They also take carbon dioxide from the facility and produce oxygen. The students/farmers are responsible to make sure that all the organisms in this ecosystem are healthy, by monitoring the environment and water quality.

The system is housed in a controlled environment, where the temperature and air quality are constantly monitored and regulated. The water is also frequently tested for PH and EC (electrical conductivity) levels, in order to ensure water quality and nutrient levels. The system is highly prone to algal blooms. Also, unlike hydroponic systems, aquaponics involve aquatic creatures that are vulnerable to illness and infections. Therefore a UV sterilizer is used to stop the spread of any microorganisms.

Fig 12. NYU Urban Food Lab (Credit:NYU)

Los Sures Community Garden

Location: Brooklyn, NY
Date: 10/01/2019

Description: Los Sures offers a hydroponic farm and a local food pantry to serve the diverse family life of Williamsburg.

Method: I visited Los Sures, where I received a tour of the indoor farming facility and food pantry, and spoke with the operations manager, Diego Rodriguez.

Key Findings:

Los Sures's main indoor farm is located in the basement of a senior housing complex. It consists of multiple vertical hydroponic systems and a small aquaponic system, where the staff runs experiments to develop their own best practices. The setup is quite similar to NYU's vertical system; however, the main method used here is hydroponics.
Due to the organization's limited resources, the vertical hydroponic systems are built with available and economical material, in a true DIY manner. Similar to the NYU Food Lab, the systems use either blue and red or full spectrum LED grow lights. However, here, they use two different hydroponic methods: in some beds the plants are placed in clay substrate; while in others, the roots are submerged in water that circulates through the system.
The water is tested for PH and EC levels, and liquid nutrient solution and salts are added to maintain optimal levels for the plants. The temperature is maintained using multiple small fans.

Fig 13. Los Sures hydroponic and aquaponic indoor farming systems

expert interviews

I interviewed biodesign experts in different disciplines including microbiology, industrial design, urban horticulture and architecture to further investigate the different facets that I integrated into my project.

Elizabeth Marie Hénaff, PhD

Location: Brooklyn, NY
Date: 09/2019 - 05/2020

About: Dr. Elizabeth Hénaff is a computational biologist and artist. She is an assistant professor at NYU Tandon, where she teaches biodesign at the Integrated Digital Media program. Her research is centered around a fascination with the way living beings interact with their environment, as well as multispecies design.[1]

Method: I continuously consulted with Dr. Hénaff throughout my thesis project, from ideation to conception and eventually prototyping. I kept a written record of discussion highlights.

Fig 14. Elizabeth Hénaff(Credit: Elizabeth Hénaff)

1 "Elizabeth Hénaff."

Key Findings:
- Importance of multispecies design
- Potential role of microorganisms
- Creating synthetic plants that can endure radiation and hostile environments of space
- Scoping down my project: Setting constraints to design the experience
- Creating a narrative to provide context for the audience/participants

Maggie Coblentz

Location: Cambridge, MA
Date: 02/26/2020

About: "Maggie Coblentz is an industrial designer and researcher who uses food as a lens to explore the future of human life and culture in extreme environments. She pursues this at the MIT Media Lab Space Exploration Initiative—a research group actively building the technologies, tools, and human experiences of our sci-fi space future. In this role she leads research on interplanetary gastronomy."[1]

Fig 15. Maggie Coblentz, Algae Caviar, Molecular Gastronomy in Zero G (Credit: Maggie Coblentz)

Method: 30 minute phone interview

1 "Maggie Coblentz."

Key Findings:

- Importance of multisensory design
- Focusing on the sensory experience of food
- Food beyond sustenance: designing food that is playful and creates joy for astronauts
- Fermentation as a potential method to “cook” in space
- Ongoing research on how deep space affects fermenting bacteria and fermented food
- Using molecular gastronomy to create new recipes with organisms, such as spirulina(cyanobacteria)

Vanessa Harden

Location: Brooklyn, NY
Date: 09/2019-2/2020

About: Vanessa is an award winning artist and designer focused on creating thought provoking experiences and installations. She is a professor at NYU Tandon, where she teaches technologies for urban gardening at the Integrated Digital Media program. She is also the founder of the Subversive Gardener, a non-profit organization for environmental education, design exploration and public intervention connected to the guerrilla gardening subculture.[1]

Fig 16. Vanessa Harden
(Credit: Vanessa Harden)

1 “Vanessa Harden.”

Method: I consulted with Vanessa Harden on multiple occasions throughout my thesis project, and kept a written record of discussion highlights.

Key Findings:

- Importance of celebrating human history and ancient fabrication methods originated from different cultures on Earth, and taking that with us as we explore the cosmos
- Various ancient and widely used biomaterial: potato plastic, beeswax, rice paper, bamboo, pussywillow, clay and silk
- Potential of leveraging low-tech fabrication methods instead of 3D printing: weaving, mold casting
- Successful examples of immersive experience design, related to food

Terreform ONE, New Lab

Location: Brooklyn, NY
Date: 2/28/2020

About: Terreform ONE is a nonprofit architecture and urban design research-based consulting group. They endeavour to combat the extinction of all planetary species through pioneering acts of design. Their projects aim to illuminate the environmental possibilities of habitats, cities and landscapes across the globe. They operate as an interdisciplinary lab of specialists advancing the practice of socio-ecological design. The group cultivates resilience through innovations in building, transportation, infrastructure, water, food, waste treatment, air quality and energy.[1]

Method: I visited their main office and interviewed Mitchell Joachim, Ph.D., who is the Co-Founder of Terreform ONE and an Associate Professor of Practice at NYU. I had the opportunity to see some models of their previous projects as well as their current research projects related to mycomaterial.

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1 "Terreform."

Key Findings:

- Mycomaterials are versatile
- Mycelium could be used to create textile, packaging, furniture as well as building material
- It is important to create a sturdy or flexible mold or scaffolding for the mycelium to grow in
- Example of current research project:
- Integrating mycelium and higher plants into one symbiotic structure
- Growing architecture

Fig 17. Terreform ONE, mycelium bench

Fig 18. Terreform ONE, mycelium studies: mycelium and tree dome

experiments

Through my graduate studies, I designed and developed technologies for urban agriculture. My goal was to create semi or fully automated systems that would empower people to grow their own food in small urban environments.

Emerald: Automated Algae Bioreactor

Emerald is a decor object with an automated system to grow and harvest spirulina algae at home.

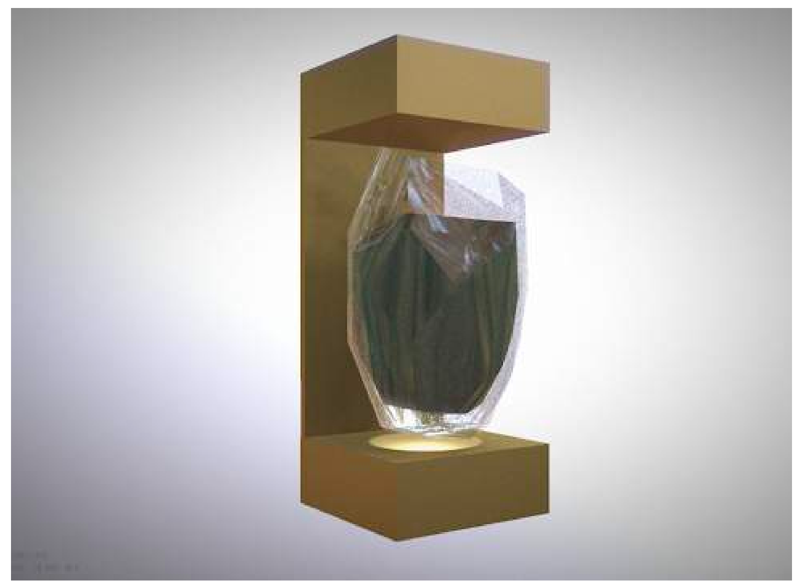
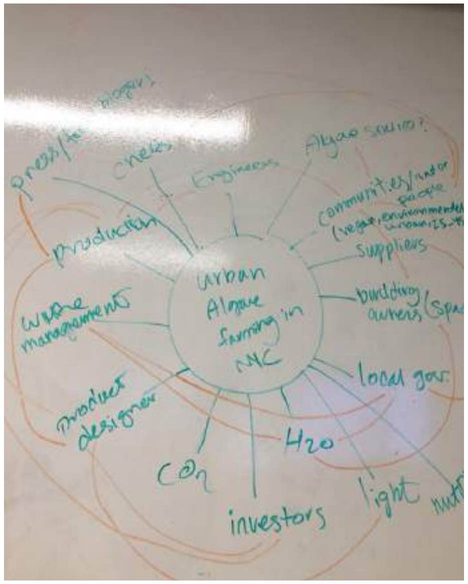


Fig 19. Emerald. 3D rendering

I designed and developed a prototype for this project with Timothy Lobiak for the Biodesign Challenge in spring of 2019. In essence, Emerald is a bioreactor that creates the perfect environment for spirulina to grow.
The system consists of automated blue and red LEDs to provide light for photosynthesis. The temperature of the growth medium is constantly monitored by a sensor that activates the heating pad underneath when necessary, in order to maintain an ideal temperature range for algae to thrive. The system also includes an air pump that automatically aerates the medium periodically throughout the day.

