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Growth as an Alternative Approach to the Construction of Extra-Terrestrial Habitats

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Abstract

A critical component of human space exploration and eventual settlement is the ability to construct habitats while minimizing payload mass launched from Earth. To respond to this challenge, we have proposed the use of fungal bio-composites for 'growing' extra-terrestrial structures, directly at the destination, significantly lowering the mass of structural materials transported from Earth and minimizing the need for high mass robotic operations and infrastructure preparations. Throughout human history, the construction of habits has used biologically produced materials, from bone and skins to wood and limestone. Traditionally, the materials are used only after they die. Currently, the idea of working with living biological organisms, and the phenomenon of growth itself, is of increasing interest in architecture and space applications. Here, we describe the use of mycelium-based composites as an alternative, biological approach for constructing regenerative and adaptive extraterrestrial habitats, a continuation of our research program initiated under the auspices of the 'Myco-architecture Off Planet' NASA NIAC Team. These composites, which are fire-resistant, insulating, do not consist of volatile organic compounds from petrochemical products and can be used independently or in conjunction with regolith, could employ the living biological growth in a controlled environment, for the process of material fabrication, assembly, maintenance, and repair, providing structures resilient to extra-terrestrial hazards. The paper will outline the potential and challenges of using bio-composites for space applications and will present how these might be addressed, in order to make this biological approach feasible, providing new, growing materials for design habitats on long-duration missions.

Keywords: mycelium biocomposite, ISRU, space architecture, biotechnology, engineered living materials

1. Key to Space Exploration

A key to human space exploration is the ability to construct habitats with minimal payloads being launched from Earth and with construction methods that will work in extreme environments and provide, not only shelter but places that support human comfort and wellbeing.

There are energy-use, mass, and volume trade-offs associated with transporting materials from Earth for space exploration. The alternative is to use *in situ* resources. For habitats, large-scale robotic operations using ice, regolith or other available or transported materials have been proposed in response to NASA's recently concluded 3D-printed habitat challenge [1].

This paper synthesizes an alternative architectural approach for growing habitats, as part of our ongoing 'Myco-architecture off planet' NASA Innovative Advanced Concepts (NIAC) Phase 1 and Phase 2 work, with input by the Stanford-Brown-RISD 2018 [2] and DTU [3] 2018 iGEM Teams. It also presents the next steps of the research towards the creation of *in situ* grown, regenerative, and adaptive extraterrestrial habitats whose goal is to minimize the mass of structural materials transported from Earth and allow a more flexible architecture at destination.

2. Construction approaches for building habitats on Moon and Mars

The Lunar and Martian environments consist of a vacuum or very thin atmosphere. In order to enable humans to live there, it requires highly pressurized structures. Due to the lack of a magnetic field and protective atmosphere, the surface of the Moon and Mars are exposed to harmful solar and cosmic radiation and impacts with micrometeorites [4].

Table 1. Comparison of different construction strategies for lunar and Martian habitats [5-15]

	Rigid Modules	Inflatable / deployable modules	Regolith 3D printing	Regolith solar sintering	Ice habitats	Habitats in lava tubes	Growing habitats
References / Examples	Habitat Demonstration Unit (HDU) Deep Space Habitat (NASA AES), ISS	Bigelow Expandable Activity Module, (Bigelow Aerospace)	Lunar Habitation, (Foster + Partners, ESA) MARSHA (AI Spacefactory) Contour Crafting (Khoshnevis et al., 2012)	Regolight, (Imhof et al., 2018) SinterHab (Rousek, Eriksson, Doule, 2012)	Ice House, Ice Home (SEArch+) (Morris et al., 2016)	(Ximenes, Elliott and Bannova, 2012), (Billings, Walden and York, 2000)	Myco-Architecture Off Planet (Rothschild et al., 2018)
Up mass	very high	medium	medium	medium	medium	high	**low**
Energy for construction	medium	small	high	medium	high	high	**low**
Flexibility / Onsite changes	small	small	medium	medium	medium	small	**high**
Autonomy in construction	-	-	medium	small	medium	-	medium/high
Infrastructure preparation	medium	medium	high	high	high	medium	medium
Radiation protection	low	low	high	high	high	high	medium
Reliability	high	medium	medium	medium	low	low	medium
Dependence on Earth	very high	high	medium	low	low	medium	low

Therefore, the whole base needs to be protected. It requires structural materials, sufficient radiation protection, and infrastructure. There are different architectural concepts and construction approaches on how to build a habitat on the Moon or Mars. Mass and cost of the transportation and construction process, together with reliability and flexibility of the habitat play crucial roles in the feasibility and success of design concepts [16] [Table 1].

