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Planetary construction with ISRU on Moon and Mars: Scalability and automation of the construction processes

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Ph.D. Program
SSD: ICAR/14–Architectural and Urban Composition

Final Dissertation

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by
Vittorio Netti:

Supervisor:
Prof. Giuseppe Fallacara

Coordinator of Ph.D. Program:
Prof. Marco Donato De Tullio

Course n°36, 01/11/2020-31/10/2024

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This thesis is dedicated to my parents, Lorenzo e Gloria,
and all the friends that supported me along the way
allowing me to spread my wings.

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ABSTRACT

Human exploration of the heliosphere (and beyond) is closely related to the development of the capability to use local resources.

Despite the trend that sees a progressive growth in the useful payload of the new generation carriers, establishing a constant human presence and growth in the volumes of buildings on the lunar and martian surface will be possible only through mastery in the use of materials offered by the surrounding environment. Building on (or below) the surface requires a deep knowledge not only of the properties of materials and construction techniques but also of the form factor of pressurized and non-pressurized constructions. The environmental conditions (and properties of the regolith) between the moon and Mars, although very different, characterize the need to automate the construction processes right from the exploration phase. This research aims to analyze the construction techniques of terrestrial and space structures to define an abacus of techniques and technologies for the efficient use of resources in situ, to structure a methodology of approach to the design of structures suitable for welcoming human crews on the lunar and Martian surface. and finally to validate the form factor of these structures through numerical techniques (FEM) and prototyping (AM) with the use of simulants. In the same way, this work will address the research gap in the current research, identified in four main topics:

- Scalability of extraterrestrial manufacturing and construction techniques
- Preservation strategies against environmental dangers for the mechanical equipment needed for the construction

- Reliability of the use of simulants and space environment conditions replication in earth-based testing.
- Robustness of automation protocols to enable autonomous construction

Those four research gaps, assumed from the most up-to-date literature analysis, are a central research topic to enable the continuation of the research on construction form factor and automation. Since reproducing manufacturing construction element manufacturing with all the different techniques considered would be extremely expensive in terms of time and resources, the analysis will mostly rely on scientific literature and results from previous testing. The scalability of the construction techniques will be assessed similarly, and testing will be conducted through simulations (FEA) and field testing at reduced scale.

INTRODUCTION

SPACE ARCHITECTURE: DESIGNING FOR OUR EXTRAPLANETARY FUTURE

Architecture is often formalized as a discipline that enables the transformation of natural spaces into a liveable and comfortable environment. Sometimes this meaning of architecture even influences our evaluation of the achievements of past civilizations: the Parthenon and Giza pyramids are perpetual landmarks that outlived the cultures that built them, and they still stand today as a manifesto of their creators' achievements. Since the neolithic era, humans have used architecture to expand and colonize territories at every latitude, transforming inhospitable environments into habitable ones. Today, we inhabit every corner of our planet and beyond. Even the most inhospitable continent, Antarctica hosts more than 4000 researchers every year in more than 70 different research bases. Humans also have been continuously occupying the Low Earth Orbit since 2001, thanks to the International Space Station (ISS).

Space Architecture ideas emerged together with visions of the human future in space envisioned by great minds before the technology level could enable such exploration in the 1960s with the first successes of the US and USSR space programs. Architecture is still influencing the direction of the built environment development for long-stay missions. Current applications of additive manufacturing in large-scale construction and automation processes for architecture on Earth, as well as utilization of traditional architectural concepts such as stereotomy, are influencing mission planning for the next generation of space habitats.

We are on the verge of a new era for architecture that will require a robust multidisciplinary approach to deal with the challenges of implementing unprecedented innovations in unforeseen scenarios. Space Architecture discipline is not only a crucial player for enabling these developments to ensure human multi-planetary future but also for achieving more sustainable construction practices on the planet Earth.

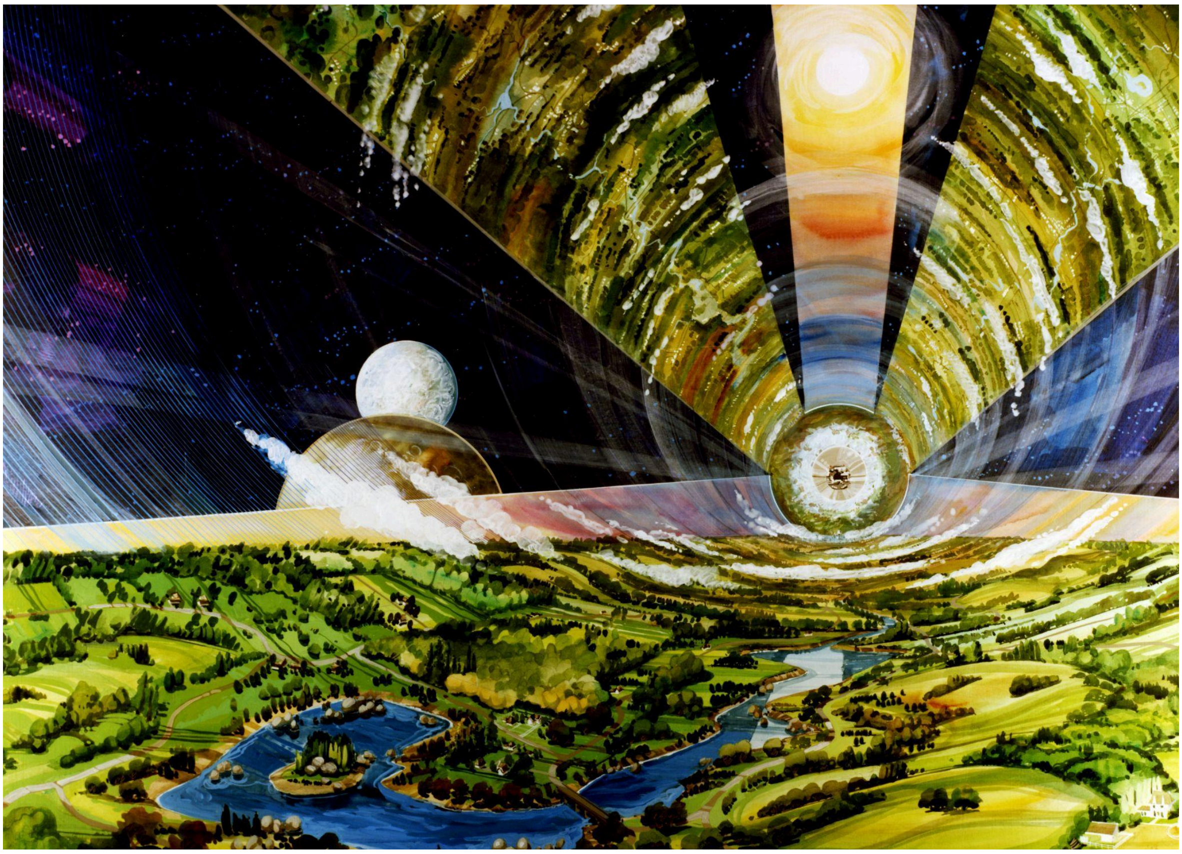
The idea of building and living beyond Earth presents multiple environmental demands and constraints that heavily impact the design process. Historically, architecture responds to specific differences in environmental characteristics such as temperature, access to resources, topography, and geological formation. When we cross the atmospheric limit, we access a virtually infinite number of unforeseen combinations of environmental characteristics with extremely low compatibility with human life. To design for space, we need to start with defining the goal of our travel because a short explorative trip or a self-sustainable surface colony requires very different design approaches. Connecting mission requirements with the design process involves the selection of assets specific to the mission and development of the Mission Architecture. Each asset brings new constraints and new capabilities or can cause new technological developments: the form factor of the International Space Station (ISS) modules is directly derived from the available space in the payload bay of the Space Shuttle. Today, we cannot reiterate that design since the STS (Space Transportation System, or Space Shuttle) retired in 2011.

The Mission Architecture generates design requirements and criteria that are used by Space Architects and engineers during the design process. These criteria are integrated with environmental constraints and other physiological and psychological requirements to produce assumptions that are useful for the development of architectural concepts: on the moon, for example, the day-night cycle is 14 earth-days long, which makes it difficult to rely on natural light for illumination.

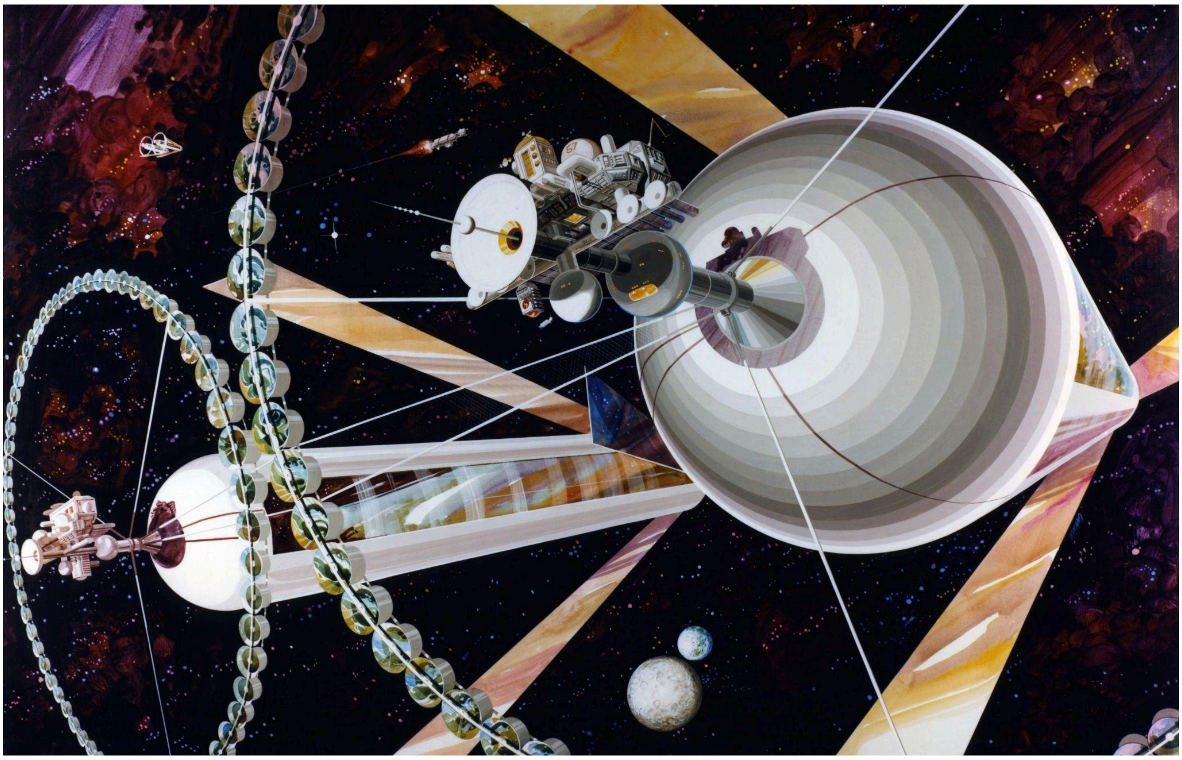
Reduced Gravity, radiation, low pressure - are just some of the aspects that space architects need to address. Gravity conditions and destinations are major determinants that can classify architectures beyond Earth. For the sake of simplifications, we identify three main categories:

- Orbital infrastructures (microgravity)
- Interplanetary spacecrafts (zero or microgravity)
- Planetary architecture (partial gravity)

These three categories coincide with very different human-centered design approaches. Orbital infrastructures and Interplanetary spacecrafts share the microgravity conditions, which eliminates the concept of up and down, forcing to rethink orientation, living volume, and perimeter. On the ISS, the node modules offer access to other modules placed in every cardinal direction. The volume substitutes the area as the main architectural design unit[2].



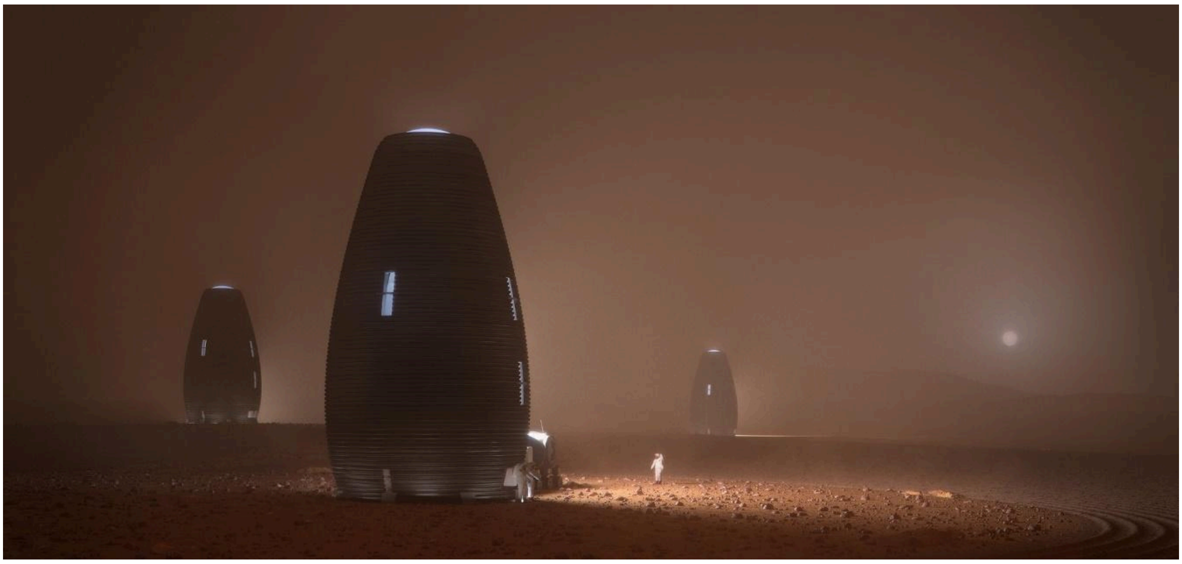
Rick Guidice, NASA, O'Neill cylinder space station concept, painting, 1972.



Rick Guidice, NASA, O'Neill cylinder space station concept, painting, 1972.

Surface construction is more earth-like: we experience at least some gravity gradient, allowing the use of some traditional architectural elements, for example, stairs. Anyway, a slightly different gravity level forces space architects to rethink those elements to fit the new conditions. The moon's gravity, which is around ⅙ of the earth's, may make it impractical to use the same ratio of tread to the riser in stairs as it is on Earth. Those conditions can pose serious design constraints but also open new capabilities, such as more efficient use of storage spaces enabled by the lower gravity[3].

In planetary architecture, the presence of an atmosphere also has a huge impact, resulting in some form of radiation protection or a lower pressure delta between inside and outside. On Mars, the presence of an atmosphere, although toxic for humans, allows wind cycles that shape and erode the dust particles, making the regolith (planetary dust) possibly less damaging for mechanisms and humans. On the Moon, in the absence of wind activity, the dust is extremely sharp and abrasive, posing high risks for any surface asset.



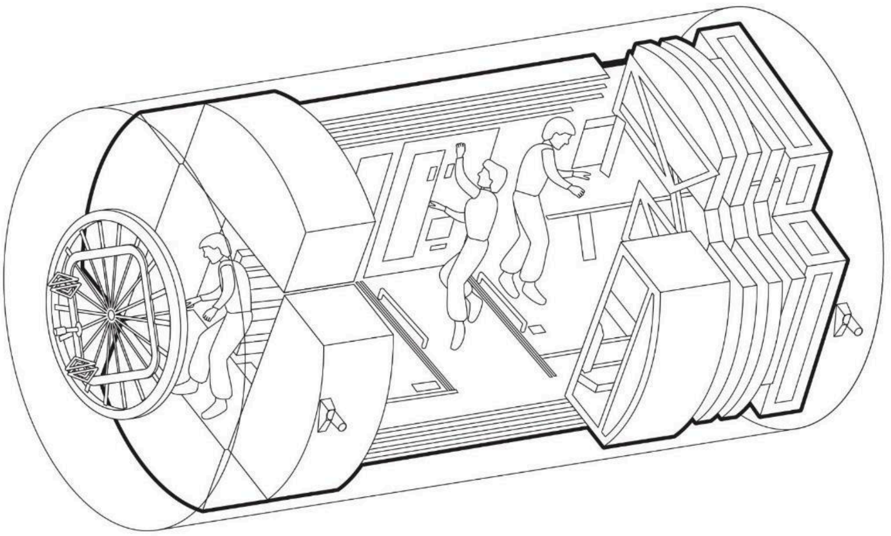
Marsha Habitat, AI SpaceFactory 2018 (Class III).

In addition, without atmospheric protection, the sunlight produces violent temperature changes between the night and day (+127 to -173 degrees celsius).[4]

To fully understand the technological span of Space habitats, we can rely on a simple classification created by Kriss Kennedy in 2002 in his paper The Vernacular of Space Architecture:

"Space habitats are categorized into three classifications. Class I is a pre-integrated habitat that is entirely manufactured, integrated, and ready to operate when delivered to space. Class II is a prefabricated habitat, which is space or surface deployed with some assembly or setup required. Class III is an in-situ-derived habitat in which its structure is manufactured using local resources available on the Moon or Mars[5]."