Initial concept



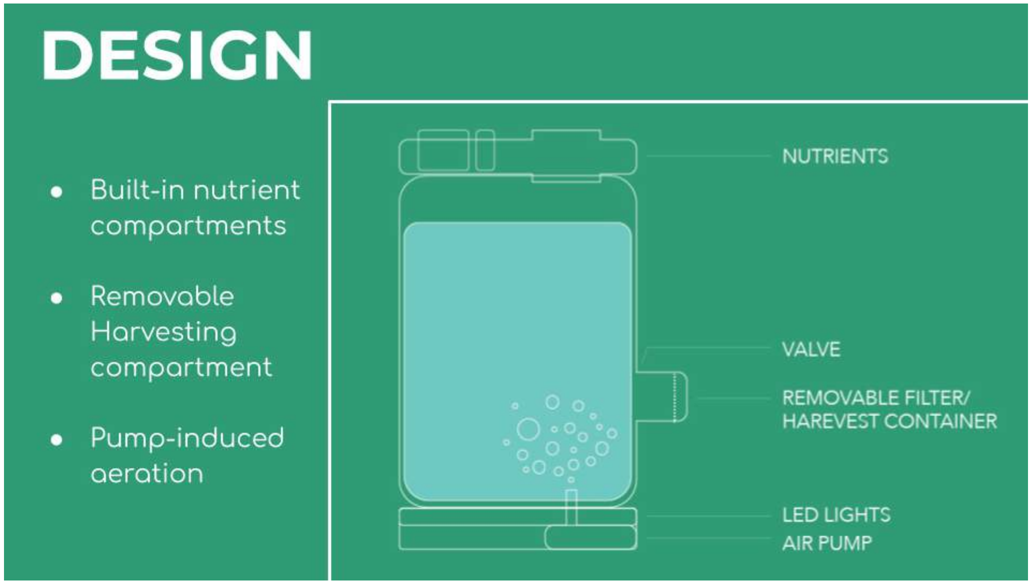


Fig 20. Ecosystem Map and design schematics for spirulina at home growing system

Prototypes

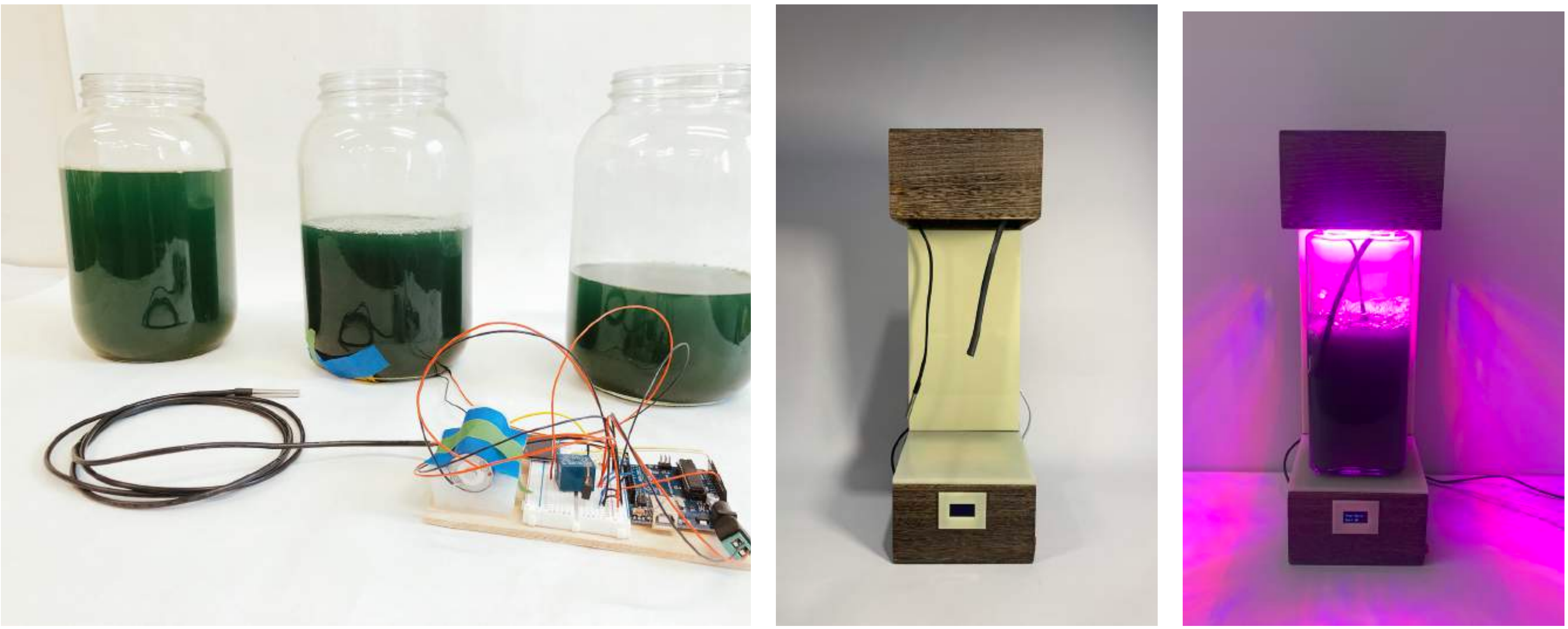


Fig 21. Spirulina Bioreactor: functional prototype and final prototype

IDM Grow Lab: Indoor Hydroponics Herb Garden

The IDM Grow Lab is a vertical hydroponic garden, germination station and interactive display. It is currently the only garden or green space in the Integrated Digital Media department at NYU Tandon.

Fig 22. IDM Grow Hydroponic System

This project is the result of team effort, and the culmination of a graduate course, called Technologies for Urban Gardening, that I completed in fall of 2019. For this project, first, I thoroughly researched different hydroponic systems to choose a design that was feasible to build, given constraints in time and budget. Next, I conceptualized multiple designs for this project with my team. I then researched all the parts needed to build the system and sourced the material. In addition, I researched and identified a collection of herbs and plants, tailored to our hydroponic system.

We created 2D renderings of our design concept, which was chosen by a committee and approved by the IDM department. I then led the design and build process with a team of five graduate students. Afterwards, I managed the system and cared for the plants from germination to harvest.

ideation

Over a span of four months, I thoroughly investigated literature in space exploration, researched the field of biodesign, and conducted primary research to acquire better understanding about controlled environment farming technologies as well as biodesign and fabrication. Then I synthesized my findings, which produce the thesis that: biology will be an instrumental tool in designing the future of space exploration. Using biotechnology, we could design genetically modified microorganisms and plants and even humans that could endure extreme levels of radiation and the hostile environments of deep space. With synthetic biology, we could design completely novel organisms tailored to the environments we explore. However, these measures are extreme and involve ethical concerns that need to be discussed. Until then, bioregenerative life support systems are a promising solution to sustaining life in space and extending multi-specie ecosystems beyond Earth. These ecosystems create an environment, where multiple organisms live symbiotically. These closed loop systems can provide future space explorers with food, oxygen and biomass that could be used as biofuel or biomaterial, while recycling air and organic waste.
My research pointed specifically to three different organisms that have been studied more extensively and show great potential to be cultivated and biodesigned for various purposes in space: fungi, micro-algae and bacteria.

Then, I started the ideation process. In order to find inspiration and generate ideas for my thesis project, I first looked closer at artists and designers whose work highlights biology and nature. I especially researched designs that feature fungi and algae. Although I found numerous artists and biodesigned examples, I was especially inspired by the works of the following individuals.

Anicka Yi

Anicka Yi is a conceptual artist, known for installations that engage the senses, especially the sense of smell, and for her collaborations with biologists and chemists.[1] The scholar Caroline A. Jones uses the term “bio-fiction” to describe Yi’s work. She describes her works as exploring “a biopolitics of the senses.”[2]

She often uses living and perishable materials, including bacteria. David Everitt Howe writes that this “incongruous mix of media” is “arranged into something elegantly allegorical about the various industries that constitute our identity.”[3] Yi manipulates these biological materials and transforms them, such as her work featuring algae(kelp) that she stretched into leather-like material.

Fig 23. Anicka Yi
(Credit: David Heald)

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1 Gregory, “Anicka Yi Is Inventing a New Kind of Conceptual Art.”
2 Dover, “The Hugo Boss Prize 2016.”
3 “Future Greats Archive.”

Biologizing the Machine (tentacular trouble), 2019

Fig 24. Biologizing the Machine (Credit: Luca Zanon/Awakening/ Getty Images)

In this piece, Yi uses a stretched leather-like kelp to create hanging incandescent sculptures that are reminiscent of human organs or insect eggs. Within these pods are animatronic insects that flutter. The use of this material draws attention to the ecological history and exciting potential applications of algae, a powerful and versatile entity that comprises the largest biomass on the planet. The ground beneath the pods symbolizes a swamp from which these organisms may have originated from. Yi uses soil combined with a bacteria that emits a specific smell. The hanging acrylic panels act as biosensors that change colors over time depending on the AI controlled temperature, light and water level. The AI element of this installation learns to understand the smell of the bacteria in stasis, decay and growth, then amending the environment accordingly. This colorful display creates a state of ‘agitated symbiosis’, with mutual benefits that could lead to unexpected findings.[1]

1 “Anicka Yi at 58th International Art Exhibition - La Biennale Di Venezia.”

Neri oxman
Architect, Designer, Inventor

Architect and designer Neri Oxman is an Associate Professor of Media Arts and Sciences at the MIT Media Lab. Her research group, the Mediated Matter, conducts research at the intersection of computational design, digital fabrication, materials science and synthetic biology, and applies that knowledge to different design disciplines, media and scales. She aims to augment the relationship between built, natural, and biological environments by employing design principles inspired and engineered by Nature. Oxman pioneered the field of Material Ecology, which considers computation, fabrication, and the material itself essential to design. Her approach to design is biologically informed and digitally engineered by, with and for, Nature.[1]

Fig 25. Neri Oxman

1 “Neri Oxman | Neri Oxman.”

Monocoque 2, 2007

Monocoque, meaning a single shell, shows a construction technique that supports structural load using an object's external skin. The project demonstrates a structural skin using a Voronoi pattern. The density of this pattern varies according to multi-scalar loading conditions. Its innovative 3D printing technology makes it possible to print parts and assemblies made of multiple materials within a single build.[1]

Fig 26. Monocoque 2 (Credit: MIT, MoMA)

1 Oxman, "Monocoque 2 | by Neri Oxman."

The Silk Pavilion, 2013

This installation was woven by 6,500 free-ranging silkworms on a nylon-frame dome. The frame of a large polyhedral dome was loosely woven by a robotic arm, using thin nylon threads, and suspended in an open room. The dome was designed with open spots that would allow for warm sun rays to penetrate, creating a desirable environment for the organism. Silkworms were released onto the frame, to which they added layers of silk before being removed. The resulting installation art was hung so that people could stand inside it.[1]

Fig 27. The Silk Pavilion (Credit: Carole Wedge)

1 "Thousands of Silkworms and One Robot Made This Intricate Sculpture."

Eric Klarenbeek

Klarenbeek is a Dutch designer who works with biological organisms, such as algae and mycelium. His research includes developing new bio-based material and bio-fabrication techniques, such as 3D printing mycelium and algae.

Fig 28. Eric Klarenbeek and
(Credit: Dezeen)

The Mycelium Chair, 2013

He developed special bioprinters that combine organic matter with bioplastics to make a light and strong composite material that can be 3D-printed. The mycelium acts as a living glue for vegetable fibers. This makes it possible to fabricate living objects, using local raw materials. These objects are completely ecological and compostable. An example of this is the Mycelium Chair, that demonstrates how an object can be constructed directly from the unicellular organism. The chair's exterior is 3D-printed as well; however, it is made from a bioplastic that the mycelium root structure grows against. The fungus spreads throughout the 3D-printed structure, reinforcing it in the process. Klarenbeek believes that this technique could be used to create larger and more complex structures.[1]

Fig 29.3D printed Mycelium Chair (Credit: Dezeen)

1 Howarth, "Movie."

Algae Lab, 2017

In addition to 3D printed mycelium, Eric Klarenbeek along with Maartje Dros also developed a bioplastic made from algae. They cultivated the algae, then dried and processed it into a material that can be used to 3D print objects. The Alage laboratory displays the production chain, so the visitor can see and experience the entire process of production from the raw material to the final product.[1]

Fig 30. Maartje Dros, Algae Lab, 3D printed algae polymer (Credit: Dezeen)

1 “Dutch Designers Convert Algae into Bioplastic for 3D Printing.”

ideas

Informed by my primary and secondary research, and inspired by the biodesigned works of the artists and designers mentioned previously, I generated a list of ideas ranging from biodesigned spacewear, to a living 'green' spacecraft. I then narrowed down the ideas for my final thesis project to three possible outcomes:

1. An installation of a futuristic algae lab onboard the space station to depict how this microorganism can be grown and then harvested for food and bioplastic, then 3d printed into a collection of speculative objects.
2. Future space wear: A wearable bioreactor that creates a symbiotic relationship between humans and microalgae. Humans' body heat and movements provide a suitable environment for the microalgae to grow. Plus, they provide algae with carbon dioxide, necessary for its photosynthesis. The microalgae creates oxygen in return for the astronauts to breathe in.
3. Dinner on Mars: an immersive installation, imagining the future of food and dining in space exploration. This project aims to depict what a "farm to table" experience could look like in space.