2.1 Build it on Earth, launch it into space

The first approach, the most extensively tested, is to bring everything from Earth. This method uses existing technology and could be one of the most feasible concepts for starting a Moonbase. The International Space Station (ISS) consists of separate modules put together, each with its own radiation protection. Although this method ensures reliability, it requires bringing all of the rigid modules from the Earth. Due to the huge energy and economic costs, the 'Build it on Earth, launch it into space' approach may cause umpass and resupply problems, and minimal surface operations. Besides the energy and cost disadvantages, the reliance on Earth, in the long run, may lead to greater mission risk. The radiation and micrometeorites protection given in this example may turn out not to be enough for long-duration missions. Additionally, that approach would be even more challenging for Martian missions, where, due to the distance from Earth, the cost of transportation of materials is drastically higher.

2.2 *In situ* Resource Utilization

The other approach is *in situ* resource utilization. Lunar and Martian habitat concepts focusing on this approach propose the utilization of the most abundant resource - regolith, by different processes such as 3D printing or solar sintering [9]. Concepts proposing regolith 3D printing suggest, for example, the use of a single multi-purpose robot for building a lunar habitat. The robot has a regolith scoop on one end which excavates the loose regolith and pours it around the dome to build the protective shell. Solar sintering is predicated on the use of 3D printing to build infrastructure and protective shells from regolith using the Sun as the only source of energy. The idea might be generally called Regolith Additive Construction (RAC). Contour crafting is based on robots that sinter the regolith to construct necessary infrastructure [10,11]. Solar crafting also uses robots and a balloon gantry system which sinters regolith. Another important resource that could be utilized for the construction of the habitats is ice. Ice could potentially provide sufficient radiation protection [12], however, this approach uses one of the most precious resources for other purposes including irrigation and drinking water, and the consultation process is energy-intensive. Although the ISRU approach requires fewer building materials being transported from Earth, to construct habitats from in situ materials, most of the time extensive dedicated infrastructure needs to be prepared first, requiring heavy-duty robotic operations.

The alternative to bringing all of the materials from the Earth or using *in situ* resources requiring robotic operations could be the use of biomaterials - literally *growing* structures at destinations.

3. Use of Biomaterials - Life as Technology

3.1 Engineering living materials (ELMs)

Imagine deploying a single "seed" that, similarly to a growing tree, contains all the essential information needed to grow the desired structure. With the use of engineered living materials (ELMs), it could be possible to implement such behavior in architectural designs and thus, like the tree, grow structures capable of responding dynamically to the environment and maintaining and healing themselves. Replicating these beneficial characteristics of living organisms, together with incorporating programmed synthetic morphogenesis, may allow for the development of an autonomous construction system [17]. Such a system could allow the fabrication, assembly, and maintenance of self-produced, functionally diverse biomaterials, for large-scale structures, in a controlled environment [Fig. 1].

The construction of human habits has involved the use of biologically produced materials since prehistory. We now have emerging technologies to alter living biological growth for the process of material fabrication and assembly [17]. With the use of materials that continue to live and change after their final form, we can revolutionize construction approaches. The use of advanced biomaterials and the ability to 'design nature' leads to the field of material ecology, which allows for the development of hybrid materials combining multiple functions and characteristics [18].

3.2 Growing (Space) Architecture

One of the key features of living organisms - growth - is being used as a framework for system and policy research that will provide innovative and sustainable solutions in the field of architecture and arts. This idea of biological growth as an alternative construction method is of increasing interest in architecture and the arts and poses important questions about the role of the designer in shaping complex and emergent biological processes [19]. A phenomenon of growth at the architectural scale - buildings exhibiting the qualities we see in growth in nature - has been identified as a "blank spot on the landscape of biomimetic transfers" [20].

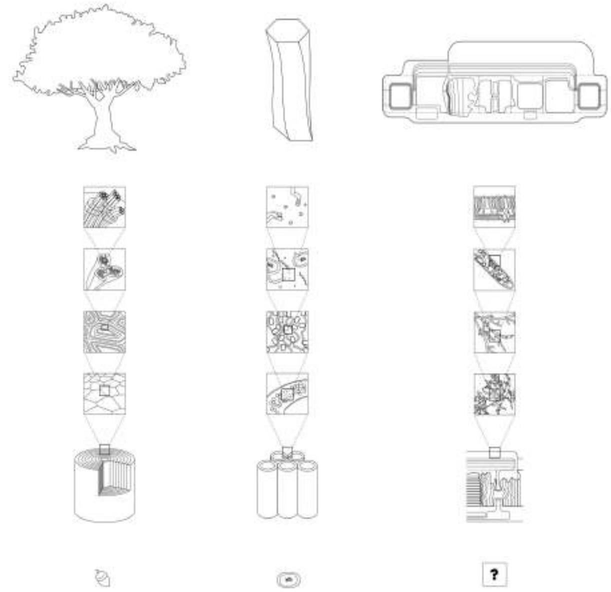

Fig. 1. Using Engineered Living Materials for creation of Living habitats, inspired by Nguyen et al., 2018

The biological approach of growing structures directly at the destination would be less energy-intensive and leave a smaller planetary footprint than mining or melting surface material [10]. The use of biomaterials could also be advantageous in enabling habitat reparations and future extensions since the material could be self-replicating [15].

