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Publication date
2022

Document Version
Final published version

Citation (APA)
van Ellen, L. A., Belling, A.-S., Brandić Lipińska, M., Nerlich, P., Azzopardi, H., Ciardullo, C., Dade-Robertson, M., Holt, A., Hyry, N., James, P., James MacCowan, R., Deakin Roberts, A., Vermeulen, A. C. J., & Zhang, M. (2022). *Bio-Futures for Transplanetary Habitats: A Summary and Key Outcomes from the 2022 Symposium*. Paper presented at 73rd International Astronautical Congress, Paris, France.

IAC-22-A1.8.9

Bio-Futures for Transplanetary Habitats - A Summary and Key Outcomes from the 2022 Symposium

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Abstract

Bio-Futures for Transplanetary Habitats (BFfTH) is a Special Interest Group within the Hub for Biotechnology in the Built Environment that aims to explore and enable interdisciplinary research on transplanetary habitats and habitats within extreme environments through an emphasis on the bio-social and biotechnological relations. BFfTH organized the online and onsite networking symposium Bio-Futures for Transplanetary Habitats to examine how emerging biotechnologies, living materials, and more-than-human life can be implemented in habitat design and mission planning. The two day symposium aimed to serve as a catalyst in establishing an international network of collaborators across industry, academia and the private sector. It also aimed to support the development of novel methodologies to move beyond discipline-specific approaches in order to address and interrogate emerging questions surrounding potential transplanetary habitats and habitats in extreme environments. The symposium was divided into five sessions which hosted a minimum of three speakers each, these sessions were: Mycelium for Mars, Plants and Agriculture, Sustainable Habitats and Travels, Artistic Approach to Extremes Habitats, and Novel Biotechnologies for Space Habitats. This paper presents key outcomes from the symposium sessions, moderated panel, and informal discussions. The trends in ongoing research are identified and summarized following the use of biotechnology and bio-design to ensure and support safety, sustainability, habitability, reliability, crew efficiency, productivity and comfort in extreme environments both here on Earth and off-world. Moving beyond pure design and engineering innovation, the outcomes of this symposium also further interrogates sociotechnical imaginaries. Biodesign-based and biotechnologically-enabled transplanetary futures are investigated to understand how we want these futures to behave, feel and be experienced. The symposium hosted a wide range of topics including: innovative material-driven processes for the design of transplanetary habitats; socio-political concerns or ethical implications to be taken into account; technology transfer and transitioning towards a sustainable built environment on Earth; multi-species narratives and relations to sustain human and other-than-human life in transplanetary habitats; sociotechnical considerations in propagating and sustaining Earthbound life beyond Earth environments; and sustainable living on Earth through a holistic systems thinking approach. BFfTH further reflects on what potential bio-social and biotechnological research is needed to sustain life in an extraterrestrial environment in the future and how it can help with transitioning towards a more sustainable built environment here on Earth in the present.

Keywords: biotechnology, bio-social, habitats, transplanetary

Acronyms/Abbreviations

BFfTH:	Bio-Futures for Transplanetary Habitats
COSPAR:	Committee on Space Research
HBBE:	Hub for biotechnology in the Built Environment
ECLSS:	Environmental Control and Life Support Systems
ELMs:	Engineered Living Materials
SIG:	Special Interest Group (from HBBE)
TRL:	Technology Readiness Level

1 Introduction

The last decade has seen a rise in biotechnological and bio-social research, expanding into fields such as material science, space exploration, architecture and design. Bio-Futures for Transplanetary Habitats (BFfTH) is a Special Interest Group (SIG) that covers all of these fields and brings together researchers from a myriad of backgrounds. The first event organized by BFfTH was a two day networking symposium in April 2022 to open the discussion and collaborations of researchers under the topic of Bio-Futures for Transplanetary Habitats. This paper presents a summary and key outcomes of this first symposium.

2 Special Interest Group

BFfTH was formed within the Hub for Biotechnology in the Built Environment (HBBE) at the universities of Newcastle and Northumbria. HBBE was formed in 2019 with the ambition to develop technologies for the next generation of buildings which are both life sustaining and in turn can be sustained by life. The research is conducted under four research themes i.e. Living Construction, Metabolism, Microbial Environment, and Responsible Interactions [1].