I then presented these three concepts to a jury of mentors and peers before transitioning into the prototyping phase. Based on the feedback I received, I decided to focus my thesis project on creating an immersive experience, called 'Dinner on Mars' to imagine a biodesigned future of space food and habitat.

Fig 31. project output ideas

Concept I: Dinner on Mars Immersive Installation

Through this project, I aimed to generate curiosity and excitement around the various applications of biodesign, and its potential as a tool to create regenerative solutions to enhance life on Earth and beyond.

My research indicated that access to food and material is a challenge in long duration space travel; therefore, through this project, I would show how we can leverage biology, design and technology to grow multipurpose organisms that produce oxygen, food and bio-material to sustain life in space.

To depict this imagined future, I would create a multi-sensory immersive installation, consisting of the following elements:

- A midsize dome or room that can house the installation and four participants
- Projection mapping: visuals of space, projected on the walls or on the inside surface of the dome
- Sound: atmospheric soundscape of space or Mars
- Narrative: audio and text narrative to provide context and world building
- Center structure, grown with mycelium: a farm/incubator hybrid that grows fungi and microalgae. Yet, it is fashioned in a model that enables it to serve as a dinner table
- Dinnerware: speculative objects made with biomaterial, such as mycelium or algae biopolymer
- Dinner: made with transgenic organisms grown in the farm/incubator hybrid

I sketched how this installation could look like and be arranged. I also created a mood-board, inspired by Klarenbeek’s 3D-printed mycelium structures and algae bioplastic objects. I also drew inspiration from Maggie Coblentz’s creation, Algae Caviar, that could be made with ingredients grown in space, and prepared using molecular gastronomy spherification techniques.[1]

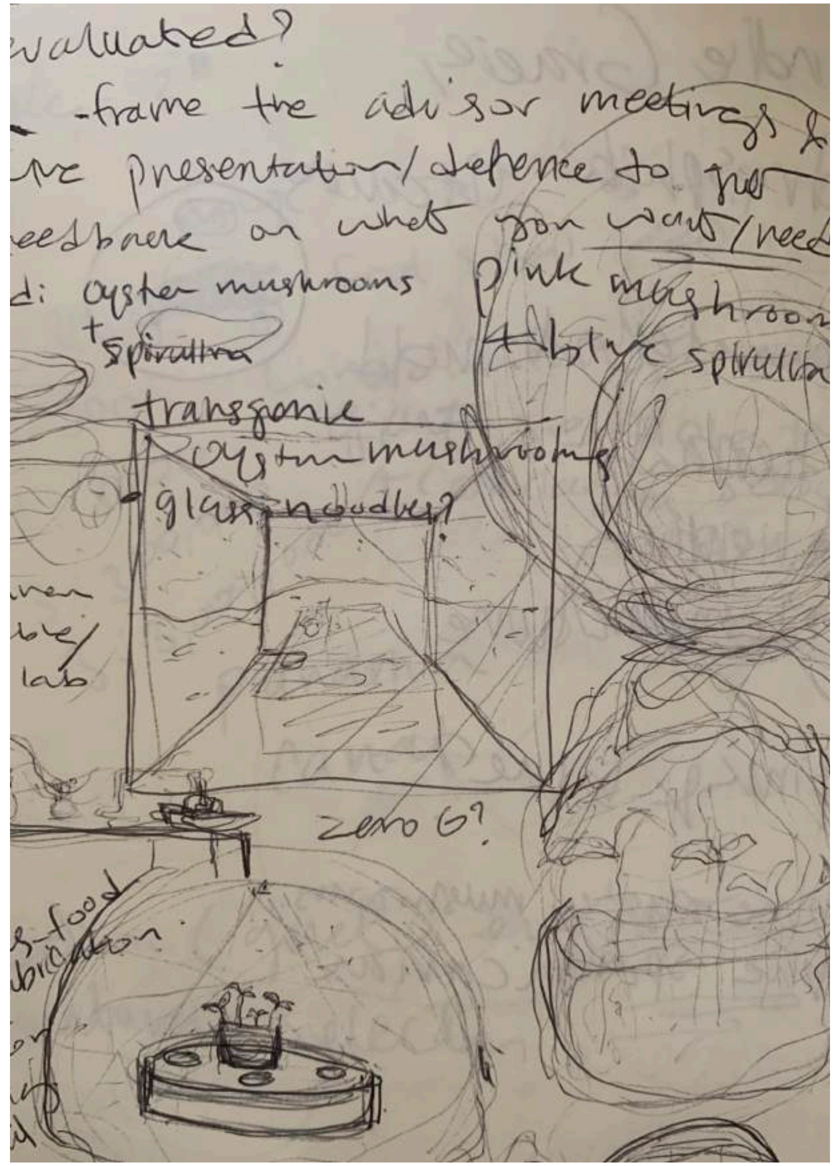


Fig 32. Dinner on Mars concept drawings

1 “Project Overview ‹ Tasting Menu in Zero G.”

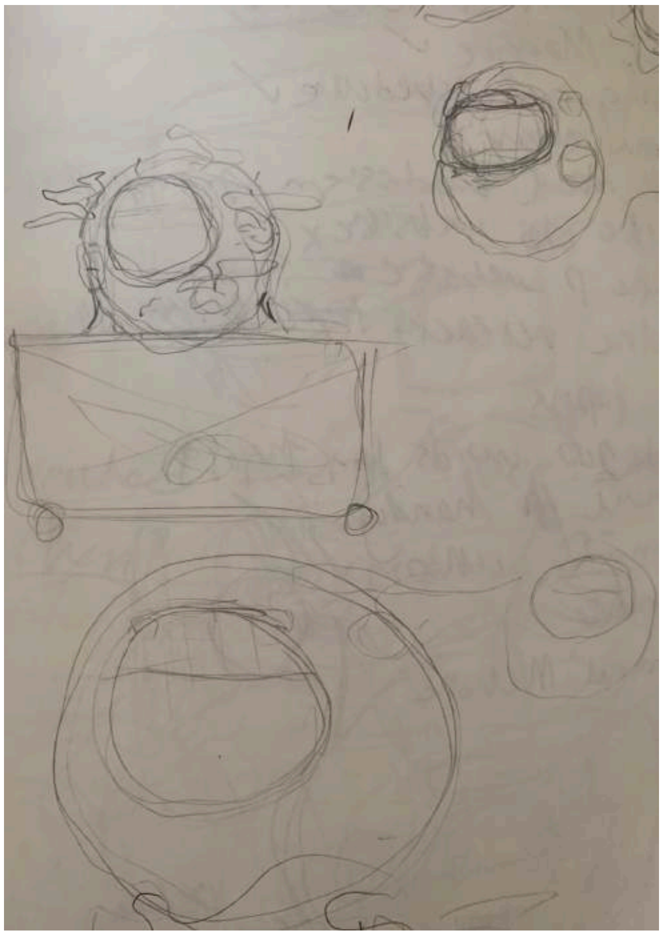
Critique round I

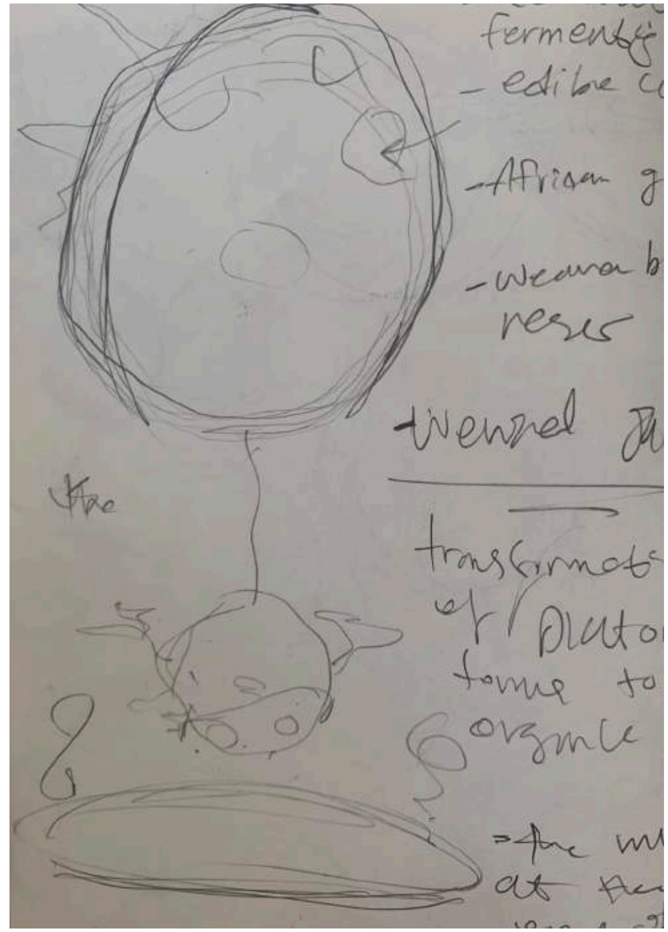
I presented my first concept sketches and moodboard to my thesis advisors, mentors and several peers for critique. I received positive feedback on the concept, especially the overall aesthetic and mood of the installation, as well as the notion of designing with biological organisms. I also realized that perhaps the most exciting aspect of the project is, in fact, food. The concept proposed that the participants would be served novel food, made with organisms that are grown as a part of the installation. People found anticipation of this novel experience imaginative and exciting.

However, after consulting with my external advisor, Chester Dols, who is an expert in installation design and fabrication, I realized that the scope of my concept was too big to execute, and creating a fully immersive installation within the time frame would not be feasible. Therefore, I brainstormed alternative designs for a more focused version of the concept that would still allow me to create a novel experience; and accomplish my previously stated goal of depicting an imagined future, in which humans, algae and fungi live symbiotically in space.

Alternative Designs

The Space Foodcart: a playful and small scale dining experience, while maintaining the interactive essence of the installation





The Hanging Farm: participants can interact with the mycelium farm and pick fruiting bodies(mushrooms).

prototyping

the symbiotic farm

After finalizing the ideation process, I started to prototype the Hanging Farm. Since one of my goals was to create a 'living' symbiotic farm with biological organisms, it was critical that I first learn more about each organism's wants and needs. The objective was to design a structure that would facilitate symbiotic relationships among three organisms: algae, fungi and humans.
My process in this step of design was inspired by works of Neri Oxman and Anicka Yi, and informed by theories of Multispecies Entanglement as well as nature itself.