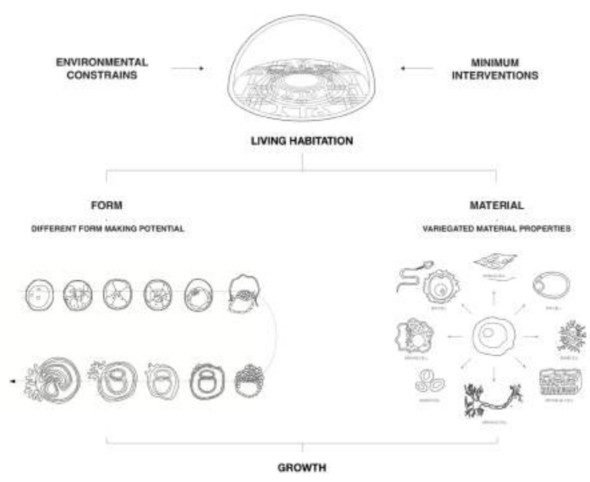

Fig. 2. Habitat development inspired by the natural growth and morphogenesis

In architecture and constructions, the final form of a building is usually specified by a series of instructions, and most structures are only required to be functional when they are complete. Additionally, construction is a coordinated activity with a hierarchy of management and a structured organization of information as well as utilizing many different skills and knowledge. Growing architecture, in contrast, may have characteristics more similar to biological organisms [Fig. 2]. There are no blueprints representing the final structure and no simple relationship between an information source and how the final built structure will look like. A grown structure would also be self-assembling in relationship to its environment rather than enabled through trained construction professionals. Additionally, a grown habitat would need to stay alive and be subject to constant change and modification with no fixed point of completion. Information governing the sequence of events that will follow, instead of coming from the 'outside' is encrypted in the 'seed'. Responsibility for biological construction is shared between all of the components involved - control emerges from the system as a whole. The information in a growing structure has to be read and acted upon by that growing structure [21].

3.3 Habitat vs. Living Habitation System

A habitat shell could be extended into a living state participating actively in waste, recycling, oxygen production, and detoxification similar to a "living roof." A green, or "living roof", has a layer of soil and plants on the surface, which provides aesthetic benefits, but from a practical standpoint, this living layer decreases runoff and provides insulation. The long-term goal of creating a living habitation system is to create a system that functions beyond structure and warmth; where the organisms can be manipulated to perform tasks like self-healing, humidity regulation, energy production, nutrient production, and bioluminescence. Such living architecture was demonstrated by a five-story Bio Intelligent Quotient building in Hamburg, Germany [22] showing that this approach can scale.

Similar to living organisms, biologically-grown habitats could utilize a circulatory system to deliver nutrients to pre-seeded microbes and spores embedded within "cells" or modules. This circulatory system can be reused after the materials are fully developed to deliver nutrients and gasses for secondary processes. The habitat itself could act as an integrated bioreactor that can supply oxygen for breathing and hydrogen for fuel and radiation protection, and biomass for food or more building materials [Fig. 3].

The proposed bio-utilitarian concept could potentially be an all-in-one self-sustaining, living habitation system [Fig. 4], competing with the comforts of prefabricated structures that are sent from Earth fully outfitted. A number of the utilities, equipment, furnishings, and fixtures could be built directly into the expandable shell.

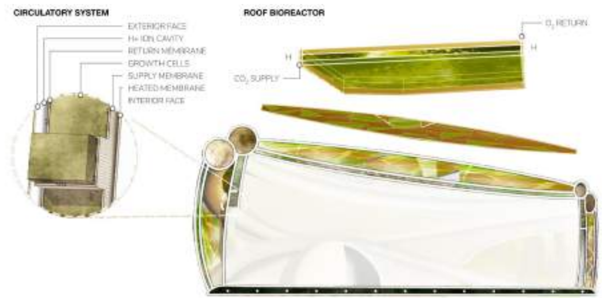

Fig. 3. Habitat acting as an integral bioreactor, redhouse studio

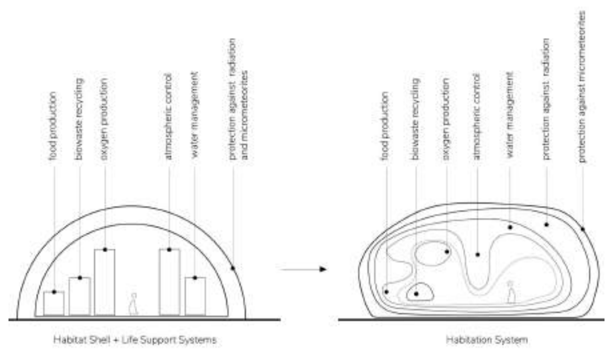

Fig. 4. Habitat vs. Habitation System

Exploration and testing the biocomposite's ability to grow, together with the fabrication, processing, and tuning methods will allow for the development of a palette of materials for specific architectural uses [23]. The final goal is to be as independent as possible, to be able to stay for a long time in space without depending on supplies from Earth.