Bio-Futures for Transplanetary Habitats is a Special Interest Group that aims to explore and enable interdisciplinary research on transplanetary habitats and habitats within extreme environments through an emphasis on the bio-social and biotechnological relations. The BFfTH objectives are:

- Enabling interdisciplinary research through projects across the four themes of the HBBE: Initiating projects within the SIG itself as well as collaboration with other research groups.
- Organizing networking event(s) hosted by BFfTH and HBBE to drive forward research and applications together with a global community (such as the first networking symposium).
- Establishing a diverse network of researchers, and encouraging a move towards transdisciplinary research.

3 The networking symposium: summary

The symposium was organized around various emerging questions with the aim to bring together research that related to the overarching theme. Research into transplanetary habitats and habitats within extreme environments is growing exponentially, and in order to understand emerging extra-terrestrial futures and infrastructures, there is a need for transdisciplinary research that can investigate the implications of integrating living materials and more-than-human life into astronautics. How can emerging biotechnologies be implemented in the design and mission planning to enable or support the creation of transplanetary habitats and habitats in extreme environments? What new socio-political concerns or ethical implications should be taken into account? How can sustaining life off-Earth in the future help transitioning towards a sustainable built environment on-Earth in the present? The aim of this symposium was to serve as a catalyst in building an international network of collaborators across industry, academia and the private sector. The symposium also aimed to support the development of novel methodologies to move beyond discipline-specific approaches in order to address and interrogate these emerging questions. An abstract call invited speakers on the following topics:

- Multi-species narratives and relations to sustain human and other-than-human life in transplanetary habitats;
- Use of biotechnology and bio-design to ensure and support safety, sustainability, habitability, reliability, and crew efficiency, productivity and comfort in extreme environments off and on Earth;
- Speculative ethics for companionship between humanity and other-than-humans within transplanetary habitats;
- Sociotechnical considerations in propagating and sustaining life beyond Earth environments;
- Innovative material-driven processes for the design of transplanetary habitats;
- Sustainable living on Earth through a holistic system thinking approach.

In total, 24 abstracts were received, of which 14 were selected for oral presentation along with two invited keynote speakers & invited guest panelists, and five presenters from the BFfTH SIG. The presentations were divided into five topic sessions following the common themes explored in the abstracts: Mycelium for Mars, Plants and Agriculture, Sustainable Habitats and Travels, Artistic Approach to Extremes Habitats, and Novel Biotechnologies for Space Habitats.

The two keynote speakers (both experts in their fields: one artist/biologist/researcher in space systems, and one architect and researcher for Ecosystems in Architecture) were also invited for a panel session at the end of the first day along with an invited guest panelist (bio futurist and multidisciplinary designer). The panel session was fluid and although some questions were prepared in advance around the topic of biotechnical and bio-social advancements for transplanetary habitats, other questions and discussion topics were explored based on the presentations of the first day. The following sections gather quotes from the panel discussion as well as the main outcomes and insights from the two days of presentations and discussions.

4 Key outcomes

At the end of the networking symposium, the organizers highlighted some trends seen in multiple presentations and discussions, crossing the original topic sessions. In total, six trends have been highlighted and this section expands on the discussion and main outcomes for each.

4.1 Biomimicry and biotechnology for space systems

In space technology, engineering, and design, the concept of biomimicry - utilizing biological solutions to solve complex problems, is not a novel approach. There is ongoing research on biology-based, enabling technologies for human space exploration [2]. Some examples of biomimicry in space are tensegrity robots, seal whisker-inspired sensors, foldable and deployable solar panels gecko grippers, sensors based on a fly's eye [3], [4], cyanobacteria-based life support systems [5] and the European MELISSA project. The MELISSA project is a bioregenerative ecosystem that is inspired by lake ecosystems [6].