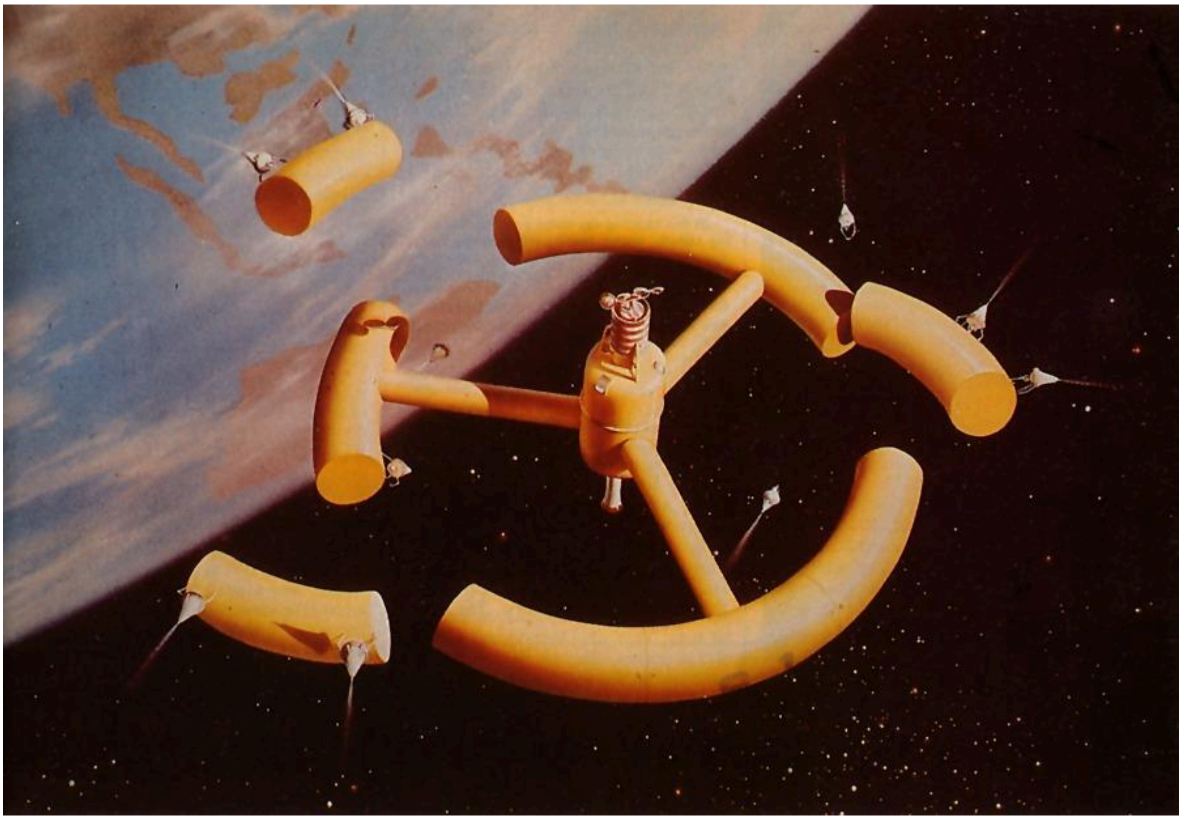
These three classifications are based on the manufacturing techniques and materials used for the construction. It is important to note that today we have examples of just pre-integrated and deployable modules in Space, while in-situ-derived habitats are still just a concept.



NASA, U.S. Laboratory Destiny schematics on ISS, 2015, (Class I).

All three categories are defined by their own limits and capabilities. While Class I modules usually provide high usability with practically no additional outfitting work required, they need to be built on Earth and transported in space. This definition forces the form factor (and their weight) of such modules to comply with the shape of a Space Transportation Vehicle that is selected for the mission. Class II modules are a relatively new concept, first developed by NASA in the 1990s, but derived by previous concepts such as the Inflatable Toroidal Space Station proposed by Wernher von Braun in the 1960s. The main advantage of a deployable module is a possibility to fit it within a payload shroud and expand in a much larger volume when it is deployed in space. On the contrary to Class I modules, Class II ones require some human and/or robotic work to outfit the interior elements after the deployment. Today we have just one example of this type of module human-tested in space: the BEAM module developed by Bigelow Aerospace and docked to the ISS in 2016.

While other kinds of inflatable elements have been tested in Space, they were mostly technological demonstrators for in-space infrastructures.



Inflatable Modular Space Station, Wernher Von Braun, 1945

When we talk about class III modules, we enter into the realm of advanced future space concepts. In-situ-derived structures are probably the technological development that shares the most with terrestrial architecture, transforming the natural resources in construction material. Regardless of the architects' experience maturity with this type of construction, building on a planetary surface with In Situ Resources Utilization (ISRU) pose some extreme challenges: designing and landing an entire family of automated construction assets similar to terrestrial construction vehicles, preparation of a construction site, collection and processing of the construction material and ensuring that buildings are structurally sound. These considerations are just some of the aspects that we need to rethink for an extraterrestrial environment.

Once construction techniques and environmental constraints are addressed, a fundamental aspect of the design process is human-system integration. Space Architects have to consider the impact of extreme conditions on human mental health and propose design practices that can be used as countermeasures to these factors. Isolation and alienation are common psychological conditions for astronauts in long-term space missions. Decades of the Low Earth Orbit occupation provide valuable lessons about the consequences of these factors. In addition to orbital experience, we use built on Earth facilities for evaluating impacts of psychological conditions of surface missions on Mars and on the Moon. Analog bases built in the most inhospitable places around the globe such as the MOAB Desert in Utah and Antarctica, reproduce with different degrees of realism Moon or Mars outposts, where trained astronauts and researchers are involved in simulated missions that can last more than two years[6].

The Mars Society, Mars Desert Research Station, 2019. Ph. Vittorio Netti.

These studies are extremely important to develop effective countermeasures for mental health decay that the next generation of astronauts will experience during their first planetary missions. In this regard, Space Architecture can count on the latest technological developments such as biosensors and virtual and mixed reality to lessen the negative effects of isolation and confinement on human productivity and livelihood.

The complexity of the topic of Space Exploration and the survivability of humans in such extreme conditions pose a set of great challenges for Space Architects. As we discover the space around us, we need to rethink most of the archetypes that we have developed in thousands of years of human history to enable an interplanetary future for the whole of mankind, and architecture is a fundamental piece of this mosaic.

1. IN SITU RESOURCES UTILIZATION: AN ENABLER FOR EXTRATERRESTRIAL CONSTRUCTION

Validating ISRU is a fundamental asset to enabling the future of space exploration. The current NASA Artemis plan identifies ISRU as one of the most important fields of development for the next missions on the Lunar surface. Agencies such NASA and ESA are currently working on this topic involving several partnerships with industry and academia. Mastering ISRU processes is not only a primary scientific objective, but also the main enabler of a new space economy based on the exploitation of extraterrestrial resources. In the Space Resources Strategy document [7], ESA estimates that the market for space resources will value at €170 Billion by 2045 supported by a connected workforce of 1.8 million workers. However, the need for ISRU development comes as an answer to a specific set of challenges that arise with the advancement of human space exploration capabilities:

- Cost: The cost of transport of payloads is high. Astrobotics LLC, an American company selected by NASA for the Commercial Lunar Program, rates the cost of transport to the Lunar surface at $1.2 million kg, while NASA, for the Curiosity rover, has established a cost of $2.87 million kg to Mars.
- Volume and mass limit: While there are multiple super heavy lifters in the advanced development stage (SLS, Starship), the current payload capability of the most reliable launchers is too limited to build a cost effective permanent or semi-

permanent outpost on any celestial body in the Heliosphere.

- Operational complexity: Landing a habitat on the Moon or Mars is extremely complex and will require work with a high number of constraints: survivability to launch forces, transportability on the planetary surface, maintainability, etc.

For those reasons, ISRU is getting a bigger role in the mission design requirements of space agencies and private companies working on the next generation of space programs assets.

There is a wide range of planetary resources that we can make use of, as will be explained in section. Water, construction materials, metals, glass and even fertile soil can be made available using the right processes. However, for the purpose of this research, this paper will concentrate specifically on construction materials that could be used to build planetary outposts on the Moon and Mars due to the rich literature coming from decades of research in this field. More precisely, this paper will consider technologies that are compatible with additive manufacturing processes and the more promising construction techniques in different stages of development.

As stated previously, there are three types of entities involved in the research of planetary construction: Space Agencies, academic institutions and private companies. Each one plays a different role throughout the lifecycle of research: Space Agencies set the scientific objectives and the utilization framework of ISRU technologies. Academic institutions explore new research concepts and set the basis for the technological development operated by the private sector. Private companies in turn facilitate a cost-effective and quick advancement of research into technological progress, fosters competitiveness, and by extension enables the growth of the space industry. The distinction between the different roles is a great strategy to speed up the development and implementation processes, yet it tends to leave some unaccounted gaps in the research due to the multiplicity of actors involved.

1.1 ISRU for construction of surface assets

In order to understand the planetary construction technologies, it is important to first understand what assets are required to build an effective permanent or semi-permanent outpost on the Lunar or Martian surfaces. The analysis of the planetary construction techniques is largely driven by the construction capabilities needed to achieve a sustainable planetary infrastructure. By analyzing case studies and development plans at various scale (small temporary outpost to self-sustainable large-scale city), common assets that are essential to host and organize human activities on the Lunar and Martian surfaces can be found and organized into the following two broad categories:

- Shelters
    - Pressurized (Habitats, laboratories, greenhouses)
    - Un-pressurized (EVA shelters, storage, dust free zones)[11]
- Infrastructure
    - Landing pads (blast shielding, equipment storage, protection berms)[10][11]
    - Landscape and navigation (Roads, Tunnel linings, dust mitigation structures)[10]
    - ISRU facilities (extraction machinery, transformation and processing facilities)

- Energy production (cables, generators, solar panels, energy storages)

Of the assets above, it is important to extract the ones that are currently possible to manufacture using In Situ materials on the Moon and Mars using available or next-future technologies with a TLR (technology readiness level) between 2 and 3.

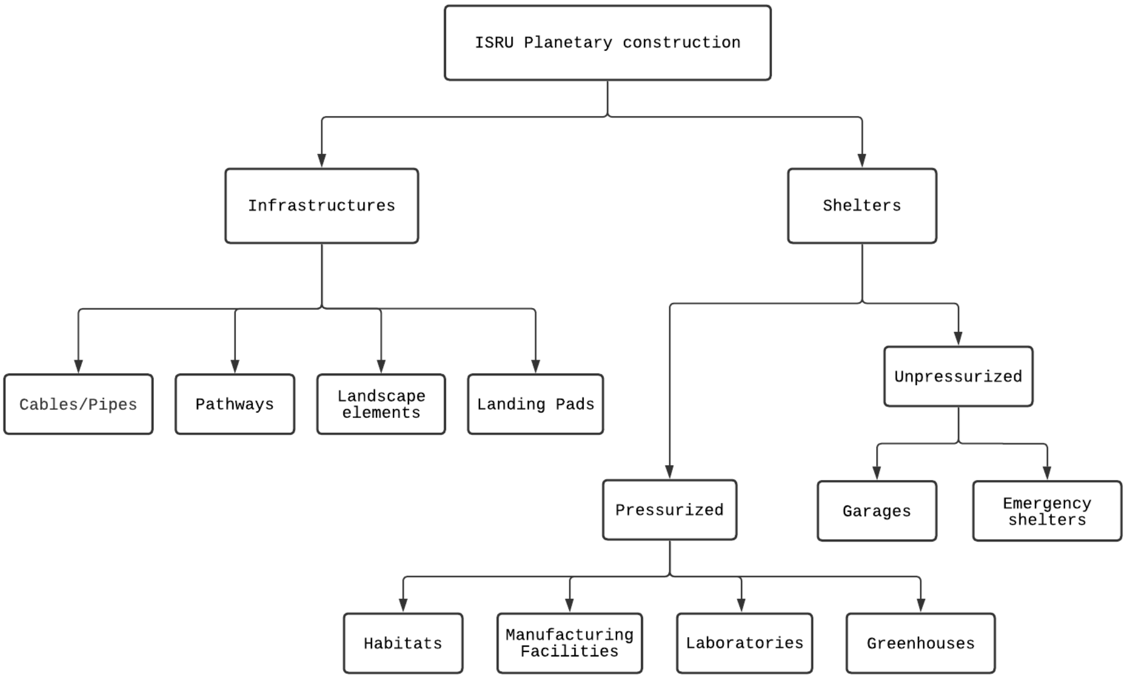


Fig.1 planetary assets diagram

In Situ Resources for planetary construction are compatible with structural engineering purposes with low technological requirements. For this reason, and in addition to the concept of prioritizing the challenges of construction techniques, an important distinction is made between what can and cannot be built with current and next generation ISRU technologies. The high costs associated with transferring payloads to the Lunar and Martian surfaces means transporting Class 1 habitats, or hard shelf structures is high, unsustainable, and inefficient if the goal is to establish sustained human presence [15]. The goal is to focus on the technological development of structures achievable in a feasible timeline. Even if the literature on advanced manufacturing capabilities with ISRU on theMoon and Mars grow constantly [12] building incremental and feasible development timeline aligned with the most recent space programs, requires prioritizing techniques compatible with pressurized and unpressurized shelters, roads,and landing pads over highly technologically advanced assets such as energy production,cabling and other elements that could be more efficiently transported from Earth. An analogy to this process can be seen when looking at Earth-based construction: Even the most advanced construction techniques involve both prefabricated and In Situ manufactured elements.

1.2 Available construction materials on moon and mars

On Earth, “in-situ” refers to the use of materials from local sources of Ordinary Portland cement-based concrete, including sand, gravel, Portland cement, water, and wet and dry additives. On the Moon and Mars, "in-situ" refers to inorganic materials extracted from the planetary surface to be used as the basis for the cementitious materials used for the construction as well as binders extracted from the same materials [11]. ISRU construction therefore involves extraction of Lunar and Martian regolith to form the bases for the aggregate as well as the binding agent in a planetary cementitious material [11].

Regolith, or planetary soil, is the product of billions of years of meteor and micro meteor bombardment of the Lunar and Martian surface [9]. This has created a fine, well-graded material which can be up to 15m deep [10]. Lunar regolith is abrasive and can rapidly damage mechanisms and seals due to its angularity and high glass content [13], while Martian regolith has been smoothed by atmospheric events such as sandstorms in a process similar to the one that lithic material experiences on Earth. These properties give the regolith its unique and distinct characteristics but also creates a significant challenge for the research on planetary construction. The scarcity of original material to conduct the research creates gaps in the research that are difficult to fill even when using materials replicated to have some of the properties of the real regolith such as simulants, which are regolith-like material derived from terrestrial materials. In the case of the lunar regolith analysis on the lunar regolith is still being conducted on the 382 kilograms of Lunar soil and rocks obtained from the Apollo missions [10]. Meanwhile for Mars, at the time of writing, research can only rely on terrain analysis conducted by generations of rovers and surface probes. A first sample return mission from Mars is planned in 2026 [17].

Fig.2 Lunar and Martian Regolith composition

Therefore, this leaves simulants to be the best available so far to conduct experimental research on Earth with new construction techniques. Early experimental research created simulants by combining, melting, cooling then crushing oxide or carbonate reagent powders in proportions which matched returned Apollo Samples [10].

Due to the limits in the amount of Lunar regolith samples brought back from Apollo missions as well as the lack of Martian regolith samples, manufacturing experiments have relied on simulants. The various number of tests and experiments performed on simulants and samples across the decades and the diverse nature of the research groups conducting research from a wide range of angles using varying range of equipment and tools and while deploying different methodologies of analysis have produced a great but inconsistent amount of data. The challenges in such research manifests in addressing issues related to the following:

- **Properties**: One of the main challenges when conducting such experiments is that in the hard vacuum of space, particles on regolith surface are lost, resulting in extremely high surface cleanliness thereby increasing electrostatic and van der Waals forces between contacting particles which increases apparent cohesion and resulting in Lunar regolith having the consistency of wet beach sand because of these effects [18]. As more sophisticated trials are developed using prototype line equipment in a simulated Lunar environment, simulants which accurately reproduce regolith geotechnical properties will be critical to assessing the suitability of regolith handling and processing equipment [10].
- **Context of trials:** Another challenge of studies and trials for small scale ISRU based construction using additive manufacturing is that Lunar gravity is extremely difficult to simulate, as such most trials were conducted in air and few trials simulated the Lunar vacuum [10]. Aircrafts following parabolic flights can provide

the medium required to conduct research trials, however access is limited and expensive [10].