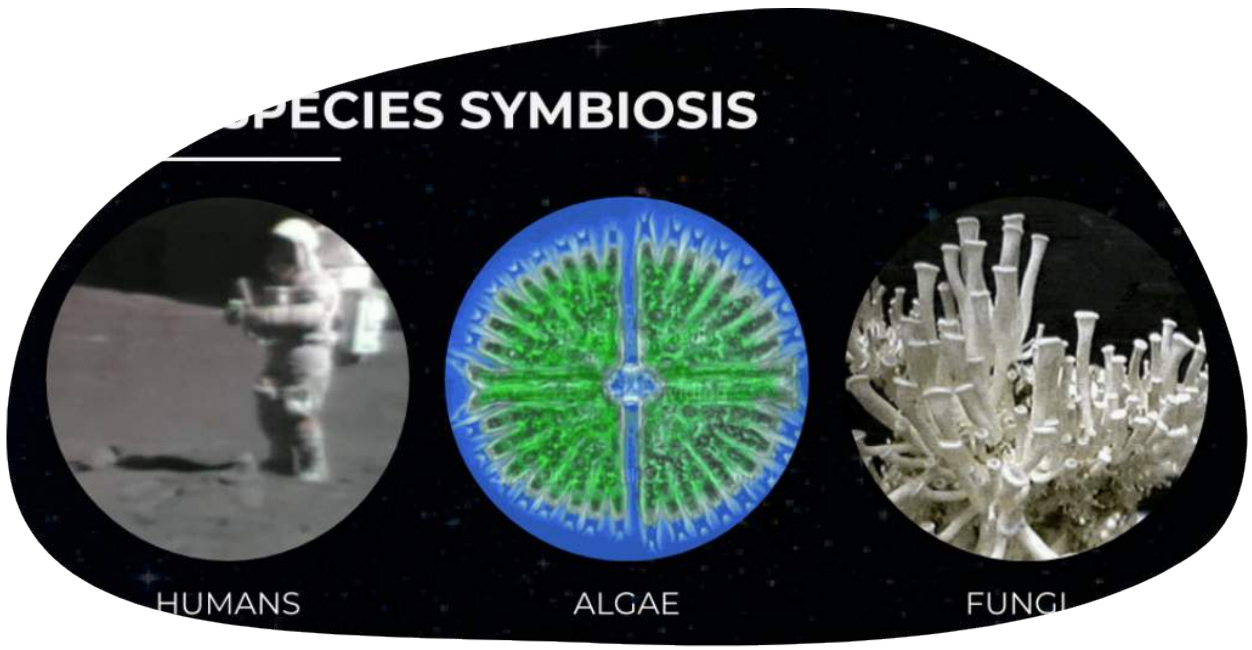


Fig 33. three species included in the Symbiotic Farm: algae, fungi and humans

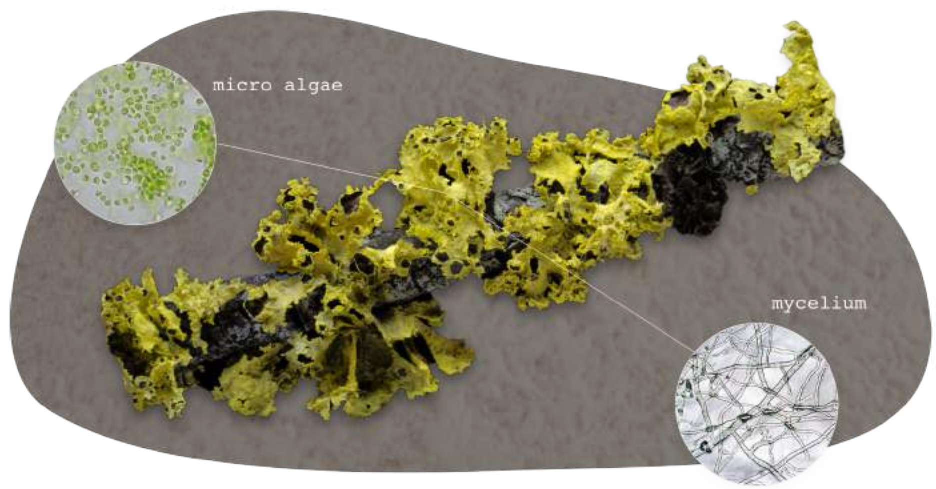
Current life support system designs do not extend beyond anthropocentrism. Designing bioregenerative systems by considering other-than-human viewpoints could introduce alternative scenarios compared to those envisioned through technocentric and humancentric means. Building on posthumanism theories and Guattari's concept of "ecosophy" -a philosophy of ecological harmony or equilibrium-[1] this installation entails that a symbiotic space habitat, or ecosystem, for humans and other species should be seen not just as the outcome of necessity, but also as a behavioral attitude, and the habitat design as an implementation of that attitude. "It is argued that following other-than-humans can teach designers to think sustainably by cultivating relations of reciprocity that help to shed light on the multispecies landscapes of the Anthropocene."[2]

> "Without modifications to the social and material environment, there can be no change in mentalities. Here, we are in the presence of a circle that leads me to postulate the necessity of founding an "ecosophy" that would link environmental ecology to social ecology and to mental ecology."
>
> —Fèlix Guattari 1992

1 Guattari, The Three Ecologies.
2 Gatto and McCardle, "Multispecies Design

Unlike mushrooms, the more widely known and accepted type of fungi, which humans cultivate and consume, algae is currently associated mostly with algal blooms. People view algae as a harmful invading organism that is taking over the open waters and killing marine life. However, only one percent of algal blooms are harmful to humans and marine life.[1] This installation shows algae under a favorable light, featuring it not as an invader species, but as an organism to cultivate, cohabitate with and even care for.

A symbiotic relationship between fungi and algae already exists in nature. Lichen, or lichenized fungus, is two organisms functioning as a single, stable unit. Lichens comprise a fungus living in a mutualistic relationship with an alga or cyanobacterium.[2] In this mutualistic relationship, mycelium provides a safe environment for micro-algae and in return algae supplies fungi with nutrients.The Hanging Farm is inspired by this natural relationship, yet it proposes humans as an additional organism living in symbiosis with the other two. This project proposes a bioregenerative life support system, in which the humans do not simply use and consume the other species, but act as their stewards.



1 US Department of Commerce, “Are All Algal Blooms Harmful?”
2 June 08 and 2016, “What Are Lichens?”

To create an object that would promote such relationships among the three organisms, I explored several designs. This explorative exercise was informed by the specific growth requirements and waste products of each organism, as well as the relationships among the three.

The relationships in this minimal ecosystem are as follows:

- Algae produces oxygen and carbohydrates via photosynthesis. It offers these byproducts as food for fungi and humans. In return, humans and fungi produce carbon dioxide for the algae to grow.
- Fungi also produce fruiting bodies, mushrooms, that humans can consume as a rich source of nourishment.
- In addition, humans can utilize biopolymer form algae and mycelium from fungi to fabricate different objects.

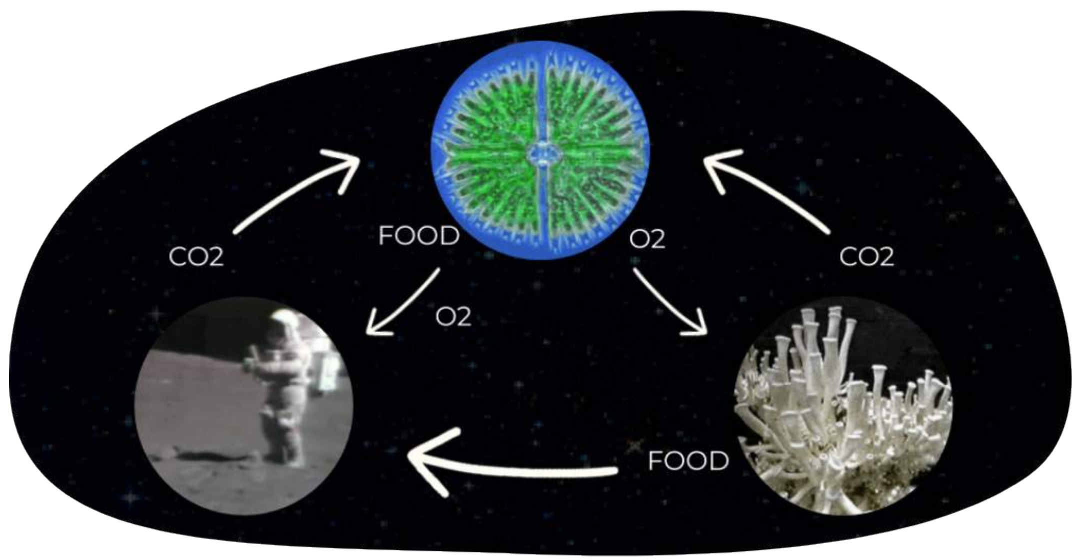


Fig 34. symbiotic exchanges among algae, fungi and humans

Concept designs

I explored possible forms for a living object that could facilitate symbiosis among fungi, algae and humans.

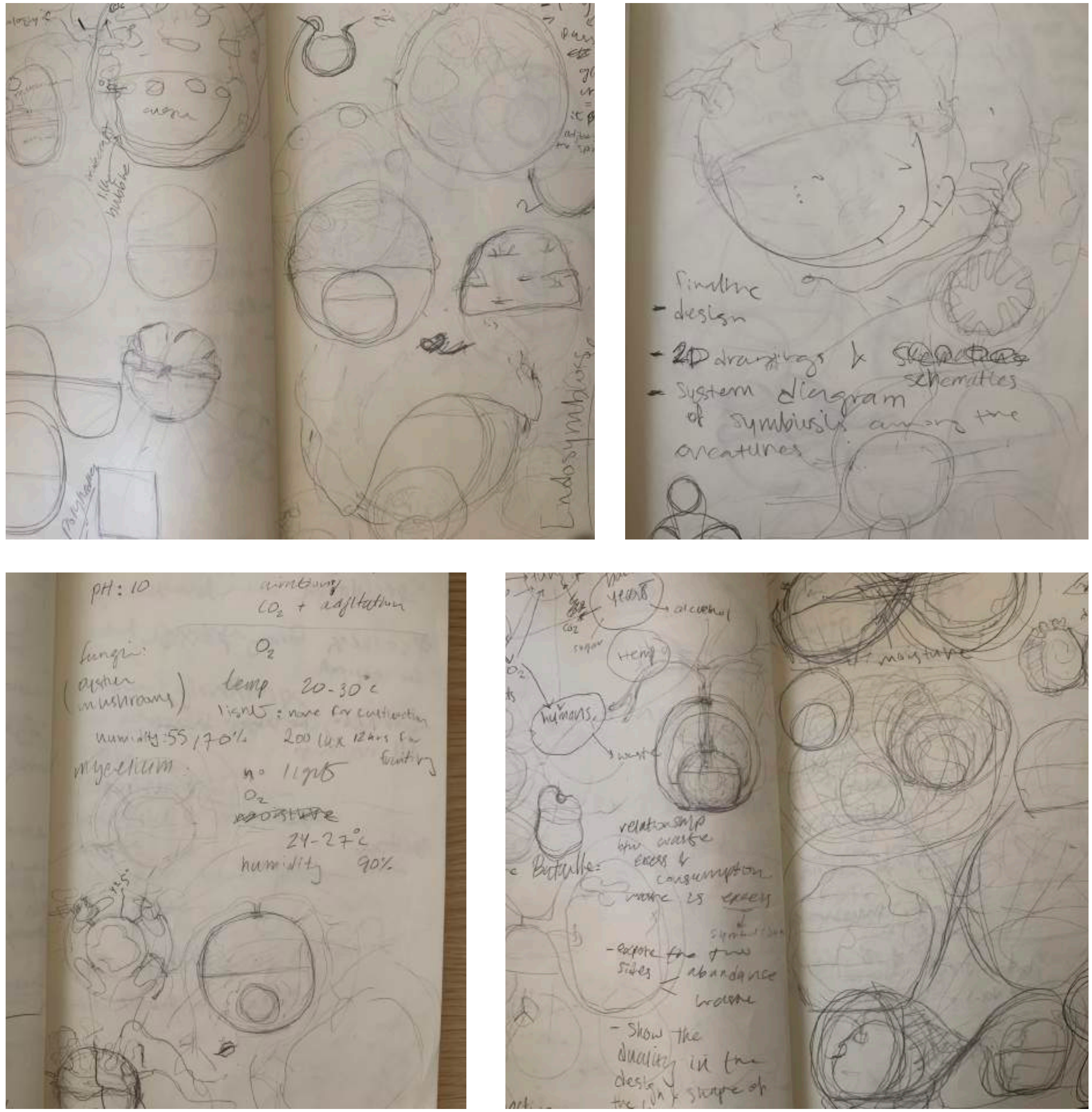


Fig 35. Symbiotic Farm concept drawings

Design inspired by nature

In addition to lichen, I also researched other symbiotic relationships that exist between algae and other organisms, including Radioloria and Elysia chlorotica.