During the symposium, many presentations included research on biomimicry particularly in the area of materials engineering. Specifically, the use of biomaterials, and the concept of Engineered Living Materials (ELMs) for space applications were presented. Biomaterials as described here are grown, rather than manufactured, and examples include fungal mycelium, bacterial cellulose, plants, and animal cells. ELMs are materials inspired by nature that self-synthesize, sense, and respond to the environment and are hierarchically structured [7]. ELMs contain living cells that provide the responsive function and polymeric matrices, required for scaffolding functions, and can therefore be designed as active and responsive materials [8], [9].

In addition to ELMs, non-living biomaterials were also presented and discussed. For instance, biomimetic composites akin to natural seashells or pearl could be produced through the low-energy hybridization of natural biopolymers and extraterrestrial mineral deposits. These biopolymers could be generated through versatile bioreactors, where phototrophic microorganisms could be engineered to produce binders though the fixation of CO_2 and N_2 with sunlight. The notion of considering inhabitants as bioreactors was also discussed; here a protein from human blood (Human Serum Albumin) could be combined with urea (obtainable from urine) and regolith to produce a biological composite with compressive strengths on par with terrestrial concrete [10].

These biomaterials, and especially ELMs could potentially play a crucial role in the future of space systems due to their unique properties. These include self-replication, self-healing, and self-assembly processes, without the need for high-energy or resource-intensive processing. These processes could significantly lower the costs of a mission since the desired materials and objects can be grown *in situ*, reducing the mass of material needed to be transported from Earth. The self-healing properties and the possibility to create on-demand materials also provide a source of reliability, flexibility, and safety. The second property of note is responsiveness to the environment. As such biomaterials are able to sense changes in the environment and respond to them with minimal energy and material cost [11]. The third property advocating for the use of biological materials in space systems is their innate potential for multi-functionality. A variety of functions and properties can be embedded in the materials, based on the given requirements and mission needs and intrinsic weaknesses of selected materials can potentially be overcome through methods such as bioengineering and synthetic biology; techniques which could be conducted *in situ* to provide flexibility and reduce mission risk [12], [13].

The ideas discussed during the sessions on *Mycelium for Mars* and *Novel Biotechnologies for Space Habitats* of using biological materials and ELMs include *growing* space habitats and creating habitats as living habitation systems. For example, during one presentation it was suggested that mycelium could be embedded into the habitat structure itself and utilized as a form of biosensor in the detection of temperature, oxygen, and pressure changes in the habitat. Such a solution would enable the creation of a habitat that could respond and adapt to its environment, and cohabiting astronauts [14]. Other potential research avenues discussed included the utilization of biological organisms in space for the bioproduction of essential or useful commodities, such as food, bioplastics or bespoke pharmaceuticals on demand.

The use of microorganisms and synthetic biology also provides the potential to create flexible bioreactors to sustain habitation and life on the Moon and Mars. For example, bioreactors containing specific microbial strains could be used in the production of oxygen from the Martian regolith, which in turn are also able to detoxify the regolith from the harmful perchlorates contained within [15]. Regolith, is one of the most readily abundant *in situ* materials found on the Martian surface, and therefore one of the best candidates for the construction of off-world habitats [16]. Several methods have been proposed for the mechanical stabilization of regolith and include heat-fusion (sintering), cement composites (concrete), synthetic polymers binders, sulfur binders, and fusion with ice [17], [18]. However, these solutions have several drawbacks, such as high energy or water use, or the need for the mining, purification and processing of specific mineral deposits - which would constrain habitat locality and add to launch mass and mission cost. By utilizing living organisms for planetary construction, it could however be possible to create regolith biocomponents, where the bound material would grow *in situ*. Examples include proteins and carbohydrates for the creation of regolith biocomposites [10], [19], or the use of mycelium for consolidation of the regolith into structural components. Presentations also suggested humans themselves be considered as *in situ* resources, as they too are able to produce, a variety of organic compounds, including urea, and Serum Albumin, both of which could be used as binders for regolith [10].

4.2 Mycelium-based materials

The use of mycelium – the vegetative, root structure of fungi - was primarily discussed during the *Mycelium for Mars* session. However, it was not limited to that session only, in fact, concepts or projects using mycelium for a variety of purposes in space exploration were repeated throughout the whole symposium. The *Mycelium on Mars* session was also not restricted to the Martian environment; it covered the wider context of using mycelium-based material for space exploration, at different feasibility levels and over varying time scales.