  - For mare simulants, it was found that sintering temperatures could be reduced by approximately 100c for a sample sintered in a vacuum compared to sintering in air, to produce a material with the same compressive strength. Voids coalesce and migrate to the surface of mare material more rapidly in a vacuum than in air, which results in greater densification [10].
  - For the Lunar trials, the majority of simulants used for Earth-based trials are mare-like (low alumina content), however, more trials need to use high-mare regolith simulants resembling polar highland regions where future Lunar bases will most likely be built [10].

- **Particle Size Distribution**: Particle size distribution (PSD) is another important factor for sintering and additive manufacturing. Challenges in using simulants for Earth-based trials would need to have PSD that would resemble that of real Lunar / Martian regolith. Simulants are usually crushed from rock, and by screening and successive crushing [10]. Therefore, the simulants that have been used in Earth-based trials have a narrower particle size range than the Lunar average and a lower proportion of the very fine particles[10]. Real regolith formation by meteor impact produces extremely angular fragments and agglutinates which affects flowability, packing density, apparent cohesion, and abrasion [8][20].
- **Form factor of the manufactured elements:** Machinery used for additive manufacturing has an inherent relationship with the materials used for such

> machinery, and in turn, materials used for AM process have intrinsic characteristics that may constrain it used for specific geometries. It is however, possible to isolate the material specifications from the manufacturing standards without unforeseen issues arising as long and the materials and methods fall into known classes [21].

Another challenge is that materials required for ISRU construction are found in different scattered areas and should not be expected to be in a single location. Therefore, producing a significant amount of a desired resource means that a large area would need to be covered for harvesting [14]. On planetary bodies such as Mars and the Moon, scattered resources call for a mobile ISRU plant, which can move over the surface to a desired location to harvest a resource, and thereby “bring the process to the resource” instead of bringing the resource to the process” [14]. This is advantageous compared to moving all the material to be processed, especially when one considers all the round-trips that haulers have to take. At low-gravity planetary bodies,mobility is relatively low-cost compared to Earth. For ISRU to be attractive, the mass of the material process must be significantly more than the mass of the ISRU plant that is used to extract it [14].

Composition and characteristics of regolith changes across the surface of the planet. When thinking about machinery that will be used to extract it, the machinery will need to be either specific to the characteristics of the landing site as well as the resources expected to be extracted at that location or adaptive to deal with different regolith compositions it may encounter. In addition, machinery will need to sustain long working cycles in complete autonomy within clouds of abrasive regolith. Therefore, the diversity of Lunar/Martian assets will require deployment of different technologies at the same time. The robustness of construction hardware as well as the diversity of environmental conditions manifest in a gap in the current technology and research. A metric to compare and evaluate different available technologies while addressing the differences in the data presented needs to be established.

1.3 ISRU construction technologies

Reviewing the current available literature, numerous regolith aggregation methodologies in various stages of development can be identified. The techniques taken into consideration are characterized by varying technological approaches to the regolith aggregation, including divergent challenges and requirements. Five distinct approaches are identified [10].

- Radiant Sintering
- Microwave sintering
- Cast regolith
- Direct sintering
- Additive manufacturing (FDM)
- Regolith Fiber

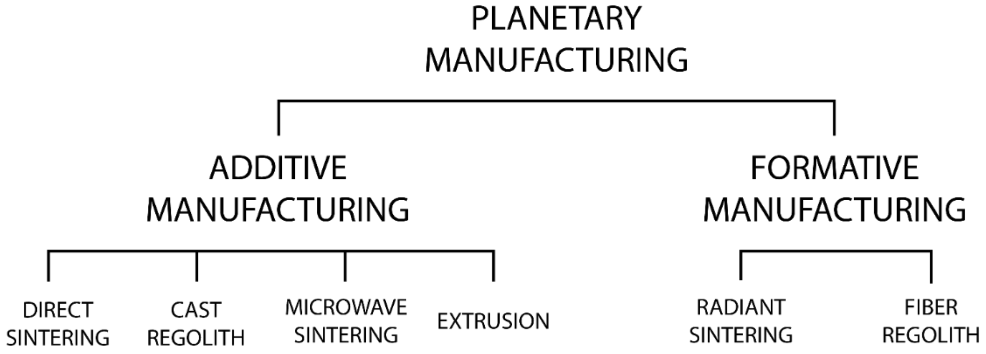


Fig.3 Map of the Planetary Manufacturing Technologies

Radiant furnace sintering: Furnace sintering is a thermal process designed to bind particles into a solid without complete melting of the material. It's an ancestral technique on which we manufactured bricks and pottery. It is particularly adapted to formative manufacturing and it is characterized by two main phases: cold pressing of the raw material and ramping of the temperature in the furnace for the sintering phase. The final sintering temperature allowed by the furnace can produce different levels of particle cohesion and therefore mechanical properties of the final piece. It is particularly suited for the manufacturing of discrete elements where the consistency of the mechanical properties is a fundamental factor.

Microwave sintering: Microwave sintering is one of the main alternatives to furnace sintering. This technique uses electromagnetic waves with radio frequencies between 300 Mhz and 300 Ghz to heat up different materials according to their dielectric properties. At the contrary of the Radiant furnace sintering, it's instead suitable to produce large elements and it is characterized by significantly lower power requirements. A critical factor is the difficulty to control the consistency of the heat distribution, which can lead to residual stresses and thermal runaway. Planetary construction has a possible role in the sintering of roads and slabs which can help to mitigate the displacement of the regolith.

Cast regolith: Casting involves heating the regolith until the particles are fully melted above the liquidus temperature. This process can produce extremely dense and strong materials which are classified in the glass spectrum. For this reason, cast regolith is even suitable to create pressurizable structure. It is a technique very well suitable for forming manufacturing to create strong and dense structural elements at the price of a very consistent manufacturing environment. With cast regolith, small heat variations during the manufacturing process can produce elements with mechanical properties unsuitable for the original purpose. Also, the cooling process needs to follow the same strict conditions.

Direct sintering: Direct sintering is identifiable as a variation of radiant or microwave sintering in which the material is sintered in place. For this reason, this technology is particularly suitable for infrastructural construction such as roads, landing pads and dust mitigation structures. For these applications, the penetration depth of the energy is difficult to control especially in the extreme lunar conditions.

Additive Manufacturing: Additive Manufacturing (AM) for construction, or additive construction, is a proven technology for earth-based applications. AM or more precisely AAC (Automated Additive Construction) is considered more of a process than a technology since it can be applied to most of the techniques already cited. The process mainly refers to the extrusion-based method whereby a mobility system (gantry, robotic arm, a crane, etc) is used to position a printing nozzle (extruder) in three dimensions to extrude a bead of cementitious material process for local resources, or in situ [11].

The melted or sintered material is released on a specific path and in consecutive layers. Methods of additive manufacturing used to sinter or melt regolith without the need for additives or binders include Powder Bed Fusion (PBF), Laser Engineered Net Shaping (LENS®), and Fused Deposition Modelling (FDM) [10].

Regolith Fiber: The idea of regolith fiber is relatively new and has many similarities with the glass or basalt fibre production on Earth. It is characterized by a very high tensile strength and suitable for many structural purposes such as tensioning cables. The production of the fiber starts with regolith heating and melting to a specific viscosity before the liquidus point of the material. The melted mass is then extruded through an orifice plate and winded on a drum where it is stored until it will be used in the construction process on site [19].

1.4 SCALABILITY OF CURRENT AND NEXT-FUTURE CONSTRUCTION TECHNOLOGIES

The scalability of ISRU construction techniques is a key factor to enable the technological readiness needed for extraterrestrial building. Given the cost factor of full-scale construction testing, the most effective strategy is to make use of the experience of private actors that can enable the technological transfer to the space sector. Additive manufacturing in construction is a strategic asset for earth-based construction as well. Mastering this technology can lead to a more sustainable and efficient way to design and build. We can list some of the advantages of this technique:

- shorter construction time
- less risk for human workers

- enabling new form factors
- reducing the environmental impact of construction processes
- enabling construction in remote and inaccessible environments
- partially and fully autonomous construction
- faster reconstruction time in response to natural disasters
- reducing building processes complexity

Due to the attractiveness of these innovative construction techniques, the additive construction manufacturing environment is already populated by many different private actors in competition to achieve full refinement of this technology. Some of those companies have already started R&D projects that include extraterrestrial construction, often supported by national space agencies:

ICON: Starting from the concept of Contour Crafting, ICON has become a prominent player in advancing 3D printing, additive construction and associated technologies including developing its own proprietary 3D printing robotics, software, and advanced building materials. ICON's broke ground in 2018 when it delivered the first, permitted 3D-printed home in the US, and later when it further expanded its portfolio to include 3D printed community of homes in Mexico, 3D printed a series of homes for the chronically homeless in Austin, TX, partnership with the Defence Innovation Unit and United States Marine Corps to train Marines to operate its technology, and a complete a field demonstration print at Camp Pendleton. ICON's advanced expertise in 3D printing technologies has awarded ICON different partnerships with BIG, SEArch+, and NASA's Marshall Space Flight Centre in Huntsville, Alabama, has allowed it to expand on the depth and breadth of its expertise in research and development. ICON's project Olympus is a demonstration for 3D

Printing analog habitat for long-duration human missions to Mars. ICON was able to demonstrate a possible full-scale additive construction system that could print infrastructure on the Lunar surface by testing lunar soil simulants with various processing and printing technologies [22].

Fig.4 Project Olympus, ICON 3D and NASA, 2020

APIS CORE: Apis Cor is another important player in 3D printing and additive construction. Their robot, Frank, is small, mobile, and easy to operate. Frank is capable of printing buildings up to two stories tall of an unlimited square footage. Apis Cor not only demonstrated excellence in terrestrial applications of additive construction, but it also aspires to become a leader in building beyond Earth [23]. Through collaboration between Apis Cor and SEARch+, Apis Core became a finalist in the 3D-Printed Habitat Challenge organized by NASA. In this challenge Apis Cor was able to construct a foundation slab without human intervention. The slabs were evaluated and tested for strength, durability, and material composition [23].

Fig.5 Apis Cor 3D printed habitat, Apis Cor, 2019

CONTOUR CRAFTING: Contour Crafting ® CC is the main player in the additive construction technology that influenced every AC technology that came after it [11]. Contour Crafting CC has been used to build structures from different materials (gypsum, Ordinary Portland Cement-based concrete, sulfur concrete, and ceramic slurries at shapes continuously flowing bead of construction material, providing structural consistency and a more appealing aesthetics [11]. Contour Crafting ® CC has advanced the endeavor of 3D printing construction to facilitate fabrication of extraterrestrial habitats using construction systems that exploit in situ resources, such as using lunar regolith as a material. By using Selective Separation Sintering (SSS), Contour Crafting ® enabled the construction of physical structures in space and won first place in the NASA In-Situ Materials Challenge. Since SSS is a powder-based process that works in zero gravity, Contour Crafting ® has proved its efficient use in the fabrication of spare parts and tools and this process was demonstrated on the International Space Station [16].

ACME project: Additive Construction with Mobile Emplacement is a NASA technology development project based on contour crafting that seeks to demonstrate the feasibility of 3-dimensional printing of surface structures on planetary materials for construction[11].

Additive manufacturing for Earth construction has the potential to become the full-scale testbed for extraterrestrial AM construction, especially with regards to the validation of machinery design and reliability of the processes.

Mastering the ISRU for construction is fundamental to enable long-duration, stable presence on the celestial bodies of the stratosphere, and the relatively low levels of technological readiness pose some challenges in achieving the necessary knowledge of the timelines of the most recent space programs. The technological transfer from Earth- based construction AM, is still possible to reduce the development and validation time, but this process needs to achieve higher levels of integration within the academia, the space agencies and the industry. The natural complexity of a multiple-actors technological development risks leaving open research gaps that would need to be addressed before starting in situ testing.

2. A PATH FOR DEVELOPMENT OF ISRU CONSTRUCTION TECHNOLOGIES

Establishing a sustained human presence on the Lunar or Martian surface depends on our capacity to leverage local resources effectively. Although there is an upward trajectory in the development of advanced carriers that can transport more payloads to the Moon and Mars, either through larger payload volume or increased frequency, harnessing local resources instead of transporting materials from Earth presents a more efficient and cost-effective solution for maintaining human presence. This becomes particularly crucial in the context of extracting and utilizing materials for planetary construction.

Over the past decades, the additive manufacturing industry has grown steadily. This progress allows for innovative construction techniques using additive manufacturing technologies in tandem with In-Situ Resource Utilization (ISRU). Concurrently, significant advancements have been made in material science. Simulants that closely mimic Lunar and Martian regolith, based on our current knowledge, have been employed to advance experiments testing these technologies and techniques. Many experiments have been conducted to examine various aspects of this issue, ranging from construction techniques to material behaviour under diverse conditions. Although these experiments could theoretically and practically share overlapping objectives, they are typically conducted for a specific set of goals, leading to different experimental conditions. This variability makes comparability of collected and reported data for scientific analysis challenging as it hinders the establishment of a benchmark that could serve as a foundation and a reference point for producing comprehensive and reliable results.

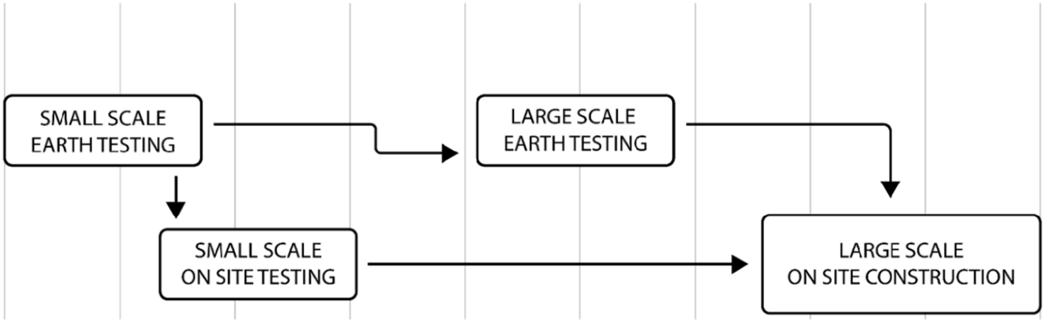


Fig.6 Proposed strategic objectives timeline

One of the outputs of this thesis is a proposal testing standard for planetary construction technologies and materials using ISRU. This proposal holds importance on multiple levels:

- It establishes a basic benchmark against which experiments can be conducted and compared, thereby eliminating numerous variables that could obscure specific findings.
- It serves as a stepping-stone that can be further developed as more data is gathered and additional conditions are required.
- Given the diversity in potential experimental objectives, this metric is adaptable. The proposed standard can distinguish between basic experiments conducted to test technologies where vacuum or microgravity conditions may not be crucial for the objectives of the studies, and those where such conditions are necessary.

2.1 Machinery and technologies

Experiments conducted for research and testing in planetary additive construction using

In-Situ resources generally fall under two broad categories of objectives:

- Technological Testing
- Materials and Additives Testing

While experiments typically align with a broader objective, they also contain specific sub-objectives that can alter the parameters and variables of the experiments. The experimental focus may centre on controlling for certain variables, while considering others as unnecessary or irrelevant. Listed below are some inputs and parameters that could influence the results and findings:

- Parameters Associated with Category 1 (Technological Testing) Experiments
    - Type of technology employed.
    - Technical specifications of the utilized technology, such as power, wattage, operating temperature, etc.
    - Exposure to the elements and operating conditions, including controlled vs. uncontrolled environments, temperate vs. extreme environments, pressurized vs. non-pressurized conditions, and the presence of microgravity or a vacuum.
- Inputs/Parameters Associated with Category 2 (Materials and Additives Testing) Experiments
    - Type of material used, be it original regolith or simulants.
    - Additives to materials, including their type and percentage composition.
    - Requirements for pre-processing and/or post-processing of the material used, if any.

Given the above, the challenge of comparing any two experiments becomes apparent. This necessitates a proper classification of variables to uphold the rigor of the experiments in terms of comparability with other experiments and ensure the relevance of their outcomes within the broader framework of planetary construction research.

Numerous manufacturing technologies for In-Situ Resource Utilization (ISRU) construction show promising results for construction using Martian and Lunar regolith. Each technology employs different processes to produce construction materials and mass for infrastructure and habitats. Not only do these technologies offer unique opportunities and limitations, but the characteristics of their outputs also vary, affecting their feasibility in the context of Martian and Lunar environments. Additive, Subtractive, and Formative technologies have all been considered for construction on the Moon and Mars. Their success is largely contingent upon their ability to utilize in-situ regolith, which is abundant on both celestial bodies. However, the list of processes below, which involve the use of sintered or melted regolith, have proven particularly cost-effective and robust [24].

1. Radiance Furnace Sintering

Radiance Furnace Sintering is a thermal process designed to bind particles into a solid without completely melting the material [24].

2. Microwave Sintering

As an alternative to radiance furnace sintering, Microwave Sintering is another thermal process that utilizes electromagnetic waves with frequencies between 300 MHz and 300 GHz. Materials interact with these frequencies and absorb heat based on their dielectric properties [24].

3. Cast Regolith

In this process, regolith is heated until the particles fully melt, surpassing the liquidus temperature. This procedure produces dense materials that exhibit strong resistance to abrasion [24].