4. Mycelium for construction of extraterrestrial habitats

Habitats could be constructed from a light, fibrous, self-produced composite material with excellent mechanical properties, radiation protection capabilities, and acting as a vapor seal. With the use of fungal mycelium - the vegetative structure of fungi consisting of branching, thread-like hyphae [23] [Fig. 5] - for the production of *in situ* grown biocomposites [Fig. 6] the creation of habitat could be possible only by sending a few spores, supplemental nutrients, and a growth framework. With the presence of nutrients, oxygen, and water, the mycelial building envelope could grow itself, reducing the energy required for constructing additional structures. The use of water, gasses, and minerals, or some combination sourced at the destination, would further reduce upmass assuming that there was no need for additional robots beyond those already needed for the mission.

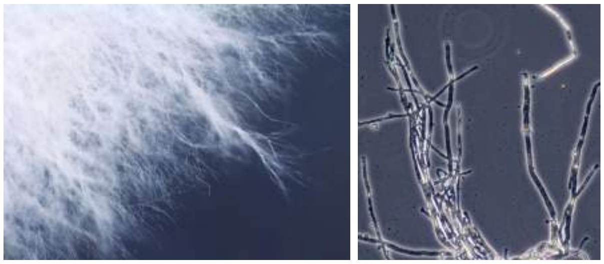

Fig. 5. Branching mycelium structure and micrograph of *Ganoderma lucidum* mycelia

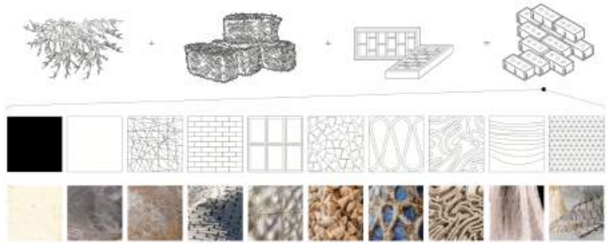

Fig. 6. The mycelial hyphae act as a binder to the material being digested and it results in a very strong and lightweight building material

Mycelial materials have excellent mechanical properties: they are fire-resistant, provide good thermal insulations, and do not outgas [Table 2,3]. The density and material properties could be adjusted during the growth. Exploration and testing the biocomposite's ability to grow with combinations of organisms will allow for the development of a palette of mycelium-based composite materials for specific architectural uses [15].

5. Potential of the mycelium use in space applications

The long-term goal of the idea of utilizing mycelium for space application is to create a biocomposite that has more functions than just providing structural support and insulation for the habitat [Fig. 7].

Fungal mycelium is an extremely versatile material and may have the potential to be genetically engineered to enhance its properties or enable the primary production of other vital materials [24].

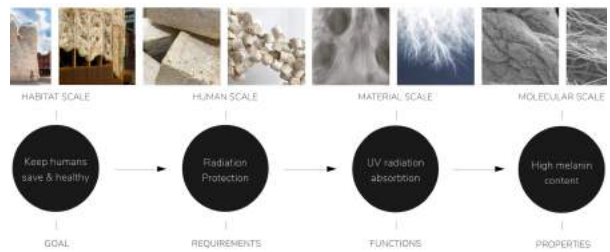

Fig. 7. Example of properties and functions of mycelium biocomposite - radiation protection

The organisms could be bioengineered to be able to self-heal, regulate the humidity levels, produce energy, light, and nutrients [15] provide building ventilation and control. The biological functions that enable the growth of the materials also bestow such benefits as waste degradation, oxygen production, and heat and electricity generation [24] and could be implemented within the environmentally controlled life-support systems within the habitat [25], or provide radiation protection [26] [Fig. 8].

Fig. 8. Variegated material properties of mycelium biocomposite in a space habitat

Table 2. Material comparison with materials under consideration for ISRU construction [10,15, 27-29].

Material	Regolith (Comp)	Sintered Basalt	Lunar Regolith	Sulfer Concrete	Ice	Mycrete
Project	Chow et al.	PISCES - HI	NASA Khoshnevis	NASA Khoshnevis	Icehouse-SEArch	redhouse
Photo						
Modulus of Rupture	40 MPa	40 MPa			3 MPa	19 MPa
Ultimate Compression	40 MPa	206 MPa	53.5 MPa	17.24 MPa	4.9 Mpa	6.7 MPa
Modulus of Elasticity					5100 Mpa	5334 MPa
R-value (per inch)		0.05r/in.			0.45 r/in.	3.8/in.
Tensile					1MPa	TBD
Temperature to Produce		1400C	1025C	130C	> 0C	15-30C
Thickness for radiation sheilding		3 meters	3.5 meters		30 cm	TBD

Table 3. Measured mechanical properties of mycelium biocomposites. The values are obtained from the curve in Fig.9. Ganoderma Lucidum has the highest modulus (~200 MPa) and highest strength (~20MPa), however, the results depend a lot on the size of the samples.