Mycelium is one of the emerging biomaterials that has a variety of beneficial, current, and prospective properties. It can even be bioengineered to provide additional properties and functions. Commercial applications (fashion, packaging material, acoustic panels, decorative furniture, or insulative material) are starting to gain traction on the market with the existing fabrication methods constantly being improved upon through ongoing research. Some examples were shown of mycelium products already at high technology readiness level (TRL). Companies like Ecovative, Bolt Threads or Biohm lead the fungi food and biomaterials revolution with mycelium based materials. Ecovative has licensed their Mushroom@Packaging technology in the US and around the world in the last few years, and more recently Stella McCartney partnered with Bolt Threads on a limited run of 100 mycelium-crafted bags that sell for up to $2950 [20]–[22]. Because of the favorable properties and characteristics it exhibits (see the next section for detailed overview of these properties), there is extensive, ongoing research on integrating mycelium into the built environment [23], [24]. Consequently, it has also been proposed as a material for applications in space habitats, adding to the pallet of space architectural solutions.

Mycelium-based materials and the idea of growing structures *in situ* are being considered both as a new construction approach for building space habitats and as an alternative for creating furnishings and interior elements inside the habitat, in a controlled environment.

The main properties in favor of using mycelium-based materials are its insulative, acoustic, and fire resistance properties, the ability for waste-degradation, and self-healing and self-replicating potential. The use of mycelium also contributes to the efficiency of material transportation. In terms of utilizing mycelium for outer space architectures, with the possibility to grow materials *in situ,* there is no need to launch quantities of construction materials, decreasing the mass of the payload. Instead, what needs to be brought from Earth are spores and some nutrients, enabling the formation of components *in situ.*

In addition to the building efficiency, another potential advantage of utilizing mycelium for outer space architecture and living systems could address human psychological factors of sustained space travel, for example enabling astronauts to outfit their environments with mycelial components. We envisage that the different texture of various mycelium-based materials have a great level of tactility. Indeed, some studies suggest that tactility may be beneficial for the psychological comfort of astronauts [13].

Additionally, certain mycelium species are also edible, could have medical applications (within the development of cancer therapeutics) [25], and could also provide radiation protection (melanin-rich fungi) [26]. Other species are bioluminescent and can sense temperature, pressure and other chemical and physical differences [27]. There are myriad possibilities for the application of mycelium-based materials in architecture and space habitats. Therefore, many visions and scenarios are being researched spanning a large feasibility scale on how fungal-based materials can benefit human habitation in space: from arrival, to resources and infrastructures, to environmental adaptation and communication. Scenario methods are discussed in more detail in section 4.5.

The *Mycelium for Mars* session not only discussed the opportunities and potentialities of using mycelium but also the trade-offs and challenges that would be necessary to overcome in order to develop the vision into prototypes and architectural materials and components. During the talks, it was explained that the material functionality is dictated by the fabrication process. Growing mycelium is a resource-intensive process. It needs life-supporting conditions: the presence of oxygen, stable temperature, H_2O, a humid environment, and nutrients (usually plant husks or cellulose-based structures). Additionally, a lot of heat is required to bake the mycelium, to prevent further, uncontrolled development and creation of fruiting bodies. Therefore, there is a trade-off in terms of the amount of equipment and resources required for processes that provide the strength and functionality of materials.

Understanding the system metabolism is critical for the development of efficiently functioning space habitats and living habitation systems. It includes mapping of the specific waste streams: gas and water quantities required for synthesis as well as the end-of-life scenario in terms of how used mycelial elements could be broken down into new components. To be able to efficiently use mycelium for space applications, we need to maximize resource efficiency within the system's metabolism. One of the proposed solutions was the integration of waste streams into the growth process [14] such as recycling of water from the drying process.

In addition, adapting an ecosystem-based approach (material ecology), is to use the most abundant resource on the Moon or Mars – regolith. Despite the fact that mycelium-based composites have a great advantage in growing into bulk materials in a short period of time, to achieve the scale for human habit, extra aggregates could significantly reduce the nutrient and time requirements. Although mycelium cannot grow solely on regolith, the regolith could provide a structural mass, and with minimum quantities of the nutrients mycelium, can act as a binder, holding the regolith-based structure together [14].