4. Direct Sintering

Direct Sintering is a variation of radiant and microwave sintering in that the material is sintered in place [25].

5. Additive Manufacturing (AM) for construction

Often referred to as additive construction, this extrusion-based method uses a mobility system—such as a gantry, robotic arm, or crane—to position a nozzle that extrudes a bead of cementitious material in successive layers, following a specified path [26].

6. Regolith Fiber

This relatively new process bears similarities to the glass production technique on Earth. Fibers are produced by heating and melting the regolith to a specific viscosity before reaching the liquidus point of the material. The molten mass is then extruded through an orifice plate and wound onto a drum where it is stored until used [28].

7. CNC Machining

CNC (Computer Numerical Control) machining is a type of subtractive manufacturing where objects are created by progressively removing material from a solid block or sheet. This process is controlled by a computer and makes use of CAD (Computer-Aided Design) and CAM (Computer-Aided Manufacturing) to create and instruct the CNC machine, respectively. The major processes in CNC machining include turning, drilling, and milling, all aimed at removing material in accordance with a 3D model [28][29][30].

8. Laser Cutting

Laser cutting is a subtractive manufacturing technology that uses a high-power laser beam to cut or engrave materials. The process works by directing the laser beam at the material, which then either melts, burns, vaporizes, or is blown away by a jet of gas, leaving an edge with a high-quality surface finish. Laser cutting is typically used for cutting sheet metal but can also be used for cutting materials like plastics, wood, and ceramics. It’s particularly known for its high precision and accuracy, making it a common choice for detailed work. The laser cutting process is controlled by a computer program, often in conjunction with CAD software for designing the end product [28][29][31].

9. Electric Discharge Machining

Electric Discharge Machining (EDM), also known as spark machining, is a subtractive manufacturing technique that uses electrical discharges or sparks to remove material from a workpiece. This process takes place in a dielectric liquid and involves no direct contact between tool and workpiece, thus eliminating mechanical stress. EDM is especially effective for hard materials and complex shapes and requires the material being machined to be electrically conductive. It’s frequently used in industries requiring high dimensional accuracy, such as mold-making [32].

10. Others

As research progresses, new technologies, materials, and additives are developed. Although most of the current capabilities fall within the aforementioned categories, a flexible research framework should accommodate future implementations.

2.2 In Situ Materials and Simulants

As outlined in the previous section, materials research plays a pivotal role in the advancement of extraterrestrial construction. Typically, the scarcity of regolith samples - such as Lunar regolith - or the absence of retrieved samples altogether, as in the case with Martian Regolith, makes the utilization of this limited material for testing and experimentation impractical. Consequently, leading space agencies, private corporations, and research institutions have turned to rely on local material simulants. These simulants aim to replicate the real samples, embodying the geotechnical, mechanical, and chemical properties of the regolith based on data obtained from studies carried out on retrieved samples, or from information collected and analyzed using planetary rovers and transmitted back to Earth.

Acronym	Name	Body	Country
C2	C2 Carbonaceous Chondrite Simulant	Asteroid	United States
CI	CI Carbonaceous Chondrite Simulant	Asteroid	United States
CM	CM Carbonaceous Chondrite Simulant	Asteroid	United States
CR	CR Carbonaceous Chondrite Simulant	Asteroid	United States
HCCL-1	Hydrated Carbonaceous Chondrite Lithologies	Asteroid	Canada
IRS-1	Itokawa Regolith Simulant	Asteroid	China
MPACS	Mechanical Porous Ambient Comet Simulant	Comet	United States
SSC-1	Surrey Space Centre	Generic	United Kingdom
SSC-2	Surrey Space Centre	Generic	United Kingdom
	UF Acid-Alkaline-Salt Basalt Analog Soils	Mars	United States
	Salten Skov 1	Mars	Denmark
CSM-MGS-1	CSM Mars Global Simulant	Mars	United States
CSM-MGS-1C	CSM Mars Clay ISRU	Mars	United States
CSM-MGS-1S	CSM Mars Sulfate ISRU	Mars	United States
ES-X	ES-X Mars Simulants	Mars	Europe
JEZ-1	Jezero Delta Simulant	Mars	United States
JMSS-1	Jining Mars Soil Simulant	Mars	China
JSC Mars-1/1A	Johnson Space Center	Mars	United States
JSC-RN	JSC-Rocknest	Mars	United States
KMS-1	Korean Mars Simulant	Mars	Korea
MGS-1	Mars Global Simulant	Mars	United States
MGS-1C	Clay ISRU	Mars	United States
MGS-1S	Sulfate ISRU	Mars	United States
MMS	Mojave Mars Simulant	Mars	United States
MMS-1	The Martian Garden	Mars	United States
MMS-2	Mojave Mars Simulant	Mars	United States
NEU Mars-1	Northeastern University Martian soil simulant	Mars	China
OUCM-1	Open University Contemporary Mars	Mars	United Kingdom
OUCM-2	Open University Contemporary Mars	Mars	United Kingdom
OUEB-1	Open University Early Basaltic	Mars	United Kingdom
OUEB-2	Open University Early Basaltic	Mars	United Kingdom
OUHR-1	Open University Haematite-rich	Mars	United Kingdom
OUHR-2	Open University Haematite-rich	Mars	United Kingdom
OUSR-1	Open University Sulfur-rich	Mars	United Kingdom
OUSR-2	Open University Sulfur-rich	Mars	United Kingdom
P-MRS	Phyllosilicatic Mars Regolith Simulant	Mars	Germany
S-MRS	Sulfatic Mars Regolith Simulant	Mars	Germany
UC Mars1	University of Canterbury	Mars	Australia
Y-Mars	Yellowknife	Mars	United States
	Oshima Simulant	Moon	Japan
	Maryland-Sanders Lunar Simulant	Moon	United States
	Kohyama Simulant	Moon	Japan
ALRS-1	Australian Lunar Regolith Simulant	Moon	Australia
ALS	Arizona Lunar Simulant	Moon	United States
BHLD20	Beijing Highlands Lunar Dust	Moon	China
BP-1	Black Point	Moon	United States
CAS-1	Chinese Academy of Sciences	Moon	China
CHENOBI	CHENOBI	Moon	Canada
CLDS-i	China Lunar Dust Simulant	Moon	China
CLRS-1/2	Chinese Lunar Regolith Simulant	Moon	China
CMU-1	Carnegie Mellon University	Moon	United States

CSM-CL	Colorado School of Mines Colorado Lava	Moon	United States
CSM-LHT-1	CSM Lunar Highlands Type	Moon	United States
CSM-LMT-1	CSM Lunar Mare Type	Moon	United States
CUG-1A	China University of Geosciences	Moon	China
CUMT-1	China University of Mining and Technology Number One	Moon	China
DNA-1	De NoArtri	Moon	Italy
EAC-1	European Astronaut Centre	Moon	Europe
FJS-1/2/3	Fuji Japanese Simulant	Moon	Japan
GRC-1/3	Glenn Research Center	Moon	United States
GSC-1	Goddard Space Center	Moon	United States
JLU-U	JLU-H Highland Simulant	Moon	China
JSC-1	Johnson Space Center	Moon	United States
KLS-1	Korea Lunar Simulant	Moon	Korea
KOHLS-1/KAUMLS	Korean Lunar Simulants	Moon	Korea
LCATS-1	Lunar Caves Analog Test Sites	Moon	United States
LHS-1	Lunar Highlands Simulant	Moon	United States
LMS-1	Lunar Mare Simulant	Moon	United States
LSS	Apollo Lunar Soil Simulant	Moon	United States
MKS-1	MKS-1 Lunar Simulant	Moon	Japan
MLS-1/1P	Minnesota Lunar Simulant	Moon	United States
MLS-2	Minnesota Lunar Simulant	Moon	United States
Mooncastle	Mooncastle	Moon	United States
NAO-1	National Astronomical Observatories	Moon	China
NEU-1	Northeastern University Lunar Simulant	Moon	China
NU-LHT	NASA/USGS Lunar Highlands Type	Moon	United States
OB-1	Olivine Bytownite	Moon	Canada
OPRFLCROSS1	Off Planet Research LCROSS Simulant	Moon	United States
OPRH2N/H2W/H3N/H3W	Off Planet Research Highlands Simulant	Moon	United States
OPRL2N/L2W	Off Planet Research Mare Simulant	Moon	United States
TJ-1/2	Tongji University	Moon	China
TLS-01	Thailand Lunar Simulant	Moon	Thailand
TUBS-M	TU Braunschweig Base Simulant Mare	Moon	Germany
TUBS-T	TU Braunschweig Base Simulant Terrae	Moon	Germany
UoM-B	University of Manchester – Black	Moon	United Kingdom
UoM-W	University of Manchester – White	Moon	United Kingdom
	Carbonaceous Chondrite Based Simulant of Phobos	Phobos	United States
PCA-1	Phobos Captured Asteroid	Phobos	United States
PGI-1	Phobos Giant Impact	Phobos	United States
UTPS-IB	University of Tokyo Phobos Simulant, Impact-based	Phobos	Japan
UTPS-TB	University of Tokyo Phobos Simulant, Tagish Lake-based	Phobos	Japan

Fig.7 List of the Regolith Simulants, 2024

“In Situ” Regolith

"In-situ" typically refers to using materials from local sources for cement-based concrete, including sand, gravel, Portland cement, water, and wet and dry additives [24]. On the Moon and Mars, "in-situ" pertains to inorganic materials extracted from the planetary surface to serve as the basis for cementitious materials used for construction, as well as binders extracted from the same materials [25].

Regarding lunar regolith, the Apollo missions retrieved 382 kg of lunar regolith and rocks [24], and more recently, the Chang'e lander procured additional regolith [33]. As for Mars, no original samples exist yet, however a return mission is planned for 2026. Due to the limited supply of original regolith, the strategy has been to analyze the original material and create simulants rather than expend it in experiments.

2.3 Regolith Simulants

Regolith simulants are regolith-like materials, often of basaltic composition, produced after extensive analysis of original material retrieved from the lunar surface or data collected from rovers traversing the Martian surface and analyzing soil samples. Simulants are typically created by combining, melting, cooling, and crushing oxide or carbonate reagent powders in various proportions [24]. Like on Earth, the composition of the original regolith varies with the region it's extracted from. Regolith across the Lunar and Martian surfaces could contain varying amounts of different components and elements and may vary in terms of physical, mechanical, and chemical properties and behavior. Hence, different types of regolith simulants would need to be produced to match the original regolith from various regions of the Lunar and Martian surface to test planetary construction in different Lunar or Martian areas. Regolith simulants that closely resemble the original regolith in terms of mineralogy, chemical, engineering, and physical properties are deemed high-fidelity regolith simulants [34].

Today, a range of high-fidelity Lunar, Martian, and asteroid regolith simulants of varying compositions tailored to different applications and research needs are available on the market. The selection of the simulant depends on the objectives of the testing being conducted.

Due to the lack of Martian regolith retrieved to date, the composition of Martian regolith simulants has primarily been determined by data and soil analysis conducted onboard NASA rovers, such as Curiosity from 2012 [36]. The simulant's composition is a general representation of standard Martian Regolith usable for various purposes. The varying compositions of simulants representative of the same environment add an additional layer of complexity to establishing a testing standard. Properties such as particle size distribution and geometry, density, porosity, viscosity, permittivity, and even dielectric properties [37] of the simulants not only impact the behaviour and performance of the simulant itself but also may influence the technology selection [38]. For instance, simulants with different particle size distributions compared to actual regolith may produce weaker material that may not provide adequate support, necessitating reconsideration of temperature, cooling rate, and layer thickness for sintering [39][40]. Factors like the chemical composition of the simulants, cost, and ease of processing are also crucial when comparing different simulants and the technologies used for testing.

The most significant differences between most simulants and real regolith are not necessarily related to composition, but rather to particle distribution and density. One of the most significant distinctions in geological composition is due to the absence of sodic plagioclase, resulting from the scarcity of anorthite deposits on Earth. In the simulants, phenomena such as the activation of regolith grains by solar wind and cosmic particles, which are not replicable on Earth, are not present. This particle activation creates strong adhesion, on top of a magnetic charge of nanophase iron, a feature that is also impossible to find in simulants [42]. For high Technology Readiness Level (TRL) applications, the use of simulants with and without agglutinates should be considered, as well as the use of real lunar soil. Sample 70050, taken from the Apollo 17 landing site, lacks the detailed provenance characteristics that would make it suitable for scientific studies, rendering it primarily suitable for engineering tests [43].

The existing research framework on extraterrestrial construction technologies is exceptionally diverse. Each unique development is shaped by a specific research objective and constrained by the resources at hand. Consequently, scientists and researchers often have to prioritize certain conditions for performing tests. The NASA-STD-1008 outlines ideal conditions for hardware testing in a planetary environment. It provides detailed instructions for testing equipment under conditions that replicate those of a planetary setting. These instructions encompass [44]:

- Moisture Levels
- Pressure
- Particle Distribution
- Temperature

Adhering to these guidelines necessitates a rigorous procedure supported by various technologies aimed at recreating the characteristics of the planetary environment. The objective of any technological testing in a simulated or relative environment should be to demonstrate the technology's viability in performing its intended function in the environment for which it is designed. For example, machinery intended for construction includes intricate mechanical elements, requires substantial energy consumption, and incorporates moving parts that can easily be damaged in a dusty planetary environment [45].

One of the challenges of space hardware testing is the cost of maintaining a scientifically relevant testing environment. The extraterrestrial conditions of space and planetary surfaces are particularly challenging to replicate on Earth [46].

Space hardware testing demands complex equipment and rigorous testing procedures.

3. THE CONSTRUCTION TESTING FRAMEWORK

In the previous section we explored the fundamental aspects of interplanetary construction technology research, briefly detailing how experiments are conducted to test regolith simulants and various technologies. This section aims to establish a reliable approach to standardize these experiments. The goal is to minimize the number of variables while maintaining flexibility to accommodate different objectives.

The Construction Testing Framework proposed in this paper consists of two primary components: the Construction Testing Element (CEL) and the Construction Testing Environment (CEN).

The initial point of comparison between various construction technologies is the process. For successful construction on another planet using In-Situ Resource Utilization (ISRU), we need to ensure a high degree of reliability and repeatability in the process, coupled with a comparable output for testing and evaluation.

As outlined at the beginning of this section, the intent of the Standard framework is to establish a benchmark for ISRU construction techniques. Each benchmark is defined by a standardized testing element, which enables the comparison of proposed technologies.

This standard is considered applicable for construction technologies tested in a laboratory environment.

Given that diverse research teams, institutions, and private companies are expected to conduct ISRU research using their own technological means and resources, it is crucial to provide a standard that facilitates easier integration of these construction technologies into future exploration frameworks.

The Construction Element

A comparison of different construction technologies should ideally be based on the product of the construction process, which is the primary reason for conducting the research. Therefore, it is essential to standardize the construction element. The Construction Element (CEL) refers to the building block that results from the transformation process of the regolith. Even though the technologies considered vary widely, as do the outcomes and the mechanical properties of the blocks, it remains important to standardize the testing element's form factor to validate the technology's versatility and its suitability to construct different infrastructural elements (or habitats). The chosen building block is a cylinder measuring 150mm x 150mm with a height of 250mm. This shape has been selected for its compatibility with Molding, Casting, Additive Manufacturing, and Machining processes, as well as its suitability for most laboratory mechanical testing equipment [47].