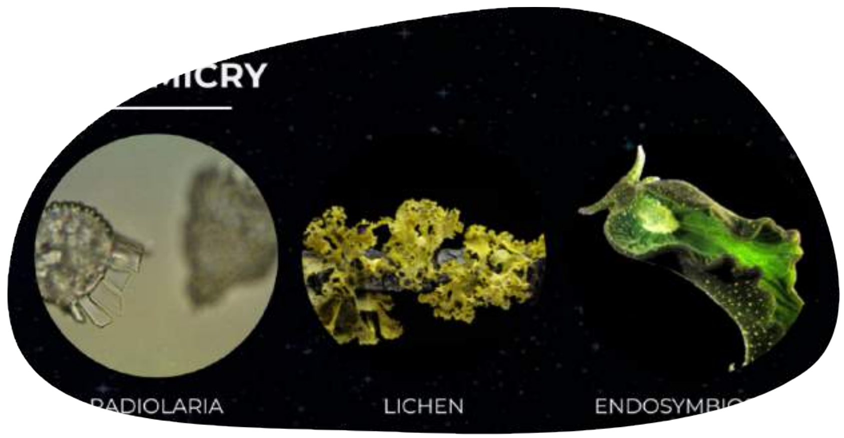


Fig 36. algae-other symbiotic relationships in nature

1. Lichen: a naturally occuring symbiome form, made of fungi and algae.
2. Elysia chlorotica: is an aquatic creature that feeds on algae but instead of digesting the entire cell contents, it retains the algal chloroplasts.[1]
3. Radiolaria: also known as Radiozoa, are protozoa that produce intricate mineral skeletons, typically with a central capsule dividing the cell into the inner and outer portions of endoplasm and ectoplasm. The elaborate mineral skeleton is usually made of silica.[2]

1 "Solar-Powered Sea Slugs Becoming Too Rare to Study."
2 "Radiolarian - an Overview | ScienceDirect Topics."

I was especially intrigued by the complex and intricate Radiolarian forms, which heavily influenced the design I envisioned for the object. So, I created a collection of 2D renderings of what the symbiotic farm could look like, using Adobe Photoshop.

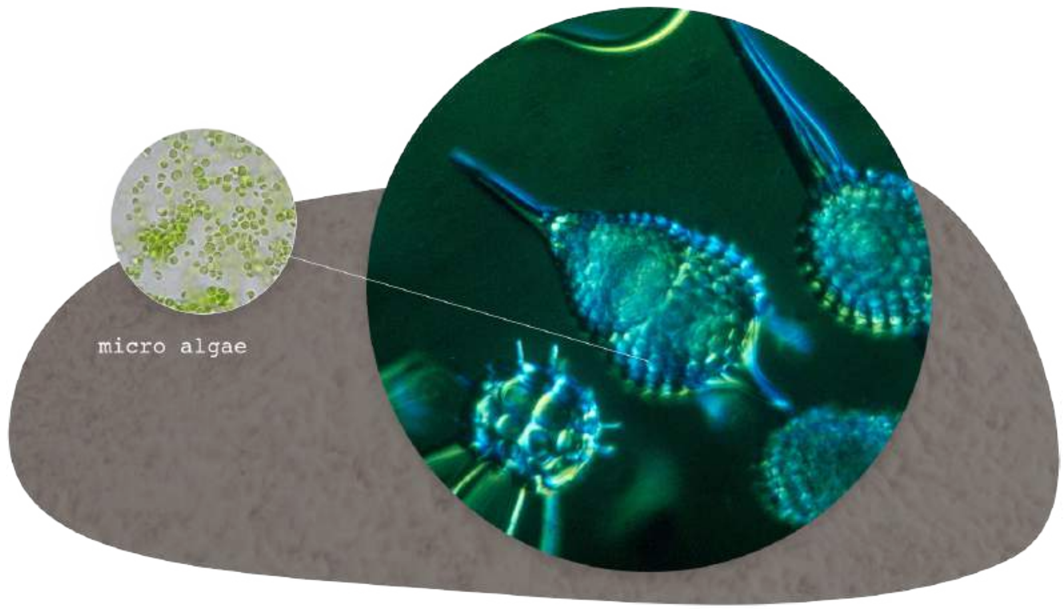


Fig 37. algae-Radiolaria symbiotic relationships

prototype I: The Symbiotic farm

Concept renderings

To create these renderings I used found assets, including photographs of different Radiolaria and fungi. I collaged the assets into these organic and alien-like forms in Adobe Photoshop.
I designed a collection of floating symbiotic space farms, then chose one to explore further.

Fig 38. renderings of the Symbiotic Farm

In order to show the main elements assembling the object, I created a diagram identifying the components and their approximate dimensions.

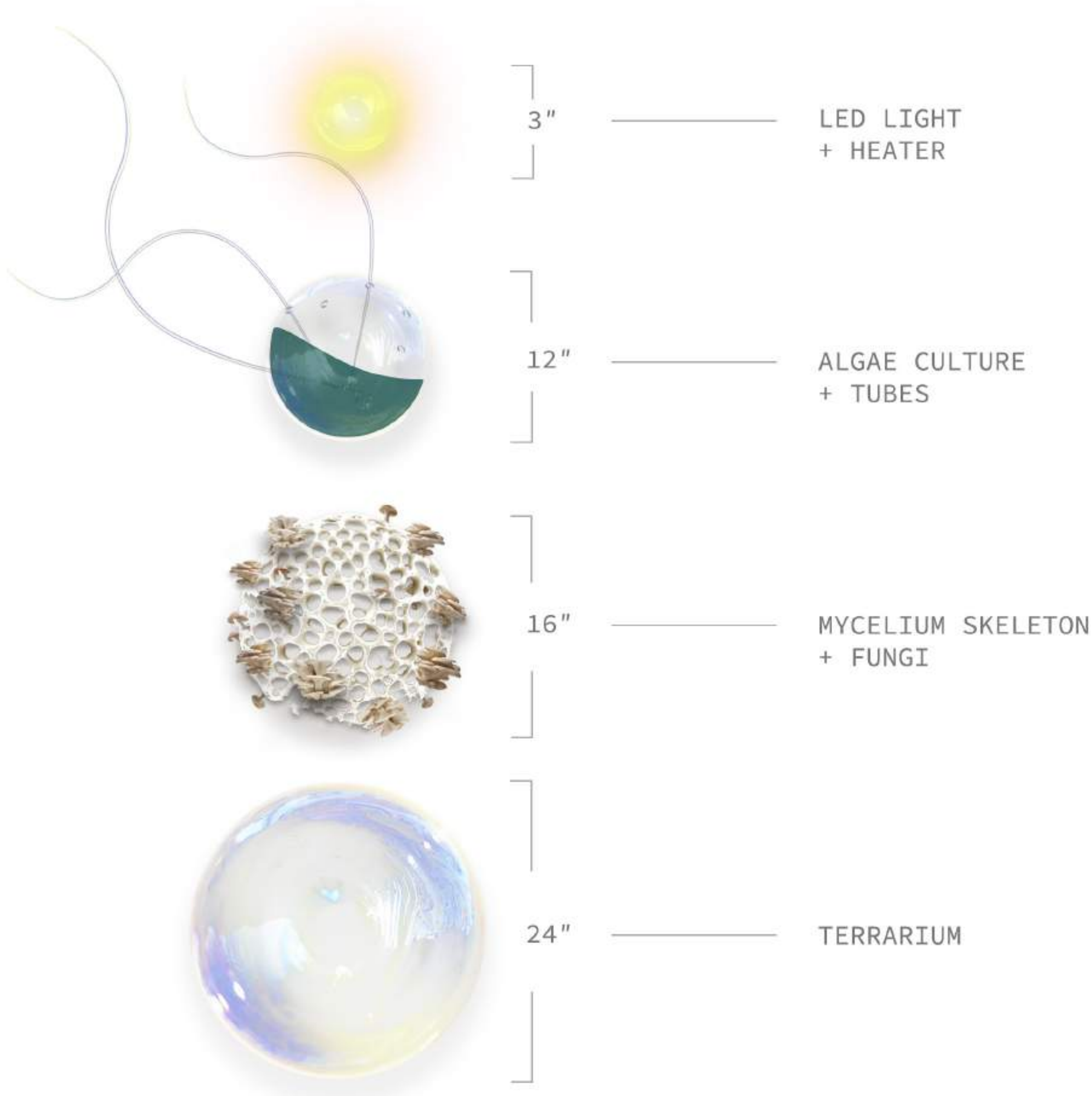


Fig 39. Symbiotic Farm schematics

Due to the strange and novel nature of this concept and its form, it was necessary to visualize the object within different contexts. Doing so would enable others to understand the concept, and imagine what the end installation could look like.

The following images show the object in two distinct settings: in outer space and in a gallery. The former is a depiction of this object in a fictional setting, created to spark the audience's imagination. The latter shows the object in the realistic and familiar environment of an art gallery. This version is meant to communicate how this object fits with other works of art in an exhibition.