There is still a substantial gap between commercially ready products and current fabrication methods of mycelial products and those that are required or desired for space-architectural applications. A steppingstone is needed between our current capabilities and the future mycelium-based space habitats, that are more achievable in the coming decade. The discussion around this topic led to questions about near-term mycelium applications for space. Some research questions are:

- Which additional applications can we research to enable us to test and validate the utility of mycelium in actual off-world conditions?
- How can we grow (mycelium) using minimal biomass and/or water and oxygen?
- How can we ensure the long-term robustness of the materials in extreme conditions?
- What are the construction methods that would enable minimal interventions in the habitat construction and maintenance process?
- It is possible to create real self-replicating and self-healing habitats?

4.3 Relations with the Natural in Space

A more permanent human presence in deep space, invites crucial discussions around the role of nature in sustaining human life, as well as the impact on wellbeing of humans on future deep space journeys, and the creation of liveable habitats on other planets that support human and non-human life in the long term. Human relations to the Natural are not only reflected upon within the Anthropocene, but further in relation to the nonhuman world. The nonhuman world is comprised of other-than-human living organisms (animals, microorganisms, fungi, etc.), the non-living and the various ecosystems present both on and off-world.

Diverse art, design, and science projects presented at the symposium showed the relevance of the bio-social perspectives with interdisciplinary and transdisciplinary projects that studied perspective shifts from human-centric to poly-centric. Poly-centric being the inclusion of humankinds' interconnectedness with the Natural, remediation of nature in the Anthropocene and in extreme environments, life-like reproducing AI systems able to create human habitats, and human-AI interdependence in future scenarios.

Humankinds' relation to nature on and off Earth has shown to be highly influenced by human-centric perspectives [28]. Past research into the creation of off-world human-made habitats included the design of controlled biospheres that are highly selective in choice of species and ecosystems, excluding what is considered undesirable and non-serving to humans [29]. This thinking has been continued into the more recent MELiSSA and Lunar Base 1 projects [6]. During the symposium, participants were speculating on 'What is nature in space?'

When humans bring living systems into otherwise controlled environments these systems have an ambiguous nature as they could either represent "nature" or the human control of it [30]. What might be considered as "nature" depends on the extent to which the living systems are allowed to evolve and adapt to new environments, and to what extent we adapt and control the environment itself. Therefore, questions about human relations emerged throughout the symposium during talks and discussions, some of which will lead future research. For example, is it a human-created and/or controlled nature? Is it designed as an evolving system that develops in relation to factors such as human behaviour, environmental resource availability, environmental changes? Can these evolving systems begin to create their own nature?

Research and artistic projects questioned the past perspective of a controllable nature and invited to be inspired by the human-caused Anthropocene to take new pathways towards complexity and inclusive futures of human existence also in space. Diverse artistic projects are exploring the remediation of Anthropocene environments by co-designing with living organisms. For example, mycoremediation has shown to successfully detoxify soil through fungal metabolism [31]. Following that natural process, fungal based burial suits were presented as a potential study for the use of human bodily wastes as part of a circular system that could be utilized within more extreme environments [32].

Presentations and discussions at the symposium highlighted explorations into co-designing and interfacing to drive poly-centric perspectives. They showed that the nonhuman world can inform, inspire, and drive research into travel and habitation in space towards healthy systems that coexist in a sustaining and evolving modality.

Specific projects addressed these relations through collaborations such as the *Human-Bacteria Interfaces* which were presented during the symposium. This project was specifically looking at microbe-human relations and the potential for one to interface with the other, potentially leading towards mutualistic symbiotic modes of being. It aimed to de-centre human agents and allow for a disassembly of established narratives of bacteria and microbes as inherently bad or harmful in their existence of highly complex, de-centred ecosystems. Ideation and prototype development was led by assessment of the ways in which microbial organisms sensorily and habitually engage with their surroundings, making potential nonhuman narratives part of the design and knowledge process. The designed interface used bacterial cellulose as a living medium to facilitate human-microbial interaction. In a modular structural system made from bacterial cellulose, textiles and glass, the interface allows for mutualistic co-creation of experimental architectural structures. The structure co-hosts humans and bacterial cellulose in an ever evolving, growing manner that is activated through signalling and supply of nutrients and shelter [33].