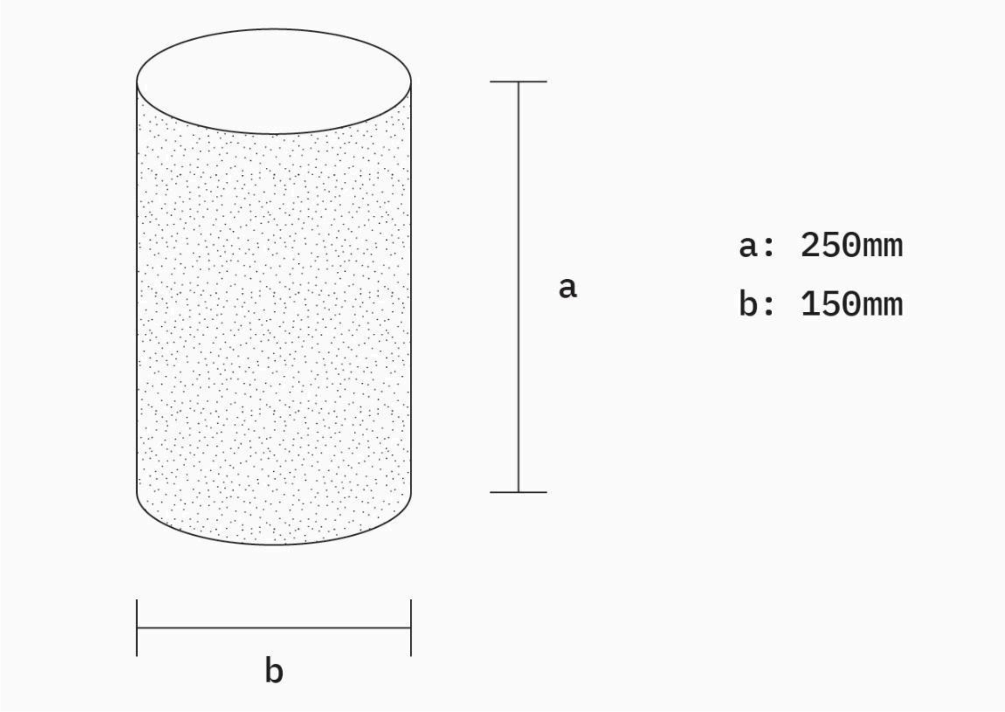


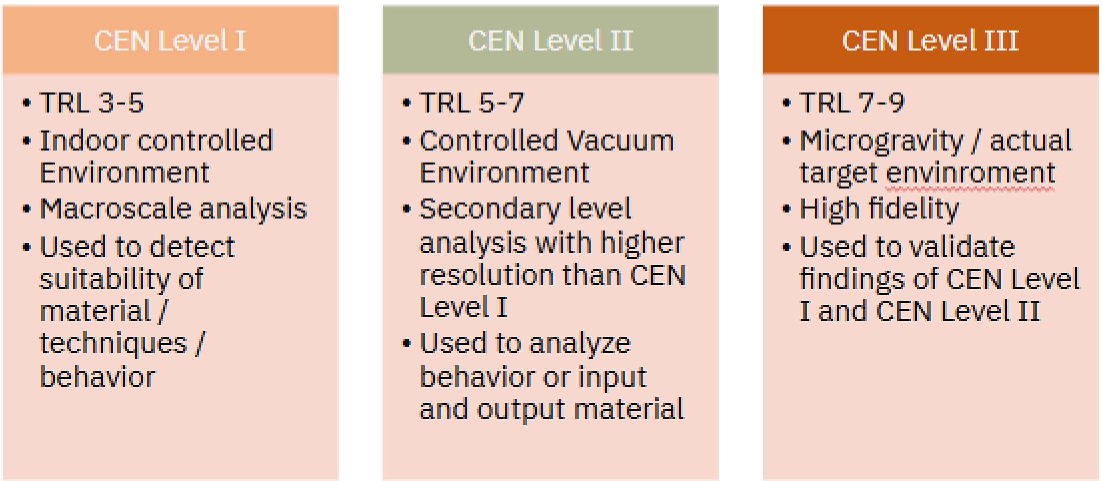
Fig.8 The Construction Testing Element

The Construction Testing Environment (CEN)

The Construction Testing Environment (CEN) pertains to the environmental exposure, or the absence thereof, and the operational conditions of the hardware and the simulants. It can be subdivided into three levels. As we incorporate increasingly accurate simulations of the environments, the testing becomes more complex and resource-intensive. The complexity and fidelity level of the testing environment can be adapted according to the development status of the technology being tested. This adaptability ensures that testing is preparatory to validating the specific technology being tested.

- **CEN LEVEL I:** CEN Level I involves conducting basic testing related to the input material and the construction technique. Therefore, the CEN Level I environment is a controlled environment that doesn't necessarily simulate microgravity or vacuum conditions. In other words, it's a standard, preferably indoor, basic controlled environment, where fundamental questions related to construction material and technology can be addressed. It is intended to provide an overarching analysis that can produce findings at a macro scale, such as the suitability of a material for a specific technique or the behavior of the output material based on the parameters/settings of the construction technique.

- **CEN LEVEL II:** CEN Level II testing involves the examination of technology and material within a controlled vacuum environment. CEN Level II environment is intended to provide a secondary level of testing following Level I. It delves deeper into the macro questions addressed by CEN Level I by turning them into micro questions, which would have more to do with the behavior of the input and output material and the construction technique in an environment that represents the Lunar and Martian surfaces.
- **CEN LEVEL III:** CEN Level III testing involves examining processes in microgravity and/or testing in the actual environments of the Moon and Mars. CEN Level III experiments are considered high-fidelity as they primarily aim to validate the findings of CEN Level I and Level II experiments.



CEN Level I

- TRL 3-5
- Indoor controlled Environment
- Macroscale analysis
- Used to detect suitability of material / techniques / behavior

CEN Level II

- TRL 5-7
- Controlled Vacuum Environment
- Secondary level analysis with higher resolution than CEN Level I
- Used to analyze behavior or input and output material

CEN Level III

- TRL 7-9
- Microgravity / actual target envinroment
- High fidelity
- Used to validate findings of CEN Level I and CEN Level II

Fig.9 CEN Levels

Element Testing Framework

The produced element will be further tested by different means to produce a valid database for technology comparison. The proposed testing standard operates at different scales to provide a complete analysis of the constructed element (CEL). The testing categories include:

- Microstructure Morphology
- Rheology of Regolith Mix
- Material Testing
- Element Testing

The Element Testing Framework is derived from the Construction testing of concrete elements on Earth, which has a long track history record [47]. The element is observed and tested at both micro and macro levels to evaluate the composition of the paste and the distribution of the particles, as well as to conduct mechanical testing on the element. The element testing aims to define parameters that are useful to determine the mechanical properties of the Regolith mix:

- Young`s Modulus
- Yield Stress
- Ultimate Strength
- Ultimate Strain

To define these properties, the following tests will be performed:

- Compressive Strength Test
- Flexural Strength Test
- Bond Strength Test
- Direct Tensile Test
- Splitting Strength Test

These tests are to be performed in the rigor of a lab environment, but there is no restriction on the machinery to be used in the tests. In addition to the mechanical testing, a micro-scale analysis on the regolith mix is performed in a lab environment through rheology of the concrete paste. This step is performed when the regolith mix is in its liquid state and is used to describe different characteristics compared to the mechanical testing [48]:

- Stability
- Compact-ability
- Flow-ability

The purpose of this proposal is to establish a foundational standard for testing planetary construction technologies that involve the use of local basaltic materials. These guidelines are derived from the well-established standard of Earth's concrete testing and incorporate elements of extraterrestrial environmental condition simulation that have been refined through decades of space hardware development and testing.

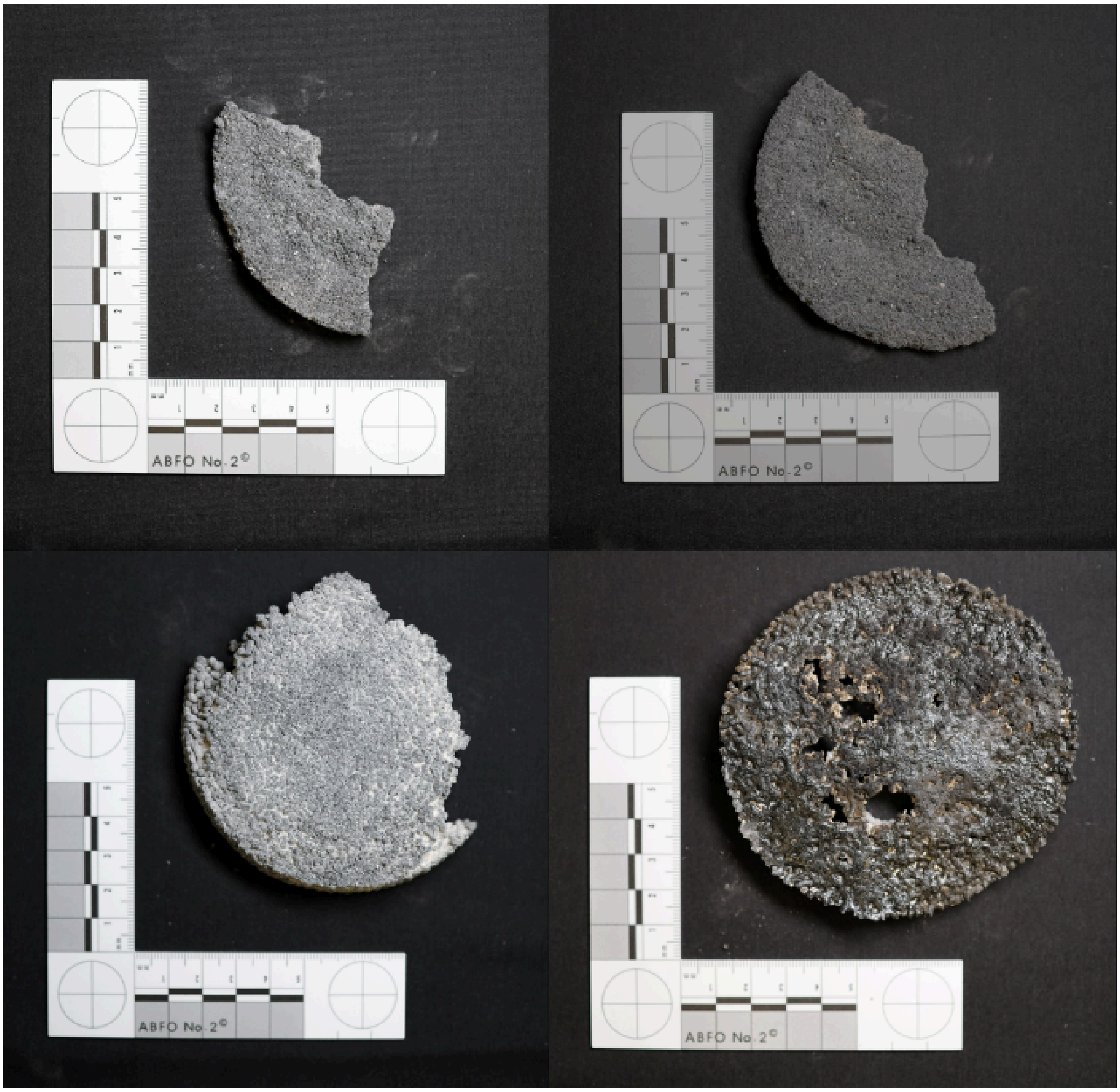
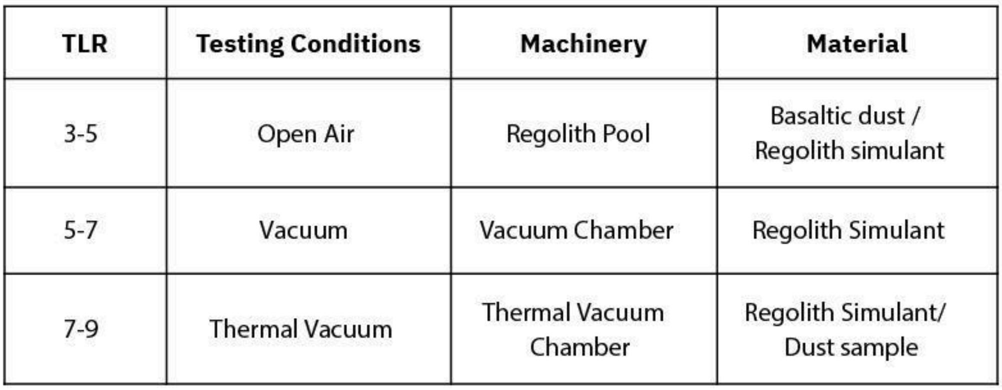


Fig.10 Initial Samples obtained with different manufacturing techniques of aggregation of Lunar Highlands lunar Regolith Simulant by Exolith Lab, 2021

For now, this proposal serves as a set of initial guidelines, recognizing that it is still far from defining a comprehensive standard. We anticipate these guidelines will evolve and mature, alongside advancements in the field of space construction technologies. Our hope is that this proposal will encourage discussion, refinement, and further collaboration among scientists, researchers, and engineers in the field, ultimately contributing to the long-term goal of establishing sustainable human settlements beyond Earth.



TLR	Testing Conditions	Machinery	Material
3-5	Open Air	Regolith Pool	Basaltic dust / Regolith simulant
5-7	Vacuum	Vacuum Chamber	Regolith Simulant
7-9	Thermal Vacuum	Thermal Vacuum Chamber	Regolith Simulant/ Dust sample

Fig.11 Testing Conditions of the framework based on the TLR level

4. AUTOMATION PROTOCOLS

The inherent risk in human space operations has restrained the application and development of automation and AI, in contrast to unmanned missions, where autonomous protocols are widely employed, proving to be essential for accomplishing mission objectives. As ventures in human space exploration advances in complexity, technologies in robotics, automation, and artificial intelligence become a fundamental capability to achieve safer and more economically feasible missions. So far, automated robots have been used mainly in serial, repetitive tasks, and since they are typically designed at the very early phases of the mission, this obscures their adaptability to future deviations from original mission requirements. This adaptability is especially crucial during mission operations when unexpected issues are not only common but inevitable. Even with additional AI capabilities in robotic systems, its benefits only depend on hardware limitations. Traditionally, the crew has been in charge of responding to unexpected problems during the mission. The assumption that the crew will have all the necessary tools to resolve unpredicted problems in space can put the crew and valuable assets at risk. This paper outlines a concept of scalable infrastructure and methodology for standardization and optimization of mission hardware and software. It also presents a possible behavioral model for decision-making protocols of autonomous framework in the context of human spaceflight. This model describes a new approach in applications of automated systems and AI. The intent is to increase crew efficiency, thereby reduce psychological load and training time, lower the risks and costs of the mission while providing an efficient and sustainable approach to space operations.

Spaceflight has always been characterized by a low level of automation compared to any other high-risk human activity. On the contrary human atmospheric flight can rely on automation protocols from decades. Military fighter pilots can rely on active targeting and data driven computer decision protocols since the beginning of human space exploration. The main reason for this asymmetric development is founded in a general prejudice towards the automated assets in risk assessment and response. This mistrust is directly connected with the "unknown risk" level within space operations. We generally rely more on automated assets in a controlled environment, where the consequences of a failure are well known but we can`t accept the inherent risk of a space mission, where the risk of unknown causes failures is higher than the expected failure rate within the operations. An

unknown cause failure is the worst case scenario in human spaceflight and there are many history cases behind this statement. From the Apollo 13 ECLSS failure to the infamous "SCE to AUX" we have many examples of how human risk response to the unknown saved many lives. On the opposite we have a history of hardware and procedures failures due to unknown or misassessed causes that have determined the loss of crew and/or payload.
The consequential assumption is that the main reason for the low automation levels in spaceflight is our hope that a human would go beyond the nominal procedure to solve a problem that has not been rated before, with possible unknown causes.
While robots and software are designed with specific tasks in mind (or a range of tasks) with a very high efficiency , it is very difficult to adapt them to mission requirements that were not taken into consideration during the design phase. Humans on the contrary are easily adaptable to almost any kind of tasks, and they are able to use tools to improve their capabilities for a specific effort. This paper will take in consideration the possible development of autonomous and robotic assets to describe the ideal operational condition of an autonomous framework created to improve the efficiency and capabilities of human space exploration.

4.1 Space Mission Automation

At the beginning of human space exploration there was a very high level of procedural automation in spacecraft with a level of situational awareness near to 0. The Gemini and Mercury capsules were run by very simple computers, programmed for a linear tasks management: there was no space for hardware failure except from the redundancies. The situational awareness was totally given to the instruments readings by the astronauts but with a really low level of interaction with the mission operations. The main objective was to test the human survival capabilities in microgravity, in a controlled environment. With the advent of the Apollo program, the engineers assessed the high mission complexity, leaving the direct control of the spacecraft to the astronauts during critical parts of the mission, such as the moon landing or the inter-spacecrafts docking phase. The general automation was very low, due to the relative simplicity of the computers and the complexity of the operations. Still the situational awareness was given to the astronauts and the risk assessment and response was a crew responsibility. The Apollo 13 accident is a clear example of how human intervention was the only fundamental asset onboard with the capabilities to solve a hardware or software failure. The Shuttle program has introduced a new range of robotic and autonomous tools in human spaceflight. The reusability requirement, the Canadarm, ECLSS and sensors autonomous awareness protocols: the STS has been our first test platform for human system integration with advanced operation support systems. The lesson learned from the STS has been a fundamental component of the ISS, the most advanced manned spacecraft in space exploration history. As we used the ISS as a testbed for advanced automation protocols, we still struggle to integrate this system in the current operation assets development. We still consider astronauts as our best option for risk assessment and efficient response to unknown events. In order to grow the human presence and to expand our capabilities in Space, we need to set the final objective for automation development and to establish a reliable roadmap to integrate automated assets in fields where it is still considered an unacceptable risk for mission success.