	Elastic Modulus (MPa)	Strength (MPa)
Ganoderma Lucidum	275	26
Phellinus Linteus	21	1.57
Annulohypoxylon	80	5.05

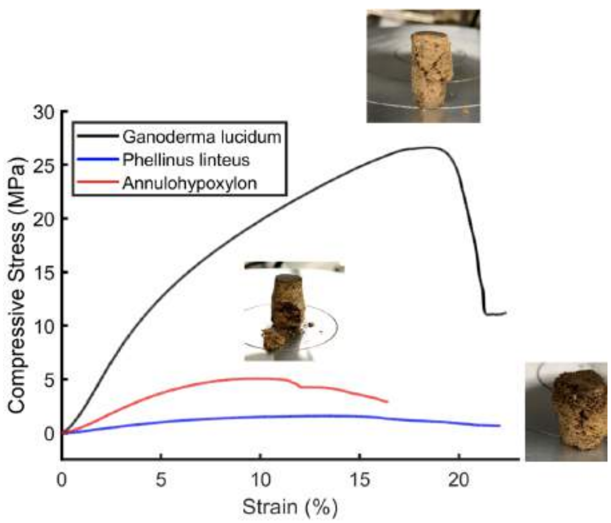

Fig. 9. Measured mechanical properties of mycelium biocomposites. It is recommended to have all the specimens with the same dimension and at least three pieces for each kind of specimen for more accurate and reliable results in the future.

5.1 Self-replication and self-healing

The concept of growth as an alternative approach to the construction of extra-terrestrial habitats addresses the need to extend the life of materials and material flow. Living mycelium within the biocomposites would start repairing micro-cracks, preventing more critical stages of damage. Self-healing and self-replicating materials would allow for any habitat repair and future extensions. Habitat could be adapted for the building site extended and perform self-repair.

Self-healing of the structure provides the ability to repair the structure without the need for manual repair, which significantly lowers the maintenance cost and is especially important in space environments, where every extra-vehicular activity involves risk for astronauts.

5.2 Sensing capabilities

The utilization of mycelium-based biocomposites could lead to the creation of the living interface between architecture and digital technologies, exploring the possibilities of responsive environments. Such physical spaces, enriched by intelligent inputs, providing the ability to receive, process, and respond to information would enable varied spatial experience and interaction with the user, especially important in space environments [30, 31]. This may mean incorporating other organisms with mycelium. For example, mycelium can live in symbiosis with bacterial such as *Bacillus subtilis*. This bacterium is genetically tractable and could be programmed as an integral intelligent input (biosensor). For example, a mycelium strain engineered with *B. subtilis* is naturally able to sense oxygen and pressure, which will produce a color change when oxygen concentrations are low [15]. This ability can be linked to a specific receiver, to monitor oxygen concentrations and pressure changes in the habitat. Mycelium composites produced through co-culture of fungus and *B. subtilis* could be also engineered to digitally report on excess stress and load in the shell, or lack of pressure and load, which could potentially relate to failures in the shell's structural integrity [24].

5.3 Waste processing and decomposition

In nature, fungal mycelia are a vital part of ecosystems for their role in decomposing organic compounds. They digest nutrients by secreting enzymes that break down materials for uptake into their cells.

The same function, which is a primary role of mycelium, could be used in space habitats. Mycelia could be used to process waste from the habitat, e.g.

non-edible parts of the plants from the greenhouse, or feedstock of mission-produced organic waste streams (human waste) into fertilized soil or into the structural material.

5.4 Radiation protection

Biological processes could also be utilized to provide radiation protection. An example of that is the utilization of radiosynthesis. *Cryptococcus neoformans* can survive simulated Martian conditions [32] and are able to shield from the radiation, twice as effective as charcoal [33]. Melanin pigments play a crucial role in the survival of fungi when exposed to radiation. Melanin-rich fungi have the ability to absorb radioactivity [33] suggesting that melanized fungal mycelia could provide radiation protection. Melanized black yeast, and some black fungi, not only survive but also benefit from exposure to ionizing radiation [33, 34]. It could be possible to supplement the mycelium-composites with either genetically engineered mycelia that bind materials such as metals or with bacteria to enhance radiation protection capabilities.

5.5 Psychological aspects

The organic nature of mycelium-based materials and the ability to fine-tune the tactile environment should additionally aid in the psychological comfort of the mission participants [35] e.g. mycofoam made out of mycelium is similar in function to styrofoam and it can be stained to look like wood [15]. 'Growing' habitats will also provide a quality of multi-sensory aspects of nature experience. This method of construction may enable us to translate complexity and variety from nature - the color variation, form complexity, light variation, pattern variation, terrain complexity, and haptic surfaces - to the built environment [36].