Growing and evolving habitats, especially in the context of spaceships, offers the potential of using so-called emergence engineering, a form of bio-inspired engineering that translates the behavior and systems of living organisms into an evolving form of AI. Self-replicating AI modules that are programmed with rules of termite architecture and replication procedures in relation to human spaceship population numbers were presented as example [34]. In a system of de-centralized swarm modules, AI can source material to replicate from their environment to build an exponentially growing spaceship structure that allows for replacement of the modules and metamorphic evolution of the overall AI swarm structure through growth, repair, and replication. In scenarios that envision such self-replicating modules for human habitats, a factor that needs to be considered is the growth of human occupancy in relation to the growing habitat structure. The life-like property of self-replication of AI and the relation to human reproduction invites the study of a non-human perspective of future habitat creation and co-dependency.

These projects challenge design and technology interventions that aim to facilitate a world of self-sufficiency for humans from the more-than-human world; and emphasize our interdependence and interconnectedness within a complex system of nature. The projects aim to move beyond the human centric idea of nature as an object to be controlled, tamed or mainly evaluated or included based on its value to us. The ever-evolving human relation to the natural on Earth and in space will continue to be challenged by socio-cultural perceptions and ever evolving technological possibilities. However, the presented projects drive futures that move beyond the narratives of what nature should be, based on human-centric ideas and the control of the nonhuman as humanity moves closer to establishing a permanent presence off-world [35].

4.4 Systems thinking

Throughout the whole symposium, emphasis was placed on the need for interdisciplinary and transdisciplinary methods to develop bio-futures. The guest panelists also emphasized the need to work together with industrial partners and policy makers, going beyond purely academic thinking. Even though, as one panelist pointed out “people are naturally territorial about the stuff they know and the stuff they do”. However, working together is about unlocking the collective intelligence of the group [36]. This process will require facilitation however, and needs to be economically viable, which is not always the case in academia.

Working across fields is difficult to achieve [37] but one way to enable this transdisciplinarity is to utilize systems thinking. Systems thinking can be defined as “a practice of seeing wholes and a framework for seeing interrelationships rather than things, for seeing patterns of change rather than static snapshots” [38]. There are different ways to approach this (and different scales) but there was an overall consensus of viewing transplanetary habitats as large dynamic systems, that encompass all subsystems within, such as the structural system, ECLSS (Environmental Control and Life Support Systems), power, logistic supply, communication, and data handling. Creating dynamic transplanetary habitats is crucial in highly unpredictable environments [39]. It increases the overall adaptability and resilience of the habitats over time. Such an approach includes conceiving the ECLSS as a bioregenerative system with dynamic and potentially evolvable properties.

During the panel session, an important distinction was mentioned: optimizing a system vs. satisficing a system (the latter being a combination of the words satisfy and suffice). Following in the tradition of the scientific method, in which we investigate variables in isolation, often subsystems are designed for optimization of a single parameter under pre-defined conditions, but at some point, we will have to satisfy a whole environment [40] in which performance variables interact with and are interdependent on each other [41]. This means preferring a system that isn't optimized for any one function but that has multiple pathways to solve problems at the same time, much like cell metabolism. Such *redundance* increases the resilience and longevity of a system.

Another important notion is that of systems integration - the consolidation of numerous distinct systems into one to simplify processes and reduce complexity. Systems integrations were presented holistically but also starting from a specific case or challenge such as using byproducts of chemical reactions. For example, fuel cells that convert hydrogen and oxygen (available as rocket propellant), into electrical power with the by-product being pure water available for drinking - is far more efficient than separate propellant, energy storage (e.g., batteries) and water storage systems. Having heavily integrated systems also reduces the need for back-up systems and spare parts for redundancy, since a failure of one system could be mitigated by others. Biological systems could integrate numerous systems and provide many benefits that would reduce mission complexity, launch mass, cost and overall risk. For instance, a versatile algae photo-bioreactor system could not only produce food and oxygen highly efficiently (negating the need for a separate oxygen production system and associated back-ups), but the organisms could also be engineered to produce bioplastics, bioadhesives or other useful chemicals or pharmaceuticals as required. Instead of needing to take every medicine that may be needed on a mission (with resupply for long-duration missions as medicinal efficacy degrades over time), bioreactors could produce pharmaceuticals as required - in addition to their other useful functions.