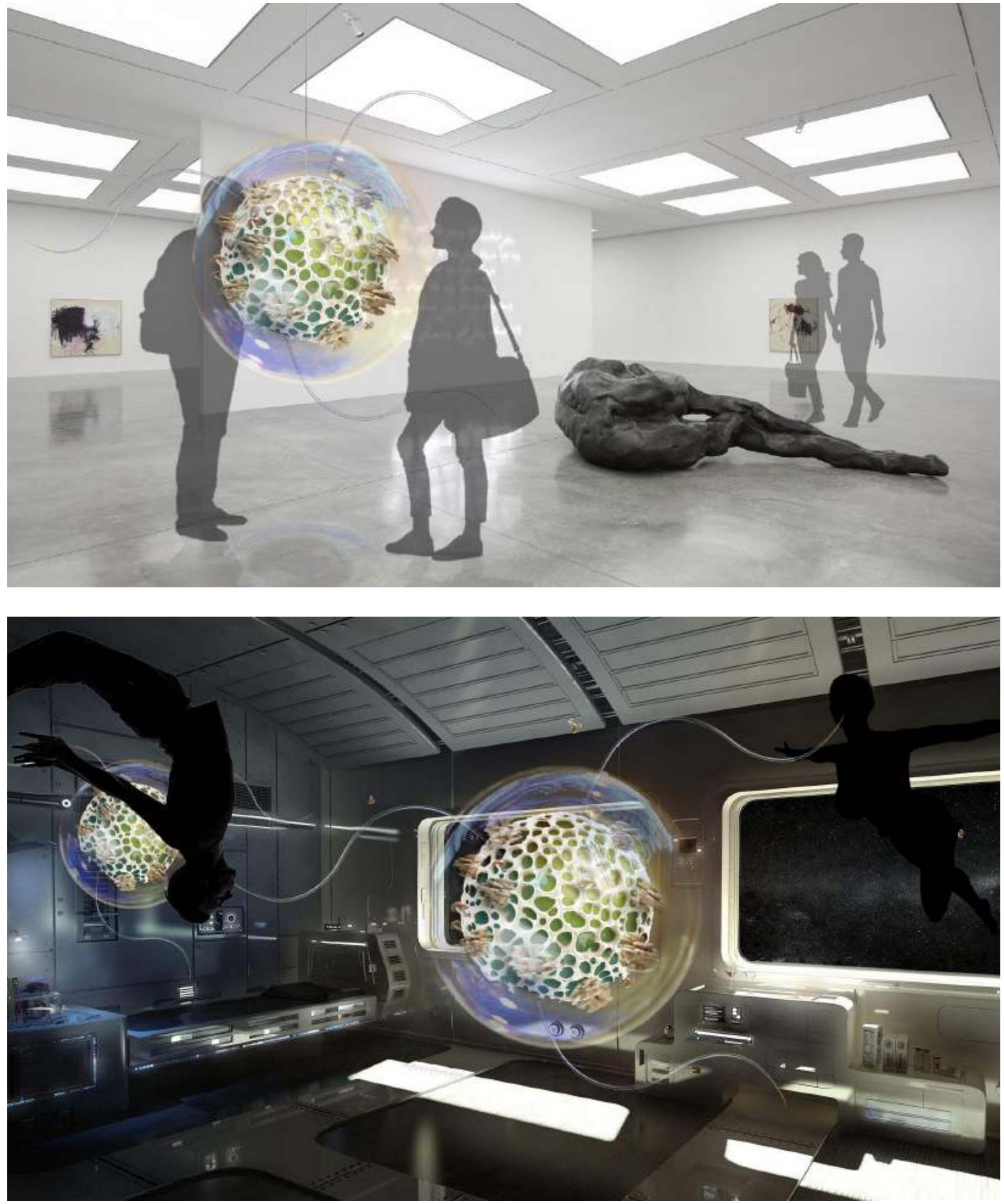


Fig 40. rendering of the Symbiotic Farm in different contexts

Bio-prototyping

A significant portion of my prototyping process consisted of working with the organisms I was designing with and for. It was crucial that I develop a tested process to create this living farm. My previous experience with cultivating spirulina microalgae provided me with the knowhow as well as the device necessary to grow microalgae. However, I did not have previous experience in growing fungi and making mycelium-based material.

Fungi

I researched multiple sources for fungi and mycelium, and opted for a GIY (grow it yourself) kit sold by Ecovative Design.[1]

I then followed the specific instructions provided by the company to create a sample mycelium block. I tested the sample for materiality, including texture, color, scent, strength and other properties in order to design and fabricate a mycelium skeleton for the symbiotic farm.

Fig 41. Mycelium grow kit

1 "Grow-It-Yourself Material."

Mycelium Block

I reactivated the dry material on February 20, 2020 and allowed the mycelium to grow for a week. On February 28th, I transferred half of the material into a bowl and broke up the material. I then added flour and water as instructed, and packed the material in a disk-shaped container. I covered the container with plastic wrap and created a few holes, so the mycelium could breathe. I then put the container in a cardboard box, covered it with bags of steel wool and put it in a dark space. By March 5th, the mycelium had grown and completely covered the hemp substrate. On March 11th, I removed the mycelium block from the growing container and baked it in a toaster oven for an hour in order to stop it from growing fruiting bodies.

Fig 42. Mycelium block growth progress

Mushrooms

In addition to growing a mycelium block, I sourced a few bags containing different types of fruiting fungi, including Grey Oyster, Pink Oyster and King Oyster mushrooms. My goal was to test how different types of fungi would interact and coexist with each other as well as with spirulina microalgae.

Fig 43. fungi growth progress

Algae

I acquired a one gallon culture of Spirulina microalgae from a trusted source, Algae Research Supply.[1]

On February 24, 2020 I started growing the algae culture inside the algae bioreactor prototype I had developed previously. The culture density doubled each week, and I kept adding growth media to provide the organism with nutrients and keep the pH balance highly alkaline. By March 5th, the culture had reached the density level required for harvestation.

Fig 44. Spirulina microalgae growth progress

1 Supply, "Algae Research Supply."

Algal biopolymer made with cyanobacteria and agar

Once the culture density reached a certain level, I harvested some for experimentation. My goal was to create an edible photosynthetic bioplastic with cyanobacteria and Agar powder. I created several samples of edible algae bioplastic to test material properties, including texture, color, transparency, plasticity and rigidity

Fig 45. algae bioplastic made with Agar and Spirulina

Critique- round II

I demonstrated my prototyping process, visual renderings and the biomaterial samples I had grown to my advisors, mentors and a group of peers to receive feedback, and improve the design before growing a life size model. Based on the critique I received, the intriguing dimensions of my installation concept were its multi-sensory properties, and interactivity between the living farm and the audience. The initial sketches showed a revealed version of the object, which would allow the audience not just to see the organisms, but to touch, smell and taste them. The renderings, in contrast, showed the living farm inside an enclosed bubble that would prevent rich interspecies interactions to take place.

Complications and project pivot

Unfortunately, shortly after the second critique session, New York University had to shut down, in order to comply with state safety measurements to contain the COVID-19 pandemic. My project involved creating a physical installation; and, therefore, my process heavily relied on using the university's labs and equipment to grow, test and fabricate material for my project and assemble a life size structure. However, due to these unforeseeable complications, I needed to find an alternative route to complete my thesis project. An alternative approach that would not need physical fabrication.

Ideation part II

I started the ideation process again and brainstormed other possible outcomes:

Virtual exhibition

I explored possible ways to create a digital version of my installation. I considered different technologies, including virtual reality, augmented reality and web-based VR.

Creating a virtual installation in VR would be the most unfeasible, given that I would need access to special equipment. Moreover, I would be limited in user-testing the experience, since only a few people have access to VR gear at home. AR provided more flexibility both in terms of development and testing, but the experience would not be as meaningful and immersive as in VR. Web-based virtual spaces, however, offered the most affordance and ease in production, distribution and testing.

Fictional futures website

The second possible route for this project would be to design a stylized narrative website with interactive elements. This website would depict an imagined far future of space exploration habitats, designed and created with synthetic biology.

This website would show a bio-designed future, in which advanced humans live symbiotically with other organisms, natural and synthetic. On SPIRIUM, the audience would be taken on a visual journey into this speculative future, where space explorers design and program everything, including food, textile and even grow their living habitats.

This narrative website would be built on Webflow, and consist of two and three dimensional visual assets, atmospheric sound and text to create the experience.[1]

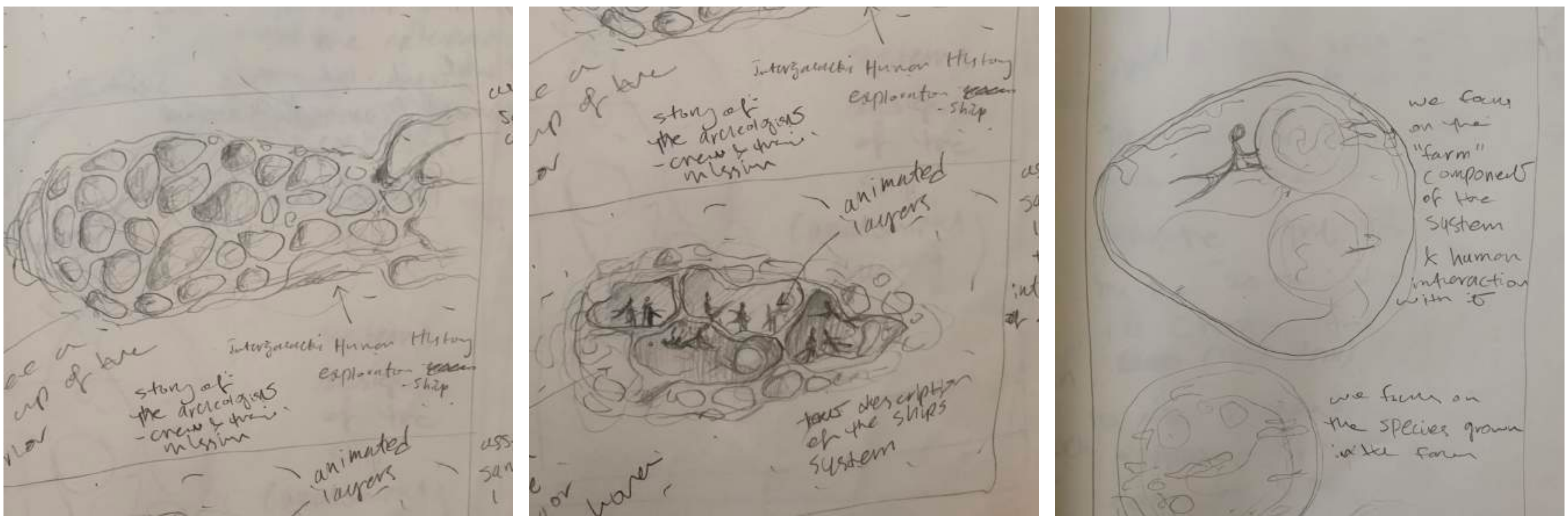


Fig 46. Fictional futures drawings

1 World building portion for the website is attached as appendix A

Exhibition design proposal

The third possible outcome for the project, as suggested by my mentors, would be to continue designing for the physical installation that I had initially planned. However, instead of fabricating a physical prototype of the installation itself, I would create a more comprehensive plan for the installation and the audience experience. I would then present this design proposal on a website.
In contrast to the other two alternatives, my audience here would include other artists, designers as well as art and science museums.