4.2 Unmanned space applications

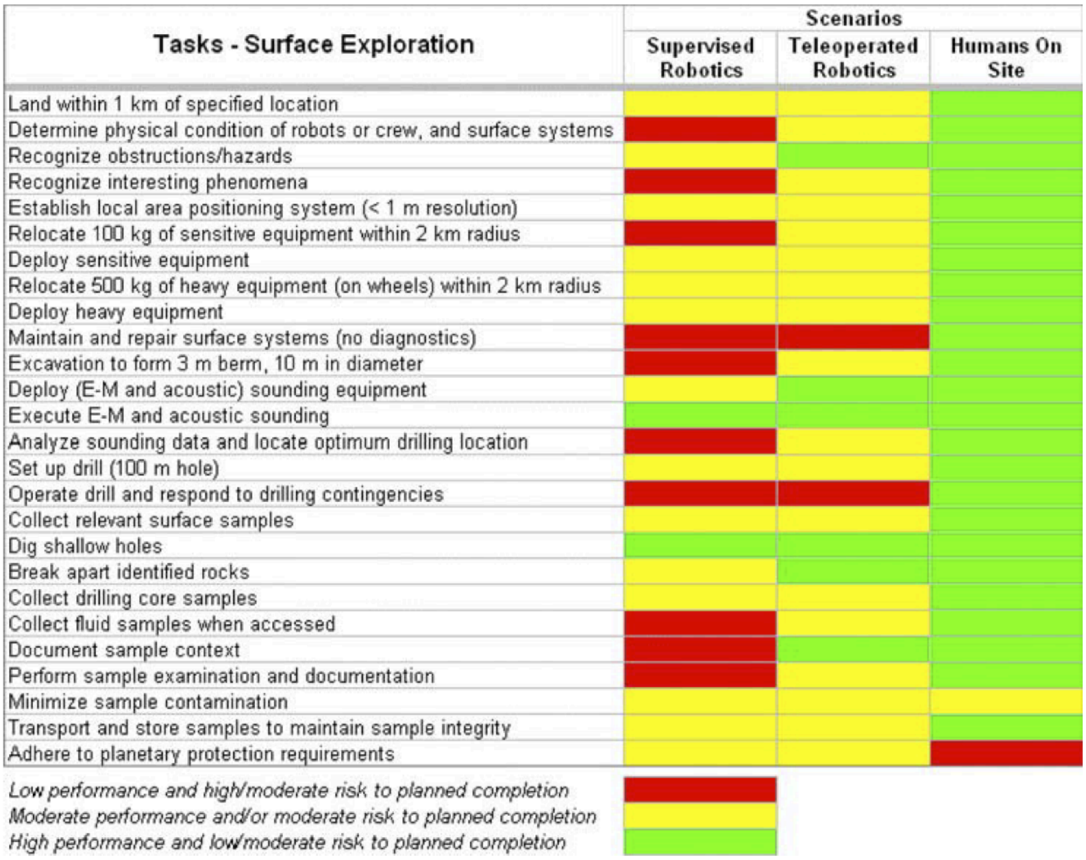
The unmanned space applications development has demonstrated a high reliability of autonomous protocols, since these operations represent the only option to overcome the limits of a direct control in terms of communication delay with the spacecraft. Still with these necessary implementations, most of the protocols used on unmanned spacecrafts don't make use of autonomous AI decision making and are just procedural.

Almost the total accidents in unmanned space operations happens for the inability of the onboard systems to prepare an appropriate response to unplanned mission development such as hardware failures and not calculated environmental events (e.g debris impact, sensor failures)

The common operations protocols for exploration class missions rely on the ground operations for failures and events management. A recent example of unexpected event management is represented by the multiple failures in the deployment of the MOLE on Mars Insight.

In Unmanned Space Operations we can distinguish two different methods on operations architecture: Autonomous and Teleoperated.

Autonomous operations represent a small part of space assets management in confrontation with teleoperations and are generally accepted just when teleoperations are not available for different conditions (delay in communications, complexity of operations), but teloperated operations are generally preferred for their high flexibility. The choice between teloperated and autonomous operations is an important design requirement that reflects on the mission architecture complexity. As we assessed the capabilities in terms of response to not nominal conditions for humans, we integrated the risk for human errors in the process: teleoperated operations require a high level of preparation that impact the cost and the complexity of the mission.



Tasks - Surface Exploration	Scenarios		
	Supervised Robotics	Teleoperated Robotics	Humans On Site
Land within 1 km of specified location	🟨	🟨	🟩
Determine physical condition of robots or crew, and surface systems	🟥	🟨	🟩
Recognize obstructions/hazards	🟨	🟩	🟩
Recognize interesting phenomena	🟥	🟨	🟩
Establish local area positioning system (< 1 m resolution)	🟨	🟨	🟩
Relocate 100 kg of sensitive equipment within 2 km radius	🟥	🟨	🟩
Deploy sensitive equipment	🟨	🟨	🟩
Relocate 500 kg of heavy equipment (on wheels) within 2 km radius	🟨	🟨	🟩
Deploy heavy equipment	🟨	🟨	🟩
Maintain and repair surface systems (no diagnostics)	🟥	🟥	🟩
Excavation to form 3 m berm, 10 m in diameter	🟥	🟨	🟩
Deploy (E-M and acoustic) sounding equipment	🟨	🟩	🟩
Execute E-M and acoustic sounding	🟩	🟩	🟩
Analyze sounding data and locate optimum drilling location	🟥	🟨	🟩
Set up drill (100 m hole)	🟨	🟨	🟩
Operate drill and respond to drilling contingencies	🟥	🟥	🟩
Collect relevant surface samples	🟨	🟨	🟩
Dig shallow holes	🟩	🟩	🟩
Break apart identified rocks	🟨	🟩	🟩
Collect drilling core samples	🟨	🟨	🟩
Collect fluid samples when accessed	🟥	🟨	🟩
Document sample context	🟥	🟩	🟩
Perform sample examination and documentation	🟥	🟨	🟩
Minimize sample contamination	🟨	🟨	🟨
Transport and store samples to maintain sample integrity	🟨	🟨	🟩
Adhere to planetary protection requirements	🟨	🟨	🟥

Low performance and high/moderate risk to planned completion	🟥
Moderate performance and/or moderate risk to planned completion	🟨
High performance and low/moderate risk to planned completion	🟩

Skill	Objective Measurement	Humans	Advantage	Robots
• Strength	Y	High strength/high torque; sometimes too strong	—●———	Load/torque can be varied over very wide range with precise control
• Endurance	Y	Limited by available consumable and physical tolerances	●————	Limited by design, environmental decay
• Precision	Y	High degree of training is required to ensure repeated performance in humans	————●	Once programmed, robot precision is limited only by electromechanical design
• Cognition	N	Creative and limited only by prior training	●————	Execution of pre-programmed routines
• Perception	N	Highly integrated sensory suite of limited use in space environment, visual accuity is very high	●————	Can detect minute environmental changes; can sense trace elements in low concentration
• Detection	Y	High detection sensitivity, though sensory paths limited during exploration	—●———	Extremely high detection ability if preprogrammed and equipped with proper sensors
• Sensory Accuity	Y	Highly integrated sensory suite of limited use in space environment, visual accuity is very high	————●	Capable of detecting minute environmental changes if so equipped
• Speed	Y	Able to cover great distances in short amount of time	●————	Able to work very slowly and steadily
• Response time	Y	Spot decisions and rapid response is customary, sometimes a disadvantage	●————	Rapid to programmed events, latency delay for "hold" events
• Decision making	N	Flexible, unlimited in either speed or capacity	●————	Primitive learning capacity to scripted events
• Reliability	Y	High in terms of meeting mission objectives but require support systems of high complexity	———●—	High reliability, but relatively short lives in space exploration environments
• Adaptability	N	Highly adaptable to new and changing situations	●————	Reprogrammable to a limited extent, otherwise limited by design and system redundancy
• Agility	N	Agility limited only by design of exoshell	—●———	Computation requirements dictate slow movements with limited agility
• Versatility	N	Readily self-reprogrammable to provide multi-purpose services and functions	●————	Generally designed to perform specific functions and poorly equipped to new applications
• Dexterity	Y	Ability to manipulate large and very small objects with high flexibility	—●———	Can exhibit very high DoF and fast reaction times
• Fragility	N	Generally robust but total system failure can be caused by small affects	—●———	Exploration robots generally very fragile, especially attendant instrument suites
• Expendibility	N	Human life is precious and we place ever higher value on it	————●	Robot also high value - today we send robots to less interesting scientific sights on Mars because value is high - return unnecessary
• Maintainability	N	Low cycle time between periodic consumable replenishments, requires expert skills to maintain	——●——	Limited only by design - can be maintained by low skill personnel

Fig.12 and 13 Automation reliability study, M.P.Garvin, NASA

4.3 Deep Learning Protocols

Machine and deep learning algorithms totally changed our way to use and perceive technology. The main objective of these advanced algorithms is to enable the recognition of data patterns that can give new insights on the information acquired. In space applications one of the main advantages in using deep learning protocols is for optimization and extrapolation of new data acquisition during flight. This approach is fundamental if we want to start relying on AI for in-flight data acquisition and processing and to reach the necessary level of safety to enable long duration, high range human spaceflight analysis.

4.4 Quantum Computing

Quantum computing is the upcoming tech that is changing the way in which we think about computing machines. Quantum computing is based on the concept of "superposition", which means that the processor not just performs an array of 0-1 operations, but can also calculate the probabilities of the position of the next operations. The consequence of this affirmation is that a quantum computer can process way more operations than a normal computer, but in a probabilistic way. Quantum computers are perfect to perform complex analysis based on a big amount of data. NASA collaborated with Google in 2010 to create D-WAVE [53], the first commercial quantum computer. NASA identified different field of applications for Quantum computer for space exploration, of which here are provided three examples from the NASA Ames researches [54]:

- Advanced diagnosis and fault management in engineering systems; for example, the detection of multiple faults in complex electrical power networks onboard the International Space Station (ISS).
- Automated mission planning to determine the best use of limited resources—including time and electrical power—for ongoing and future space missions such as the Mars Science Laboratory's Curiosity rover and the ISS.
- Scheduling algorithms to automatically determine the optimal time for making Low Earth Orbit satellite observations; and to optimize aircraft flight routes and landing patterns, taking into account weather conditions and air traffic management priorities.

4.5 Robotics

Space Robotics has been a largely explored field since the start of human space exploration. Robots have the capability to emulate human actions and to enhance them. On 28 November 1988 took place the 1st International Symposium on Space Automation and Robotics in Arlington, U.S.A. The value of robotics for space applications has always been considered very high, due to the inherent elimination of the risk factor for human crews. Since then, we have had different generations of Space robots optimized for EVA or IVA operations. Here we are listing most of them:

- **Kosmorobot** a space assembly multi-arm robot from Roscosmos
- **Spiderfab** a 3d printer robot for orbital applications
- **Aercam** Autonomous extravehicular Space Shuttle camera
- **Seeker** a couple of free-flyer inspection robots
- **Spyder** flyer a spider-like exoskeleton for Phobos exploration
- **Dextre** The multi-tool CSA Space robot on ISS
- **Astrobee** a IVA free flyer for machine and human interaction
- **Canadarm** the 11 meter satellite and capsule grabber on ISS and Space Shuttle
- **ATHLETE** a 6-legs modular robotic crane made for Constellation program
- **Lemur** Four-legged climbing robot
- **Justin** the ESA humanoid robot
- **Valkyrie** NASA humanoid EVA robot
- **Cimon** a robotic companion for astronauts with a personality
- **Fedor** the Roscosmos humanoid robot

- **Spheres** a swarm of IVA robot for test situational awareness, docking capabilities and attitude control
- **Ranger** Satellite-based multi-manipulator robot
- **Restore-L** Craft a concept for a refueller robot for expired satellite servicing
- **Robonaut** the NASA humanoid robot
- **Spidernaut** NASA concept for a 8-legs extra-vehicular robot

All this effort for In-Space automation from Space Agencies, universities and private companies is the mirror of a farsighted vision that aims to a future in which robots and AI will lead the way of space exploration, not only as humanity 's long arm, but as tools and collaborators. Furthermore the technological limit of these platforms reside in the lack of dexterity [Fig.12 and 13] and reliability for what concerns the hardware, and the impossibility to deal with unplanned situations for what concerns the software [55].

4.6 The Framework

The framework will work as a background clustered application, hosted on every networked device and server, aboard the spacecraft and in ground control. The framework objectives are:

- Data gaining and monitoring from subsystem control software and sensors
- Risk assessment for human crew and payloads
- Development of Risk mitigation strategies
- Design and protocols optimizations
- Control of robotic assets for EVA and IVA ops

- Simulation of operational scenarios
- Interaction with human assets

To choose a set of primary models on which to build a decisional model the first requirement will always be the highest crew safety level, as the primary success condition of each mission. A specific hierarchy of subsystems, crew comfort and safety level, mission requirements will be established. The pyramid generated will include some fixed elements and some specific success requirements established for each different mission. The software will also allow different levels of control and interaction that can change during mission time to fit the comfort of the crew and to reflect the flight status, as different conditions will be met during different phases (ascent, transfer time, descent, docking, etc.)

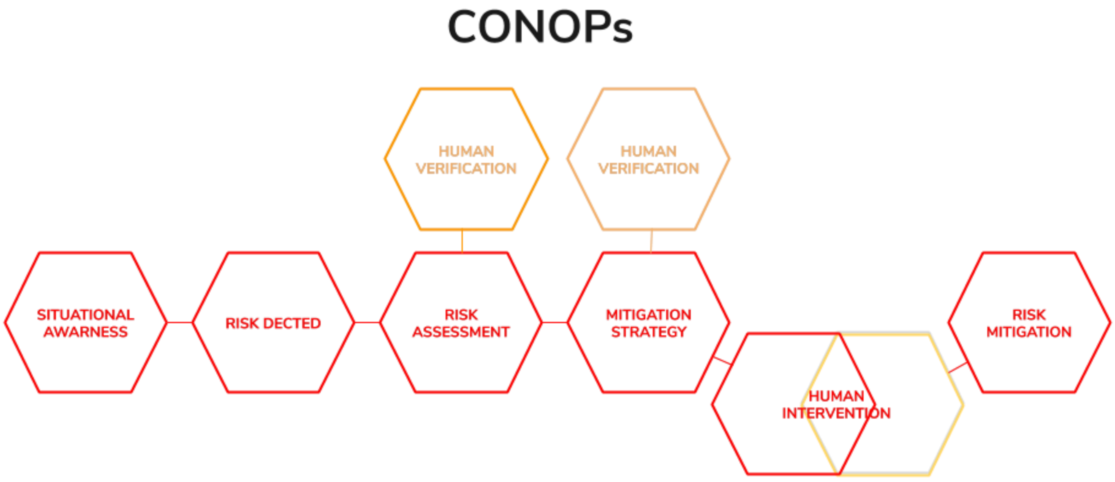


Fig.14 Proposed ConOps for the Autonomous Framework

The decisional capabilities and the behavioural model will also be scalable. The software will be built around a strong set of rules to ensure the highest level of safety for crew and payload assets. When some highest system functions will also require human validation during decisional processes such as the definition of a particular risk mitigation strategy, we can imagine that during the first implementation phase every function will need validation through software redundancy or human verification. The high repeatability achieved with robotics and AI will reduce the training time of the crew for specific operations to the minimum.

4.7 The Framework Infrastructure

Before has been stated that the framework infrastructure consist of a multilayered decisional matrix.The framework is a microservice-based cloud infrastructure that permeated the functions, the subsystems and the and the actions aboard the spacecraft. The core of the system contains a set of rules and basic definitions that help the framework to understand the different data inputs from the microservices. The core set of rules can be expanded to deal with unprecedented situations but cannot be changed or damaged. The core is provided of sockets to interact with the microservices. The microservice is an independent software package able to process a narrow variety of data. Its purpose is to fulfill a single function and to interact with the core. Every microservice can be easily replaced or updated without compromising the core [Fig.15]. The core sockets have in-built translators, thanks to they can deal with microservices developed in different moment, with different technologies and coding languages. With this approach, each company, agency, research center or university can develop their own control software for their hardware without compatibility issues with the main system or need for redundancies.

4.7 Scalable Architecture

The scalability of the system is a very important factor: if we want to standardize the approach and shift from a single-project development to a multi-mission capable infrastructure we will need an adaptive system. The shortest way to standardization is flexibility: a bright example of this strategy is Ardupilot.

Flexibility is scalability. Today we can't imagine all the challenges, the conquests and the needs of space exploration in the next 20 years, so our framework needs to stay as open as possible to new iterations and integrations. That has been exactly the opposite strategy of NASA until the last 10 years, when with the advent of cloud technology there has been an opening through distributed computing (already widely used in other scientific institutions, such as the SETI institute). In the traditional view, inherited by a more hardware-specific based architecture, each system or subroutine runs on a different machine, and the input was occurring manually, as a human verification step of the calculation runned by the machine. It was the case of the Apollo program: the guidance computer was just calculating the values needed to run the engine and RCS subsystems. The data output from the computer had to be manually rewritten in the attitude control computer. The Space Shuttle wasn't so different. The software didn't even use an operative system, and was running directly on the relative subsystem machine. With the ISS, we're still stuck midway in this evolution process: to overcome the high lifespan of the space station, we just overlapped new hardware and new software over the old one, without updating it or even taking care of the integration between different technologies.

The result is now almost 100 different machines from the last 20 years are present on the ISS, from different technological eras and many of them not even in use anymore. Even if more "scalable" than in the past, this system totally lacks sustainability and suffers from a very low efficiency, affecting even the comfort standards of the astronauts.