6. Challenges of the mycelium use in space applications

6.1 Planetary Protection

One of the biggest challenges when working with biological materials for space applications is a need to respond to planetary protection requirements for robotic or human missions, and comply with current Committee on Space Research (COSPAR) human mission principles and guidelines. The level of restrictions depends on the location. The Moon is in Category II, which means that the requirements ask only for simple documentation: a short planetary protection plan, primarily to outline intended or potential impact targets, brief pre-launch and post-launch analyses detailing impact strategies, and a post-encounter and end-of-mission report providing the location of inadvertent impact, if such an event occurs. Mars, on the other hand, is in Category IV which means detailed documentation is required including a probability of contamination analysis, a bioassay to enumerate the bioburden, an inventory of the bulk constituent organics, and an increased number of implementing procedures (trajectory biasing, cleanrooms, bioburden reduction, possible partial sterilization of the direct contact hardware and a bioshield for that hardware) [37].

6.2 Growth requirements

Mycelium, in order to grow, needs oxygen, water, and a source of nutrients. Although water is a resource present, both on the Moon and Mars, its extraction is a very energy-consuming process, and it is an extremely valuable and precious resource. It is for sure, that once humans will be establishing a base on one of these celestial bodies, there will also be a water extraction system in place, however, the primary use of it will be for sustaining human life, and not for constructing habitats. The same holds for oxygen production, which is essential for human survival.

6.3 Material properties under extreme environmental conditions at the destination

Material properties under lunar or Martian environmental conditions are not known. In order to understand the biocomposite behavior in the space conditions (even if grown in a closed environment), it will be necessary to conduct tests for UV and ionizing radiation, low temperatures, pressures, wind and abrasion, and other environmental factors different due to the terrestrial forces. It would be helpful to test how the mycelium grows at different pressures and temperatures, in order to find the optimal growth conditions for the implementation in the growth chamber. Performing the environmental tests will be necessary to give an assessment of how the developed mycelial biocomposites will behave in the lunar and martian conditions. This information would be crucial in order to enhance space technology readiness levels [38] levels. The other, more complicated to test, aspect, which could significantly affect mycelium growth is the low gravity environment.

7. Directions of the research

The aim of this research is to develop an alternative habitation system that would compete with "Built-in on Earth, launch it to space" and ISRU construction approaches. A starting point is the creation of the composite that has structural capabilities at the same time eliminating dependence on a heavy substrate launched from Earth. There are two approaches to achieve that [Fig. 10]. The first one is a 'standalone' approach where mycelium for the construction of habitats could be used independently, in a sealed deployable "bag" (with lightweight, deployable mesh-like, compressible scaffolding). The other approach is to use mycelium in conjunction with Martian or lunar regolith, reducing the amount of biomass needed to be produced (water extracted and energy used).

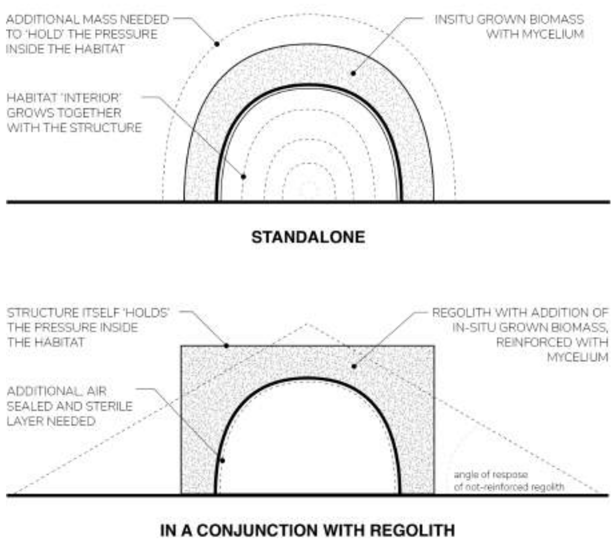

Fig. 10. 'Standalone' approach for construction base with mycelium bio-composites and 'In conjunction with regolith approach for construction base with mycelium bio-composites.

7.1 Standalone structure

The idea is to create a self-supporting structure based on the membrane system (shell) - with layers and channels for nutrients delivery and oxygen exchange - that would enable the growth of mycelium and self-assembly of the biocomposite-based habitat.

Fig. 11. Fully encased structures self-assemble when water, CO2, and heat are added by a robot (image credit: rehouse studio)

The shell, which acts as a vapor barrier, would be deployed by releasing a lightweight folded frame as in a pop-up tent or it would be inflated. It would then be dampened with extracted water and heated. The temperature rise would activate growth - the cyanobacteria or algae would start growing, releasing oxygen and sugar which would be consumed by fungal mycelia [Fig. 11]. Alternatively, the fungi could live off dry algae or other lightweight nutrient sources [15].