4.5 Speculative approaches and scenarios

Many approaches to the presented research were speculative, and science fiction was often quoted as inspiration to imagine possible futures in space. The methods - originating from the design approach - to develop these visions and turn them into concepts (and eventually high TRL applications) are [42]:

- Scenario building and speculative design.
- Material experimenting and rapid prototyping.
- Observing results on the small scale before going to larger scale to avoid failing in the very early stages of the process.
- Bottom-up approaches.
- Computer simulation

These speculations were sometimes more defined using scenario theory and the Futures Cone. The Futures Cone is able to define and detangle futures from each other by categorizing them into futures that are: preposterous, possible, plausible, the "projected" future, probable, and finally preferable future [43]. Speculative design critically examines the futures and not only prepares for preferable futures but also the undesirable, unexpected and unbelievable futures [43]. It is a way to open up the thinking process and suggest another way of looking at the future from various perspectives and to raise questions about them.

With the help of futures scenarios, the desired future can be built with existing tools and materials. Futures scenarios also prepare humans to confront the obstacles they may experience on their way to space and observe the critical turning points.

One way to develop those scenario's is to experiment with materials and learn from those experimentations as one presenter highlighted. It was explained that material experimentation is a way to deepen the understanding of the material behavior and understand the properties which leads to exploring all the possible usages and create more in-depth futures scenarios. The hands-on material exploration process is more about learning through the failures that happen during the development process as the material does not react as planned.

These scenarios were developed and presented by architects and designers showing through drawings and collages the possible future scenarios for life in space. Some presenters also tried to simulate how these futures will evolve with computer models. For example, there were talks about simulating the development and evolution of a spaceship during decades of deep space travel, but also simulations of social species interactions such as ants, bees, and termite colonies.

4.6 Considerations - Biological safety

Finally, the last key outcome of the symposium are considerations for biological safety. Indeed, using biology as an enabling technology for human exploration of space - sustaining orbital stations, and especially building habitats on the Moon, and Mars, is not coming without any constraints. There is a biosafety issue of bringing living materials (spores, bacteria etc.), and using engineered living materials in space. This is an issue particularly in the case of in-situ production of base materials, which may not be tightly controlled.

In order to avoid interplanetary contamination, all biological materials used for space applications would need to comply with planetary protection requirements for robotic or human missions and also with the current Committee on Space Research (COSPAR) human mission principles and guidelines [44]. In some cases, e.g the Moon, requirements ask only for a short planetary protection plan to outline intended or potential impact targets. In other cases, e.g. Mars, detailed documentation is required including a probability of contamination analysis, a bioassay to enumerate the bioburden, an inventory of the bulk constituent organics etc. [44].

On the other hand, the issue of safety and contamination works the other way around too (backward and forward contamination). It is important to make sure that astronauts, or in the case of using biological materials, the biological organisms, are not exposed to harmful, toxic environments. In case of any potential danger or toxicity, these issues should therefore be solved before progressing further with a mission (e.g. detoxifying Martian regolith). These issues may lead to the need for a detailed design of the whole process of creation of the habitat, where each step (including the choice of the site and site preparation) is carefully considered. The proposed solutions need to be tested in the intended relevant environment to understand how to progress the TRL, to ensure maximum safety, and the reliability of the mission. On top of that, working with synthetic biology and engineered living materials by itself also raises certain ethical aspects that should be considered [45].