4.8 Distributed Intelligence

The redundancy itself is an obsolete concept with a cloud infrastructure: the distributed software doesn`t need a single physical machine to run. On this aspect, we can outline two different strategies.

- **cloud cluster server:** The core runs distributed in a cloud cluster made of different server machines. The microservices are installed in the cluster or they can run remotely from single devices. The loss of one or more machines can determine a loss of information or remote microservices, but not the loss of the core. The network is limited, the infrastructure is stable, the performances constant.
- **Distributed blockchain nodes:** The core runs distributed in a network of nodes composed by every machine onboard the spacecraft. Every machine shares its own processing capability with the other to create a cluster network. Every machine added to the network raises the system capabilities, information packages are shared between the machines-nodes through unique "contracts" ; the loss of one or more machines cannot determine loss of information, nor the loss of the core. The microservice will run in the nodes, so the loss of the node determines the loss of the associated microservice. The infrastructure is liquid, the performance variables.

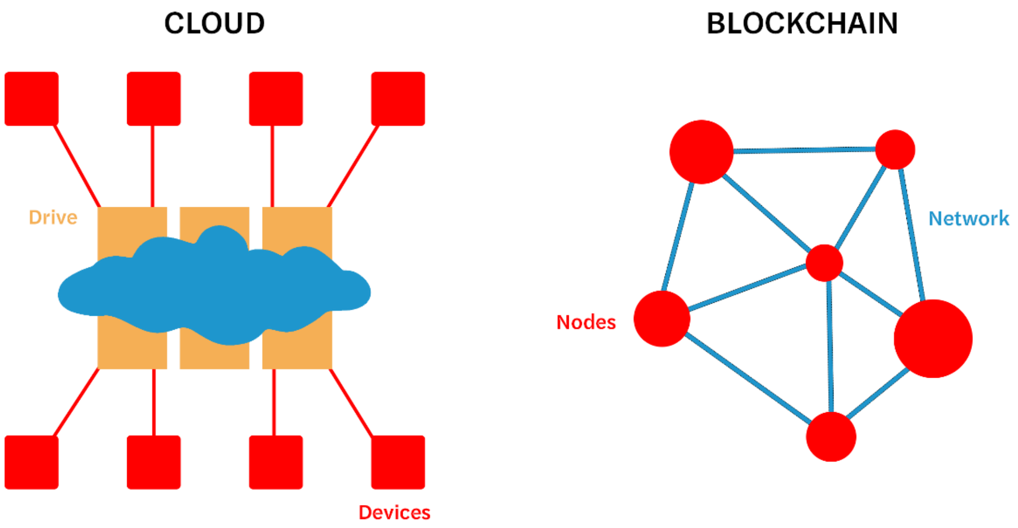


Fig.15 Cloud vs. Blockchain infrastructure

More in-depth studies need to be conducted in order to choose the most efficient. can be outlined using the same use case. A set of API allows to visualize the data processed by the core for each different microservice from every device that accesses the network.

4.9 Behavioural Model

In order to be scalable and sustainable, we have to adopt a holistic approach to infrastructure design. Our long-term objective is to increase the autonomous capability of the system: we need to provide a behavioral matrix to the framework in order to teach him the most effective way to process the data that we had been fed to him, but in respect with the human hierarchy of objectives.

This necessity has been revealed fundamental in the last years, thanks to the fast development of guidance algorithms for autonomous cars. In 2018 a Tesla vehicle, guided by a provisional version of the autonomous driving software (and a distracted driver) hit and killed a cyclist that was crossing the street, in the dark, away from the crossing lines.

Even if the investigations found that nobody could have avoided the accident, (since the cyclist started the crossing when the car couldn't in any way stop in time before the hit) and so proven the AI innocent, a deep doubt has been raised: what if the computer had the choice to deviate the vehicle outside the road in order to avoid the cyclist? What if that behavior would have caused the death of the driver due to the off-road deviation? What if the AI had to choose between two human lives?

Projected in space applications this concern grows bigger and bigger, due to the possible catastrophic consequences of a "wrong" or unethical choice from the AI. This is the main reason why the definition of a complex behavioral model is a fundamental step through the automation in space applications.

As we determine the boundaries of this model, the complexity of this task can become INSORMONTABILE. For this reason the best way to elaborate a model is to make it flexible and scalable. The model can be represented in a matrix of choices that will grow together with the smartness of the infrastructure. We'll start with a basic set of ethical and solid rules, that will be written as necessary conditions in the core of the framework. These rules will create relations between themselves and the different mission objectives. If the primary conditions (the core ruleset) are not met, the secondary conditions will not be considered valid. If the crew safety defines condition 1, and it's not met, condition 2 (Scientific objectives) is ignored. Human validation is still a very good method to give a progressive imprinting to the framework: every new choice or every not-clear outcome will require one or more human validations to be considered viable, even more if the objective is to grow the core rule dataset. A condition has to be met several times to be proven as a valid new standard.

In order to enable a safe and accessible human presence in space, automation is one of the most valuable assets to take in consideration, as it configures itself as the intersection of different technologies that find use in many earth applications, and for this reason, characterised by a rapid development. The automation for space applications should be distinguished by a multiple goal approach: the value of this asset is connected to its capacity to adapt to totally automated scenarios and human collaboration scenarios. A general software framework should be created to define the different protocols of interaction between the robots, the spacecraft and humans. The framework will coordinate the efforts of both robotic and human assets regardless of the hardware specification, thanks to a multilayer deep learning algorithm based on a set of unbreakable rules and regulated by a strictly human validation flow. Furthermore a new generation of robotic assets capable of fulfill the new mission objectives need to be developed. Acting both in EVA and IVA scenarios, the robots and the framework will collaborate with human crews to reduce the human workload and the tasks complexity, also limiting the high-risk operations, enabling an unprecedented level of safety in human spaceflight.

5. PROJECTS: HiveMars and MoonFiber

This section takes in consideration two projects that I have led during those years of research with Politecnico di Bari, HiveMars, a Martian outpost project and MoonFiber, a lunar Lava Tube Installation. Both projects represent Hybrid-class (Class II and III) surface architecture, using completely different principles and ISRU technologies. While HiveMars makes use of FDM Additive technology of Martian Regolith, MoonFiber uses a net of Lunar-Regolith fibers to suspend inflatable modules in a lavatube.

5.1 HiveMars: an Hybrid-class, scalable Settlement on the martian surface

Utilization of in Situ resources is a fundamental capability to be developed for the construction of permanent and semi-permanent structures on Mars and the Moon. Nevertheless, direct human contact with regolith would jeopardize crew health. New design strategies that address such problems need to be explored and developed.

This paper presents a feasible design for a hybrid class 2/class 3 outpost that includes ISRU structures integrated with prefabricated inflatable and solid elements, both for pressurized and infrastructure elements.

The Architectural Design Thesis Laboratory of the Polytechnic University of Bari conducted research on this topic, and, under the name of archi.mars, the group designed a permanent and self-sufficient settlement: “HiveMars”.

The proposal explores a concept for the integration of ISRU-enabled and prefabricated structures to create a scalable infrastructure capable of supporting human life on the surface.

To reduce mission costs and launch load from Earth, eight different automated rovers will prepare the site area before the crew’s arrival. Following the site exploration phase (identified in the Hellas Planitia, in the martian southern hemisphere) the automated surface assets will proceed with the material collection, processing, and construction of the main infrastructures, including Landing pads and roads. The first habitat nucleus is composed of three self-supporting, inter-connected domes, built with Martian regolith using additive manufacturing, and outfitted with an inflatable, pressurized core that hosts the pre-integrated ECLSS systems and the internal infrastructure. A pre-integrated dome on the top of the prefabricated core ensures the right amount of natural light while protecting the internal habitat from radiations and micrometeoroid impacts.

The priority of the first human outpost on Mars will be to protect the health and safety of the crew and to support life through good design practices for habitability and human factors. This project aims to provide both the living and working environment for eight crew members during 670 – sol mission duration. The project is focused on the architecture of Martian habitats to be built through automated surface assets which will support the site preparation for human crews, collecting resources and construction materials from local resources. The project, named Hive Mars, presents a feasible design that aims to reduce the launch mass and cost of future human surface missions, considering extensive usage of in-situ resources and current and near-future technologies to guarantee crew self-sustainment for a Martian settlement.

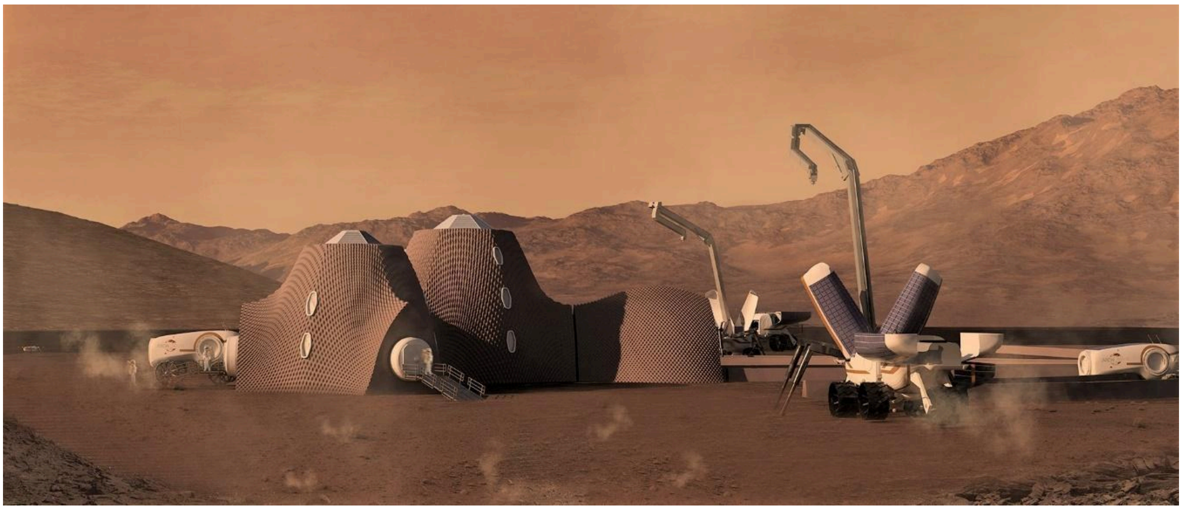


Fig.16 HiveMars Settlement, PoliBa 2021

Hive Mars is based on three case studies: the Marsha Space Habitat by Ai SpaceFactory group, winner of the NASA 3D-Printed Habitat Challenge 2015. This project proposes the use of a recyclable biopolymer composite to manufacture the habitat's inner structure and to use processed local regolith for the external shell. The second case study, the NASA Design References Architecture 5.0, is the most recent version of the Martian mission Architecture conceived by NASA. The architecture proposes three different missions in three different sites. In the preliminary phase of the project, consequentially to the definition of the geological, biological, and human factor objectives, a monolithic, class 1 habitat is proposed as the main outpost, while all the exploration activities make use of pressurized and non-pressurized vehicles to conduct medium and long-range research missions. This project also considers the use of in situ resources for the production of consumables such as oxygen, water, and propellant. Finally, the last chosen case study is the Mars habitat created by the Hassell+Eckersley O'Callaghan who participated in NASA's 3D-printed habitat Challenge [56]. To address the radiation problems, the group designed an external shell manufactured in Martian regolith with autonomous robotic rovers to protect a hybrid class 1/2 habitat [58]. The three different case studies have been chosen for their relevance to the topic and the different approaches, achieved through the use of the latest innovations in the field of additive manufacturing using ISRU.

5.2 Mission Architecture

To bring all the necessary assets on the surface and eight astronauts to begin the crewed phase, the launches of various heavy-lift rockets will be required. For this mission, architecture has been chosen: SpaceX Starship for the cargo mission and NASA SLS Block 1B for the crewed part of the mission.

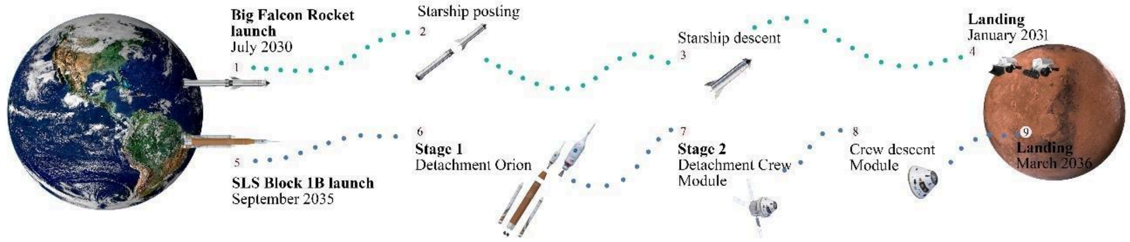


Fig.17 HiveMars Mission Architecture, PoliBa 2021

The proposal is focused on a mission not only to set foot on Mars but also to enable scalable colonization of the red planet. Before showing the outpost proposal, a mission architecture diagram that represents the launch, travel, and landing phases. The diagram shows the mission timeline and launch sequence that ties each launch to a specific launch window, to exploit the minimum traveling time between Earth and Mars to enhance crew and cargo safety and reduce the interplanetary travel unknowns. The mission consists of two phases and will last a total of fifty-three months [57]

Cargo Mission: The take-off of the first spacecraft is set for July 2030 with the SpaceX Cargo Starship departing from the LC-39A launch pad. The vehicle will transport six specially designed Rovers of the Bee family, such as the explorer, the flattener, the excavator, the transporter, the 3D printer, the processor, and the bee lifter. The goal will be to collect raw materials, such as regolith, and ice, and process them, through chemical processes, into refined materials suitable for construction, together with all the prefabricated assets to be integrated with the 3D-printed structures.

The journey will last about two hundred and fifty-one earth days and will include the landing of the specially designed machinery in January 2032.

Crewed Mission: The infrastructure deployment and the first habitat core construction (second phase) will last approximately 5 years. After that time, the third and last phase will begin: in September 2035, the SLS Block 1B will depart from the Kennedy Space Center LC-39B pad. The SLS will fly the first crew of eight members to Mars in approximately two hundred and thirteen days.

Upon their arrival, the mobile assets on the surface will have already built the first habitat core, consisting of two cylindrical habitats and an unpressurized vehicle storage area, including all the functions necessary to sustain life, including the work area, crew quarters, and leisure spaces. The mission will last at least 680 sols, around two Earth years, the time necessary to perform the exploration activities and carry out all the main scientific objectives of the first human exploration phase.

5.3 Surface Assets

Surface assets are assets used to move, store, protect, secure, and monitor a long-duration mission on Mars. These Assets are brought from Earth in the first phase of the mission and are intended for exploration, site preparation, material collection, and construction.A. On top of the habitat and infrastructure design, the design team focused on the construction sequence, outlining appropriate surface elements to support the construction. This role is performed by the Bee Family Rovers which include all the autonomous and semi-autonomous mobile assets, based on a common chassis to ease the maintenance operations. The design of each machine is inspired by Epigenetic-based insects [59], belonging to the Apidae family, a particular genetic characteristic that allows insects with the same DNA to evolve in different physical features, designed to fit their role in hive societies. Each of the Bee Rover assets plays a different role in the construction process. The BeeFamily Rover consists of eight machines. In order of arrival, we find:

- **Spider Explorer**, designed to explore and analyze the outpost area to define the site conditions and resources localization.
- **Bee Flattener**, whose main task is leveling the construction area to avoid unevenness in the ground that compromises the structural integrity of the habitats.
- **Bee Excavator**, will collect the regolith for the construction from the top layer of soil.
- **Bee Transporter**, used to move the construction material around the building site.
- **Bee Processor**, that has the task of processing the regolith into building material
- **Bee 3D Printer**, is a printer with a three-axis mechanical arm capable of building the outer shell of the housing modules through additive manufacturing process
- **Bee Lifter**, is used to lift, transport and place the prefabricated assets.
- **Archimars Pressurized Rover**, to be used by the crew for the exploration activities and transportation between the different outpost areas.

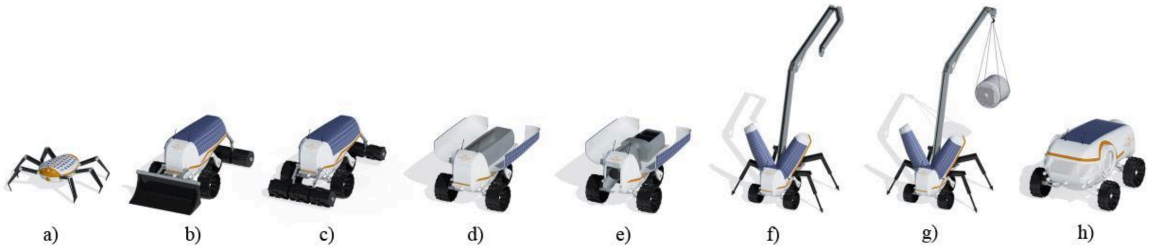


Fig.18 BeeRover Family, PoliBa 2021

5.4 Infrastructures

A complex outpost needs a robust infrastructural system that can support surface development. This system is composed of different elements designed for tasks such as energy production and distribution, material processing, and storage. Most of these elements are technologically too complex to be manufactured in situ and they will be prefabricated on Earth. Since these surface elements are fundamental for the settlement self-sustainment, proper redundancy and tolerance need to be assessed, to overcome unknown danger and malfunctions that can jeopardize the life-sustainability capabilities of the human-rated systems. These elements will be mostly located in two different areas at a distance from the habitat: the ISRU and Power production area, which are described in the Masterplan section.