To enable three-dimensional growth within the structure, at the same time eliminating the dependence on a heavy substrate, commonly used in mycelium biocomposites (e.g., wood chips or sawdust), it is proposed to introduce a lightweight, compressible, porous scaffold, that mycelium can use for the growth [Fig. 12]. The exact design of a scaffolding structure, its form, geometry, size of the cells, and the material are yet to be defined. Initial tests were conducted on paper origami foldable structures [Fig. 13], however ultimately a lattice with a much finer pore size (1-5mm) and more durable material should be tested.

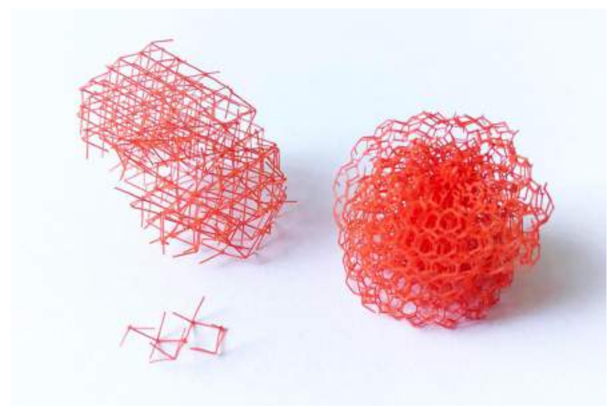

Fig. 12. Example lattice from Solus printer available in Rothschild's lab

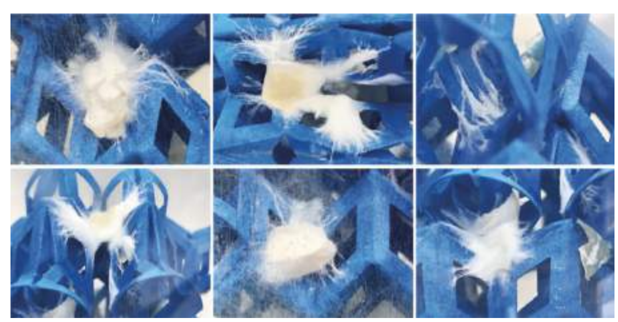

Fig. 13. Mycelium climbing on paper-based origami scaffold coated with Agar-Agar

To ensure proper nutrient supply to promote fungal growth, the scaffolding structure could be coated with a nutrient-rich hydrogel. The mesh size of hydrogels can be engineered to store nutrients and deliver them in a sustained fashion through mass diffusion [39]. Growing mycelium would 'climb' on, and solidify the scaffolding, binding it all together, so the whole structure becomes rigid [Fig. 14].

Fig. 14. Mycelium grown on paper-based origami scaffold coated with Agar-Agar

Another idea for creating scaffolding for mycelium growth is the use of drop-stitch technology [Fig. 15]. Drop-stitch is a technology used for the production of inflatable drift boats, floating docks, high-pressure rescue lifting bags, and airplane wings. Due to the utilization of fine threads along with the structure, this technology enables the forming of flat-surface inflatables with high rigidity. Similarly, a multilayered habitation system could be created utilizing drop-stitch inflatables [Fig. 16]. The bioreaction would occur in the cavity and biomass would fuse with stitches.

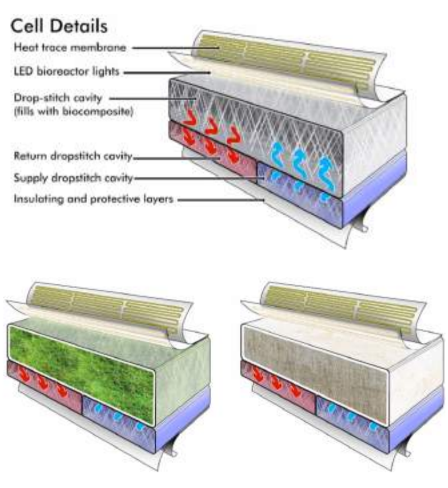

Fig. 15. Drop-stitch technology, (image credit: redhouse studio)

Fig. 16. Drop-stitch inflatable, (image credit: redhouse studio)

Table 1. Opportunities and obstacles - standalone structure scenario

Opportunities / Pros
Minimizes the mass of structural materials which must be brought from Earth.
Reduces onsite infrastructure preparations and heavy-duty robotic operations.
The bag protects from potential contamination (externally and internally).
A number of utilities, equipment, furnishings, and fixtures can be built directly into the expandable shell, competing with the comforts of up-massed prefabricated structures that come fully outfitted.