5 Discussions

This section reflects on the talks, panel discussion, and informal discussions over the two days of the symposium. The panel discussion started with a debate concerning the increased use of biomaterials in architecture, and whether this might be emerging more from a biophilic or biomimicry design standpoint. It was mentioned that in the 60’s we were embracing synthetic materials but now we have a more sensitive approach to materials (especially considering environmental safety and personal health). However, researchers are also now aware that nature has already developed a variety of solutions to complex design problems that have evolved over time through natural selection. Studying and taking inspiration from such problem solving abilities is now well known as the biomimicry approach to design [11], [46]. All panelists agreed that the biological approach should come from a technical perspective of efficiency and redundancy and as such use frameworks (such as systems thinking described in section 4.4).

Moreover, if we connect the biomimicry approach to computational methods, we can start recreating and simulating natural systems and ecosystems. Some important aspects are the balance between carbon sources, sugars, and other nutrients within a system, which are being explored by many researchers at the moment and was evident across a range of presentations. However, it should also be noted that the complexity and chaotic nature of living systems cannot simply be replaced by computational systems such as Digital Twins.

To drive the field forward, the challenges that need to be overcome are: biodiversity and individual health, scale-up, but also our relations with the Natural. How can we ensure these aspects (biodiversity and individual health) are maintained during deep space missions? How do we allow other things to live in symbiosis with us? Do we need to control more-than-humans relations? How do we scale up whole ecosystems?

One panelist emphasized that monitoring and data gathering is vital, but creating a separate environment hosting different, less controlled systems, might be how we can “engineer” more resilient biological systems in space and on Earth. Both the MELISSA project and biosphere II were mentioned as both being at the more extreme ends of the spectrum, and that meeting somewhere in the middle will be our next challenge.

The discussion finished with a question from the audience on building more in symbiosis with biology versus moving into a more virtual world. The discussion highlighted that it is not so dichotomous, as even in a virtual world, the devices used to interact with the virtual are indeed still very physical. It was added that moving to a virtual world or platform is also still very social as people connect with each other and with biological elements such as food. Indeed, food is flooding our social media platforms, creating stronger relations between biological elements and digital worlds. This raised the question that maybe virtual platforms could also be a tool to communicate with organisms and plants. This notion has been researched by Sue Thomas [47] which she called *technobiophilia*, where we put the essence of nature into our technology. However, another panelist argued that proper communication between humans and more-than-humans has not yet been achieved and also might not be what we want to achieve. It was suggested that aiming to design and activate interactions as the first stage of exchange towards communication is the next challenge to tackle. Thus, while communications might not be the goal, based on the discussions on relations with the natural and systems, respect for biological elements might be a more appropriate approach.

Good quality communication across disciplinary boundaries also requires a common set of standards and methodologies, therefore a tool for gathering interdisciplinary research interests and outputs was suggested in the form of a database of biomaterials and their properties [48], [49]. Such a database would help facilitate the appropriate identification of materials for a given task and allow iteration between smaller scale scientific projects and larger scale architectural applications.

6 Conclusions

To conclude, the networking symposium gathered researchers and professionals together from many different disciplines and backgrounds. Even though the field of biosocial and biotechnical futures for transplanetary habitats is highly transdisciplinary, many talks highlighted the same challenges to overcome, and similar uses of biological research to address those challenges. There was a consensus on facilitating humanity moving into space *together* with ecology.

To develop bio-futures for transplanetary habitats, transdisciplinary research is, therefore, crucial. The fields of material science, biology, microbiology, architecture, aerospace engineering and systems design should be encouraged to work together in order to maximize the exchange of ideas but also including social scientists to challenge our relations with more-than-humans. A material database is one of the concrete future works that could enable this transdisciplinarity, but also events such as the BFfTH symposium to enable conversations around the topic. Further, the growth of multidisciplinary international networks such as BFfTH enables and elevates opportunities to find collaborators, support project developments, and access specialized expert knowledge. The symposium was a great success as the BFfTH SIG grew with new members being enthusiastic about the topic and new project ideas being developed across fields.

Acknowledgements

This research is funded by Research England's Expanding Excellence in England (E3) Fund and Northern Bridge Consortium as part of Arts and Humanities Research Council, and supported by the SIG Bio-Futures for Transplanetary Habitats.

BFfTH would like to thank all the speakers, panelists, and participants of the symposium for their contributions.

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