Critique- round III

I presented these ideas to my advisors, mentors and selected peers. Based on the feedback, the first two alternatives, while providing a visualized experience of a speculative biodesigned future, would fail to communicate the rich nonvisual properties of biomaterial and organisms that make up this living object. The third option however, would enable me to develop my idea further, and create a richer experience beyond just the object itself. Therefore, I decided to pursue the latter: A web-based exhibition design concept and proposal.

prototype II: installation design concept

The alternative prototype that I chose to design is a website, containing a proposal plan for a speculative multi-sensory physical installation that depicts a symbiotic future habitat in space.

- The website features the following:
- The concept and background research
- Master Plan
- Visual renderings of the installation
- Descriptions of various compartments, making up the installation
- Audience experience and interaction

The website is designed with three main stakeholders in mind: artists and bio designers, scientists and technologists, and lastly, art and science museums.

This website aims to serve as an accessible medium to communicate the concept to stakeholders. First, for feedback and improvements. Second, to generate possible collaboration opportunities with other artists, designers and technologists interested in the field of space exploration and biodesign. And third, to serve as an easily distributed and accessible proposal to submit to museums and other potential stakeholders.

Concept sketches

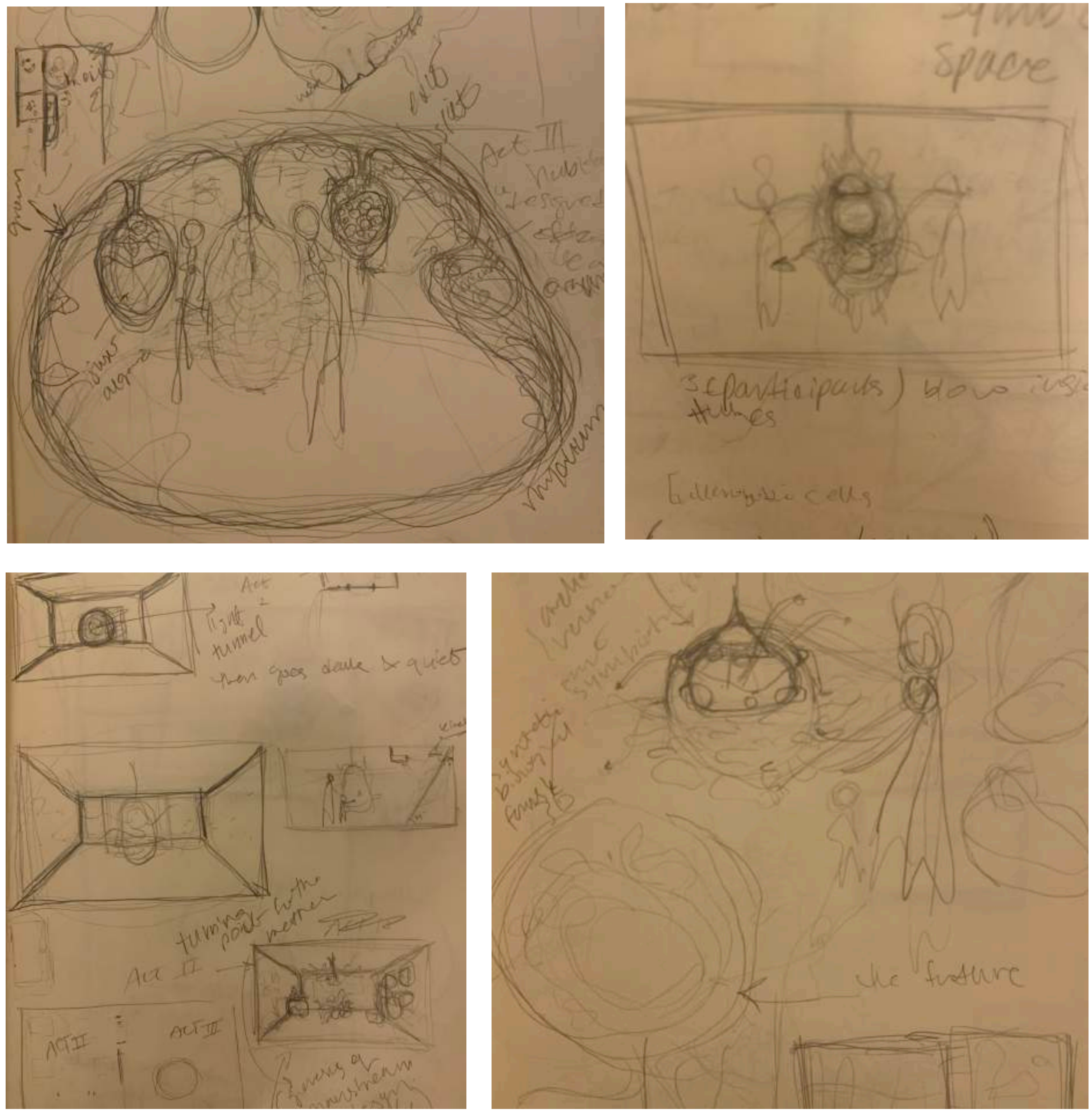


Fig 47. installation concept drawings

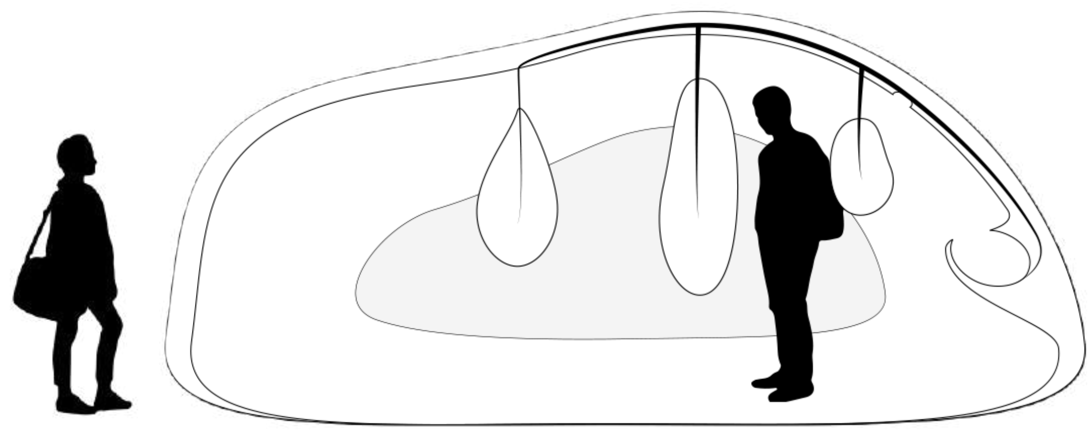


Fig 48. Section view of the installation

Visual assets

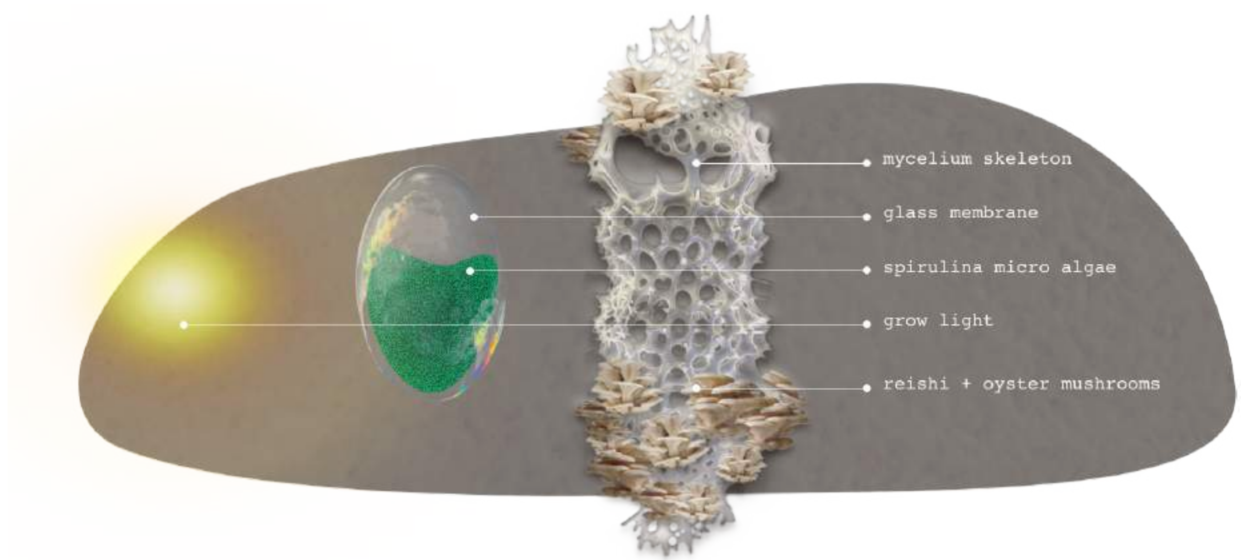


Fig 49. The Symbiotic Farm Schematics

I n t e r a c t i v e s c h e m a t i c s

I created an interactive schematic in Adobe XD and used the embed code on the main website.

This interactive schematic allows the user to click on different elements in the installation to learn more about each part of the system and the relationships among them.