Obstacles / Cons
All of the mass has to be produced in-situ (biomass) or brought from earth (scaffolding etc).
A lot of water is needed to produce needed biomass and nutrients for mycelium growth.
It may not be sufficient to protect against radiation.
An additional layer of regolith may be needed to “hold” the structure due to the pressure differences

7.2 In conjunction with regolith

In the same way, as steel is held together by molecular bonding and concrete is held by a binder, soil strength depends on internal friction between the soil particles themselves. However, any kind of soil, whether it is sand, earth, or regolith, is not strong enough to act as a construction material itself. Following the principles of geotechnical engineering, the mycelium, grown on lunar or Martian regolith [Fig. 17] with minimal addition of (in-situ produced) biomass and/or nutrients could potentially act as a binder, ensuring the stability of the regolith and enabling the construction of inhabitable surface structures [40]. With the use of such a biological approach to reinforce the regolith mass it could be possible to build a stable structure with a smaller amount of biomass, water, and oxygen used, comparing the standalone approach. The regolith would also provide sufficient radiation protection, and mass needed to hold the pressure of the habitat, caused by the pressure differences (inside and outside environment).

Fig. 17. Mycelia growing on Martian regolith simulant.

Table 2. Opportunities and obstacles - in conjunction with regolith

Opportunities / Pros
Radically minimizes the mass of structural materials which have to be brought from Earth.
A smaller amount of biomass (and/or nutrients) is needed to be produced - less water and energy are needed.
The structure would hold internal pressure by itself.
A lower gravity environment may enable the creation of taller structures (smaller compaction on the bottom of the structure) reducing the planetary footprint.
Regolith's toxicity may be reduced my mycelium

Obstacles / Cons
Onsite infrastructure preparations and robotic operations are needed (collection of the regolith).
Risk of the potential contamination of the environment - protective layer needed.
A lower gravity environment may act contradictory to the geoengineering principles.
Regolith could be toxic

8. Discussion

The development of the two proposed approaches will add not only to the research on space architecture but also mycelium composites themselves.

In the standalone approach, the growth of mycelium will be tested in the developed inflatables and drop-stitch cells. There is ongoing research on optimizing mycelium for strength and radioprotection (melanin and lipid production). We are testing materials for strength, UV protection, and melanin content (Raman spectroscopy). The next step is to develop "cells" that grow biomass in-situ and build a scale model of the building that grows in-situ.

In the *in conjunction with regolith* approach mycelium growth will be tested first, on the sand, to observe the principles of mycelium growth on inorganic soil, and later, when the grade of the soil and chemical composition will be taken under consideration, on Martian regolith simulant. The goal is to explore the mycelium biocomposites in resource-limited conditions and understand how mycelium grows on sand, and if it needs extra nutrients. This research aims to answer the question of what is the minimum amount of biomass needed to enable mycelium growth on inorganic soil (sand or martian regolith) and potentially bind the soil together, progressing the field of mycelium biocomposite. In the later stages of the research, it will be interesting to study the behavior of the soils in lower gravity conditions, and the compaction of the regolith in the lower gravity conditions, and how that may affect the growth of mycelium.

In both cases, the main constraint is to develop a construction strategy that utilizes as little brought-from-Earth materials as possible, as little energy as possible, and giving maximum reliability and flexibility. The development of a biological material system that utilizes only in-situ materials - biomass from the greenhouse as a source of nutrients (non-edible parts of plants), and/or regolith, will contribute to future development in space architecture.

A similar approach as proposed for the construction of extraterrestrial habitats could be adapted for the building industry in general. Currently, the building industry is responsible for 40% of Earth's carbon emissions. The concept of a biodegradable, rapidly deployable, growing and self-healing structure, potentially with embedded biosensors, responses to the UN Sustainable Development Goals 9 (Industry, Innovation and Infrastructure), 11 (Sustainable Cities and Communities) and 12 (Responsible Consumption and Production). Combining ideologies of the circular economy (considering all energy and sources of impacts) and human-centered design (creating spaces responsive to the users), and using biotechnology to create sustainable, adaptable construction system, resembling ecosystems (to increase resource efficiency and create cyclic resource loops) [41] this research aims to respond to the need for a more holistic approach to building design.

9. Conclusions

This research explores the potential and challenges of using mycelium-based biocomposites for space applications. The further development of the research on ELM's and mycelium-biocomposites will allow for the advancements in the field of biotechnology in the built environment, providing functionally graded, bio-composites for the construction of regenerative and adaptive extraterrestrial habitats. The concepts employ living biological growth in a controlled environment for the process of material fabrication, assembly, and maintenance. Features include the modest upmass requirements of a few spores, nutrition for mycelial growth, and a growth framework, along with the potential to reproduce using in situ resources, the ability to grow to accommodate on-site terrain, and the control granted by the tunability of the materials.

There are myriad possibilities for mycotecture off-planet, however, the research is still in a very early stage. There is still a lot of technological gaps that will need to be identified, for example, defining the mycelium species, growth conditions, enhancements and post-processing methods, design of growth containers, shells, scaffoldings, etc, integrity during deployment (environmental damage), systems integration for habitation (heat, power, light, etc.), end-of-lifetime (re) use. Once the enabling technologies are identified, a technology roadmap and recommendations for further development could be generated, allowing for the feasible implementation of this approach, for growing extra-terrestrial habitats.

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