Fig 50. Interactive schematics screens

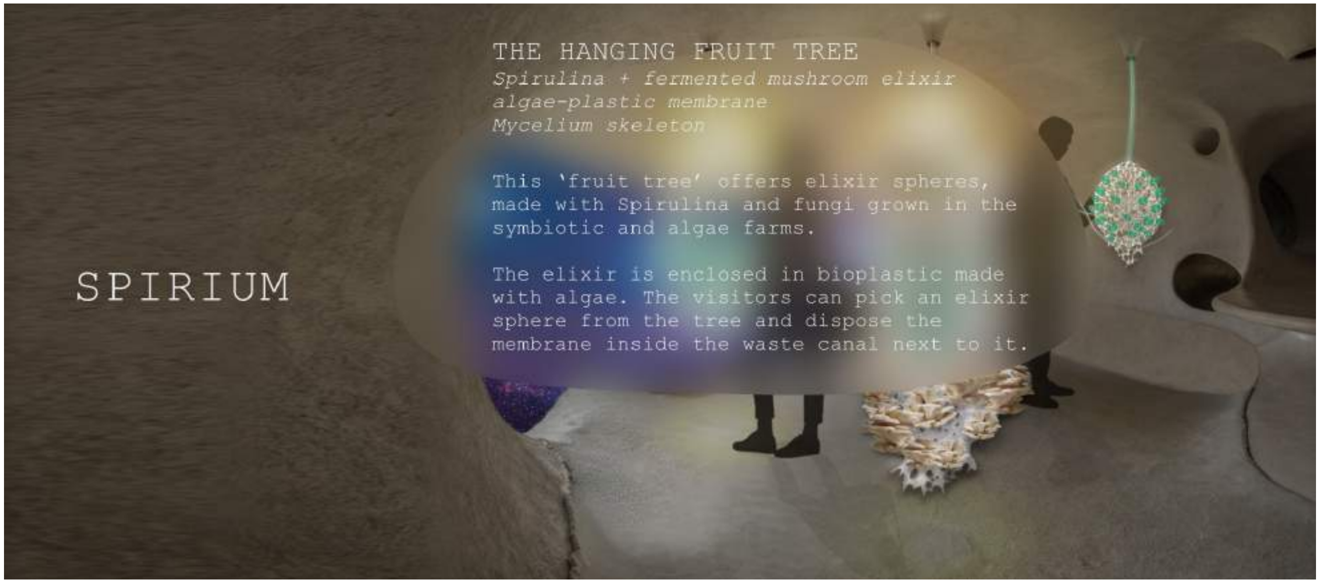


Fig 51. Interactive schematics screens

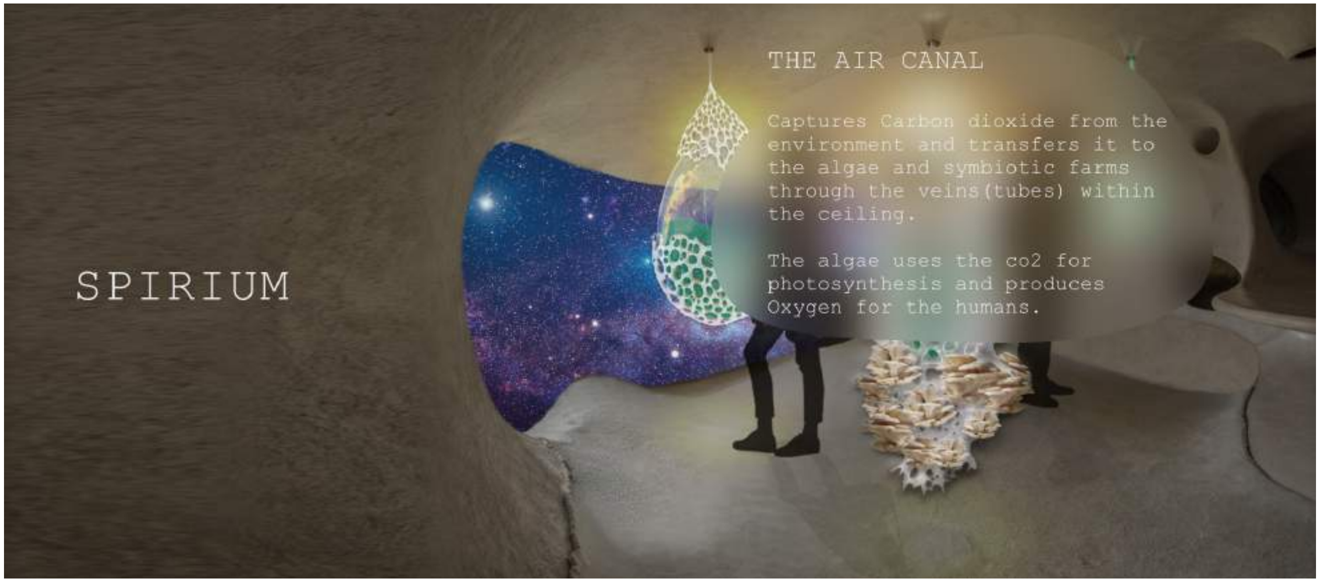


Fig 52. Interactive schematics screens

website: spiriumexhibition.com

SPIRIUM HOME MASTER PLAN CONTACT

abstract

This installation is inspired by sustainability, biology and space exploration. Biodesign has a unique potential to help us design closed loop regenerative systems in different industries here on Earth; yet, it is still considered a fringe alternative to conventional technologies. Space exploration, however, introduces unprecedented challenges that require radical design and technological solutions. Nature driven design could be integral in developing such solutions.

This speculative multi-sensory installation aims to show the audience a living life support system, inspired by nature and created with biology. This symbiome is designed to create a closed loop bioregenerative system that promotes harmonious co-habitation among humans, fungi and microorganism.

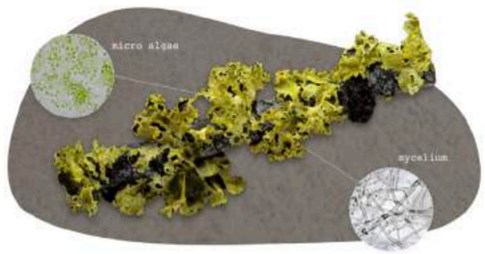
In this habitat, humans provide stewardship for the other organisms, assuring a thriving environment for these non-human lifeforms. The fungi and microorganisms, too, play a part in creating a habitat that supports life, while also providing humans with essential resources, such as oxygen, food and biomaterial.

LEARN MORE

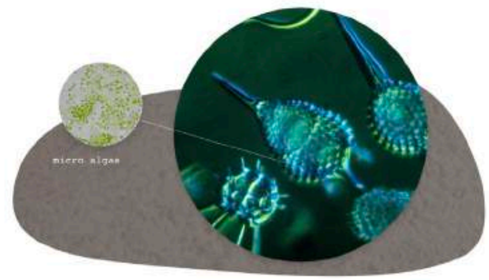
Fig 53. Website,home page

inspiration

inspired by symbiosis in nature



Lichen



Radiolaria

concept

This living farm is a bioregenerative system, inspired by symbiotic forms and function in nature. It consists of a mycelium skeleton, modeled based on the Radiolarian mineral skeleton. The mycelium produces fruiting bodies(mushroom), while serving as the structure holding the algae capsule. The inner portion of the system contains a glass membrane that grows micro-algae. The algae photosynthesizes, using light(grow light), co2 produced by the fungi and nutrients provided by bacteria recycling organic food waste.

Fig 54. Website,home, concept

interactive schematics

click on an object to learn more about it…

audience experience

This installation immerses the audience in a surreal, intimate and multi-sensory environment where they experience what a symbiotic habitat could be like in the future of space exploration. It engages the audience's five senses, including tactile and olfactory. The audience can touch the living structures and feel what mycelium material feels like.They also smell the scents produced by the fungi.In addition, the audience actively participates as an integral element of this closed loop system by breathing, consuming the bio-designed 'fruits' and disposing of their food waste.

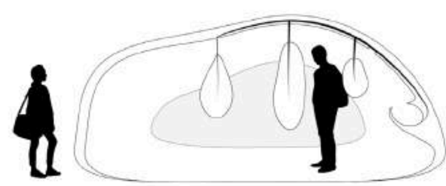


Fig 55. Website,home,interactive schematics and audience experience

conclusion

key takeaways

This project was inspired by my passion for sustainability, biology and space exploration. My goal was to create a multi-sensory installation that would bring humble biological organisms like fungi and algae and show their beautifully symbiotic relationship with each other; and, to create an opportunity for people to interact with these organisms in a new way: to touch, smell and taste them, and also to actively fall in symbiosis with them.

The unforeseen circumstances following the COVID-19 pandemic forced me to change course. Unfortunately, growing a living installation and sharing it with others was no longer a viable option. The very essence of this installation, however, demands to be experienced by all senses. A virtual version simply will not accomplish the impact I aimed to create with this project. Therefore, I decided to maintain the ultimate vision for a physical installation, yet adapt the output of my project to a concept proposal instead. My rationale for choosing this project output was to create a multi-purpose document that I could use in the future, in order to create a physical multisensory installation.

The multisensory installation aims to show the audience an organic life support system, inspired by nature and created with biology. This symbiome is designed to create a closed loop bioregenerative system that promotes harmonious cohabitation among humans, fungi and microorganism. In this habitat, humans provide stewardship for the other organisms, assuring a thriving environment for these non-human lifeforms. The fungi and microorganisms, too, play a part in creating a habitat that supports life, while providing humans with essential resources, such as oxygen, food and biomaterial.

This installation shows the audience the potential of designing and fabricating with biology. Biodesign has a unique potential to help us design closed loop regenerative systems in different industries here on Earth; yet, it is still considered a fringe alternative to conventional technologies.

The website aims to serve as an accessible medium to communicate the concept to the stakeholders. First, for feedback and improvement. Second, to generate possible collaboration opportunities with other artists, designers and technologists interested in the field of space exploration and biodesign. And third, to serve as an easily distributed and accessible proposal to submit to museums and other potential stakeholders.

Next Steps and future considerations

My goal is to continue developing this project further. I plan to do so by following a three-step plan.

Step One: I plan to test the concept further by sharing the website with various mentors, artists and designers, as well as those specifically specialized in the area of biodesign and space exploration.

Step Two: After testing the concept with a wider audience, I will create a virtual version of the installation. I'll do so by creating 3D assets in Maya. I will then create a virtual gallery space using Artsteps, which is a web-based platform to create and publish virtual galleries. This virtual gallery could easily be embedded within any website and shared with stakeholders. I will repeat step one, upon developing the virtual installation, in order to reach potential collaborators.

Step Three: Based on a short survey that I conducted to gauge public awareness and interest in the topic of biodesign and biofabrication, 59 percent of the participants were not familiar with the subject. Yet, 95 percent of all participants expressed interest in learning more about the topic and seeing examples and different applications of biodesign. Therefore, I envision this installation as a part of a more comprehensive exhibition centered around current and future applications of biodesign. This immersive exhibition consists of three distinct acts that aim to contextualize the present and potential applications of biodesign and biofabrication. This exhibition creates an opportunity for artists and designers with various expertise to collaborate. It also provides a unique platform to feature artists and designers with existing works, biodesigned specifically with algae and fungi.

Appendix A: World Building

Dr.X, a galactic archeologist, specialized in Earthian artifacts and head of research visits Etahr, previously known as Proxima Centauri B, the almost earth like, but barely habitable planet orbiting one of three stars that make up the greater Alpha Centauri System, the closest solar system to earth.[1] Etahr remains a galactic landmark, where the Earthians concluded their first successful interstellar journey in 2500. They took refuge on the dark side of Etahr, then built underground cities on the side that always faces the sun. For the next 500 years they built a posthuman civilization, engineering themselves to be more adept for interstellar travel, before venturing out into the galaxy again, on a quest to find another Earth. That event marked a new era for the human species, now a type III civilization, expanding over 1000 solar systems in the Milky Way Galaxy.

The year is 2020 AE (After Etahr), X and her research team are digging the site, where the first spaceship from earth was reported to have landed. They are looking for archeological remains, when they find what appears to be remains of strange organic artifacts preserved deep in the icy zone of Ethar. While sequencing the DNA, they make a shocking discovery: a hidden message stored in the DNA of an ancient Earthian microorganism. The message contains the complete record of Earth's information and Internet history before Etahr. A record that revealed a different narrative than what X and the rest of the posthuman civilization had been led to believe.

1 Meadows et al., "The Habitability of Proxima Centauri b."

The message revealed the following:

- The first “long-duration” spaceflight was in 2033, when a small crew of astronauts ventured on an explorative mission to Mars
- A small minority of pioneers left Earth and built a base on Mars in 2050
- Despite some efforts to mitigate climate change, humans made earth nearly uninhabitable by 2100. (This is the opposite of what posthumans were taught about their Earthians origins as a superior and intelligent civilization that was nearly wiped out when the earth was destroyed by an asteroid)
- By 2120, the base on Mars had developed into a self-sustaining civilization of a million people, consisting exclusively of the most educated, wealthy and powerful and a minority of the general public who won the lottery to move to Mars
- Dr.X finds a possible match for the organic remains in the Earthian records: A Thesis book from 2020 proposing speculative designs for a regenerative system to grow organisms symbiotically for the future of space exploration
- She attempts to recreate the farm, by following the book, recording in her journal as she studies the process.

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