- **Energy production area:** where solar panels and kilopower reactors are located.
- **ISRU area:** entrusted to prefabricated elements which allow production, processing and storage of water, oxygen and manufacturing materials.

5.5 Prefabricated habitat elements

Some of the components for the construction of the pressurized habitat need to be manufactured, assembled and tested on Earth to ensure the precision and safety suitable for hosting human life. These components, brought from the Earth, are:

- **Deployable inner modules:** inflatable/deployable elements that host human activities, including work, leisure and crew quarters.
- **Hatches, suitlocks and payload airlocks:** deployable cylindrical elements which connect deployable modules with one another or with the external module environment.
- **Window modules:** prefabricated and pre assembled elements that allow external light and view.
- **Skydome elements:** light-transmitting structure that enclose the external shell at the top.

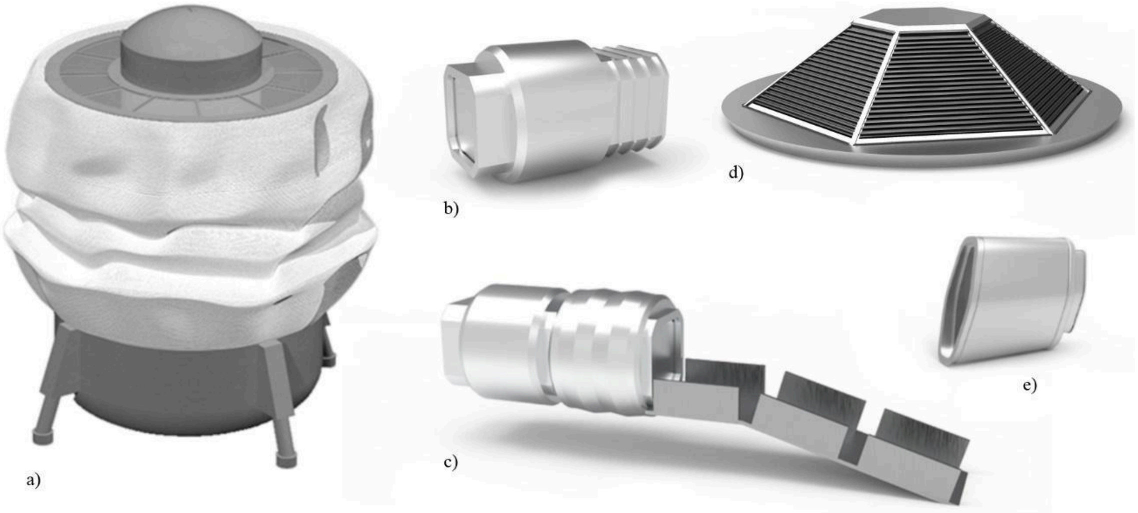


Fig.19 HiveMars prefabricated elements, PoliBa 2021

5.6 ISRU for Crew Sustainment

To live on Mars, crew members will need oxygen to breathe, water, propellant, and energy to power their habitat.Instead of bringing everything they need from Earth, they will use in situ resources to produce them. This way is self-sufficient, economically, and environmentally sustainable. Per day, one crew member needs approximately 3.52 kg of water for drinking and about the same amount for cleanliness and approximately 0.84 kg of oxygen [60]. To fulfill these needs, different strategies have been assessed using established technologies considered by NASA and ESA for long-duration missions, such as Sabatier process [61], Water Vapor Adsorption Reactor (WAVAR) [62], Mars OxygenIn-Situ Resource Utilization Experiment (MOXIE) [63].

5.7 ISRU for construction

The use of local materials for the construction of the entire settlement has a fundamental role in the HiveMars proposal. The use of the principal Martian resource, regolith, together with other surface minerals such as basalt, sulfur, and ice can be processed to obtain processed materials to be used during construction. The production of the material in situ is closely linked to construction technologies that see new applications and new experiments already on Earth [64].

Additive manufacturing and the use of local materials can reduce the amount of material transported from Earth, construction costs, time, and even environmental impact, greatly reducing the cargo capacity and number of launches needed to build on the planetary surface. To ensure the achievement of the mentioned benefits for this kind of construction, the habitat module has been designed around additive manufacturing technology capabilities.

Additive Manufacturing of Regolith

As stated before, the construction of the external structures of the settlement involves mostly the use of the Martian regolith. Powders are characterized by distinct morphologies and highly inhomogeneous sizes, where the dust particles are rough, but mainly rounded. The printable ink consists of three main components: the powder, the elastomeric binder, and a mixture of solvents. The powder, previously examined, occupies 70–75% of the volume of the mortar while 30–25% of the volume is occupied by PLGA, an elastomeric polymer based on organic acids. Instead, the mixture of solvents, easily available in situ, includes the majority of the volatile solvent dichloromethane (DCM); lower amounts of 2-butoxyethanol (2-Bu), a surfactant that mitigates and cancels the electrostatic and steric interactions between suspended particles and dibutyl phthalate (DBP), a plasticizer that improves the flow properties of dissolved PLGA and further inhibits the interaction of the particle during the flow [65]. After thickening, through evaporation of the excess DCM, a 3D printable consistency is obtained at a linear deposition rate of 1–150 mm/s. All the elements used for the preparation of the regolith mortar can be recycled. The polymer, PLGA, can be synthesized from biologically derived lactic and glycolic acids. It could be used to process and recycle unrelated organic wastes, such as urine and plant waste, into PLGA and similar elastomer-derived bio-waste. Optionally, the 3D printed elastic structures could potentially be transformed, by sintering, from solid form into gas, water, hydrocarbons, and into diatomic oxygen and hydrogen by electrolytic methods. Finally, the sintered regolith structures could be pulverized into primordial regolith powders [66], which could be used to create new regolith inks for 3D printing. The entire process of transforming the regolith into Martian mortar or cement takes place inside the Bee Processor rover and subsequently transferred to the Bee 3D Printer rover which performs the printing of the external structure. The printer technology uses the “additive” principle of depositing the material on layers [67]. The rover is equipped with a mechanical arm adjusted through a numerical control mechanism and it performs two types of movements: a circular one, along the x and y axes, and a vertical one, along the z-axis, following the deposition of the various layers. The nozzle, located at the upper end of the arm, has a diameter of 0.14m and is heated to melt the regolith mortar.

Shielding with regolith

The habitat structure consists of an external Class 3 shell and an inflatable Class 2 internal structure. The external structure refers to historical models of the Nubian dome and takes the shape of a dome with an ogival section truncated at the top. It reaches an external diameter of 15m and a height of 13m for the central dome while the two lateral ones have an external diameter of 13m and a height of 11m. The thickness at the base of the ogival dome reaches the size of 1.5m and narrows as the highest point is reached, becoming thinner to 0.50m which is equivalent to a minimum thickness required in the design of planetary habitats. This thickness favors adequate protection of the inflatable living module, placed in its internal volume, from the Martian severe weather such as sandstorms, meteor showers due to the weak magnetic field and shielding from solar and background radiations which are extremely harmful to the humans, especially for long exposure time [68]. The ogival profile of the wall thickness is interrupted by the presence of joints placed along the lines oriented at 120° from the center of the main dome. Each joint follows an ogival arched section and in the central part, has a circular passage that allows the correct positioning of the prefabricated modules such as the airlocks, windows, and Hatches. Between the domes, there is a joint of suitable thickness that allows each dome to be detached to avoid collision between the independent external shells during seismic events, although less frequent than those on earth. In particular, the shell presents a smooth surface on the inside while the outside is modeled onto a parametric tridimensional texture that allows better thermal management and protection against micrometeoroid impact.

The choice of an external textured finish responds to two determining factors such as the self-shading of the structure itself and the ability to retain the dust that is deposited on it. Over time, this dust stiffens the structure and also increases the wall thickness, resulting in additional protection.

External Shell Construction Sequence

The construction of the dome structure begins with the excavation of a 1.6m circular hole that will host the habitat foundation; the typology chosen is the continuous foundation with a circular bed, lower than the ground level, in which the internal shell will sit. Subsequently, the Bee 3D printer will proceed to print the base of the external shell starting from the foundation level. The first interruption of the printing takes place in correspondence with the ground-level hatches placed inside the side connections. The Bee Lifter rover transports and places the airlocks undeployed. The rigid section of the hatches and airlocks works as a support for the upper layers. A second interruption occurs at the level of the windows, directly transported from Earth, and placed in position using the Bee Lifter. In particular, the window frame consists of two polycarbonate panels, one in contact with the external casing and one internal; a shutter, which protects against micrometeorites and debris and, in addition, favours control of external lighting that reaches the internal environment; bulletproof glass panels that are attached at the rear and in the front of the latter. The printing of the ogival dome continues after the placement of the first three openings, interrupting in correspondence with the upper ones, positioned in correspondence with the second and third floors. The upper part of the dome is truncated because the printing technique would not allow adequate structural support to close the shape. Furthermore, once the construction of the envelope has been completed, this shape allows the placement of the undeployed inflatable module from the upper cavity using the Bee Lifter rover. Once placed, a truncated-pyramidal skylight is placed to seal the external shell. This element is inspired by the ISS dome and provides greater illumination of the internal environment.

Pressurized habitat}

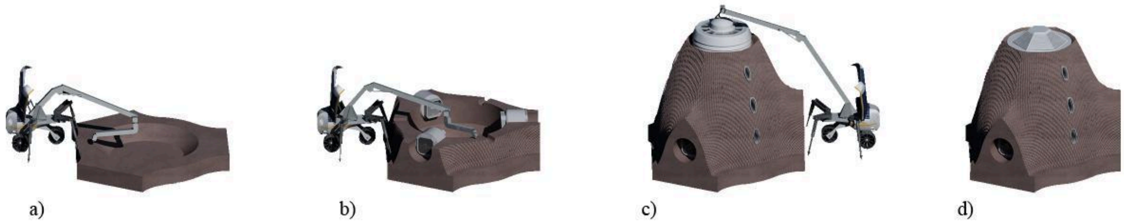


Fig.20 HiveMars Shell printing sequence, PoliBa 2021

Once the class 2 protective structure has been defined, it is possible to establish a class 3 housing module that is part of the infrastructures brought from the Earth. It is important to understand the formal choice of the external inflatable module, the deployment phases of the internal structure, and the specific function it assumes.

A long-term stay requires a habitat capable of reducing the mass and costs of launching and at the same time capable of guaranteeing large pressurized spaces to allow all human activities to be carried out. The choice for the habitat inside the regolith structure, therefore, fell on an inflatable habitat. Its advantages are remarkable: it is lighter than a rigid aluminum structure; it also allows greater flexibility of the internal layout and greater internal volumes; allows automated outfitting and easier assembly; manages better the thermal and structural stresses, while keeping the weight low [69]. Assuming that an inflatable habitat is more advantageous for site preparation before the arrival of crew members, the form factor becomes a fundamental choice to address in the design process. Cylindrical, semispherical, and toroidal shapes have been considered. Different studies and evaluation mockups built on earth Earth have shown that the toroidal shape is ideal for a small habitat. Compared to the hemispherical shape, the torus has important advantages: it is characterized by a ratio between mass and surface which is more advantageous for transport from the Earth; it has inherent stability; needs less gas for inflation. With the same external volume, the torus has a larger internal habitable volume than that of the sphere. The torus is safer thanks to its "segmentation into separate pressure compartments". In the case of the Hive Mars human settlement project, having an ogival section of the dome, neither the torus nor the sphere was suitable. Considering all the advantages of the torus, including its characteristic of having a central distributive core, and considering the shape of the sphere more narrowed upwards, to fit as much as possible the space available inside the external shell, an egg-like shape has been chosen. This shape is the best to deal with the pressure delta between inside and outside in a reduced gravity condition. It is also able to exploit all the volume available inside the dome, covers more space in height and width, allowing better management of the internal environment.

Habitat Construction Sequence

Once the undeployed inner module is lowered from above into the dome, the inflation begins. Integrated air pumps the pressurization needed to reach the final shape of the inflatable module, using filtered martian atmosphere in place of the precious oxygen mix. In the first phase of the deployment, the telescopic central core deploys vertically; in the second phase, the module inflates. After the deployment is complete, a flooring system characterized by a mobile octagonal floor, deployed radially from the central core. At first, two of the three cores scroll upwards; then the mobile floors open and then the wings of the ground floor, which unload the weight on a system of beams deployed from the central core. The unfolding of the structure continues with the opening of the movable floors, then of the wings, and then of the pillar on the first floor. Upon the arrival of the crew, it will be possible to outfit the internal space, through 3D printed and prefabricated elements transported from the Earth. To move the furniture between the floors, the elevator in the central core will be used. When not in use, the elevator platform is stored in the service module on the bottom, while allowing the deployment of a helical stair system mounted between the same tracks that allow the deployment of the structural pillars.

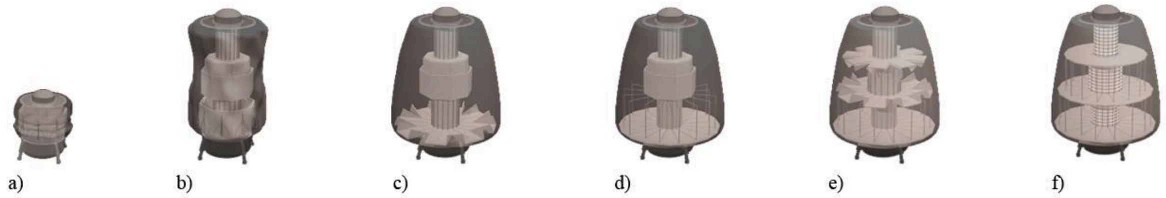


Fig.21 HiveMars habitat construction sequence, PoliBa 2021

The result is a large habitat characterized by an internal steel structure on three floors connected by the distribution core, which occupies the entire volume of 780 m3 of the external inflatable egg, functional for daily leisure of all activities of four crew members.

Internal layout

The layout of the interior space revolves around the crew activities. It derives from decades of human experience in minimal habitat design and the ISS experience. Designing for human factor means to affect human performance in a dangerous environment through design solutions that need to enhance the focus and the mental health of astronauts. The primary purpose of the design of the internal environment is therefore to ensure, together with the aspects related to the safety of the crew, all that concerns the physical, psychological, and social health of the inhabitants.

The living module of Hive Mars is a deployable structure on three levels. The internal arrangement of each area and the arrangement of each living module, in general, derives from the presence of three connecting airlocks arranged on axes of 120° from each other. Each floor has an increasingly smaller walkable area from bottom to top, given the egg shape of the external inflatable module. Each of them has three windows arranged on 120°axes from each other, which do not so much perform the function of illuminating from the outside, but rather that of offering people a view to the outside, partly freeing them from the sense of isolation.

Fig.22 HiveMars Interior renders, PoliBa 2021

The function of illuminating the internal environment is instead performed by a circular skylight dome mounted on the top that closes the core system. This skylight, thanks to a system of automated shutters, opens during certain hours of the day to radiate the internal module from above. The light, therefore, filters from above through the skylight, illuminates the second floor, and partially reaches the lower level from the gap between the inflatable module, the floors, and the internal structure. Each functional area is made accessible and connected vertically by a helical staircase placed at the center of the structural core. On the external walls of the core is placed a continuous hydroponic cultivation system, characterized by columns of 3D printed vases and a system of led grow lights, to produce part of the food, perform experiments and stabilize the internal hygrometry. The plants have also a proven beneficial effect on the crew mental health [70].

The Ground floor is 70 square meters of space, suitable for carrying out work, research, meeting, and care activities.

The area, initially empty, will be outfitted by the first crew of four. The instrumentation rack outfitting is the first step. Subsequently, on this floor, A 1m3 delta 3D printer will be installed to print all the furniture and partitions. The doors, such as the other elements, are prefabricated. The rest of the furniture will be gradually arranged within this area until the configuration of the planned distribution of spaces is obtained. The Medical area is positioned north-east, to the south-east laboratories for scientific research, to the north-west, there is the Local Mission Control Center.

The First floor has an area of 60m2, characterized by a distribution corridor around the core that leads to the common areas, represented by the living room to the north-east and the dining room with the galley to the southwest, and the private quarters, i.e. the four bedrooms of the first crew members. The area, therefore, is dedicated to feeding and sleeping, but also personal and private activities. The floor is served by two complete bathrooms.


a) first floor
b) second floor
c) third floor

Fig.22 HiveMars habitat plans, PoliBa 2021

The second floor is the area of 45m2, a single open space that is configured for relaxation, leisure, and physical activities.

5.7 Masterplan

The HiveMars project takes into consideration the entire infrastructure, not only the habitat module. This section will describe the different areas that characterize the system, and their roles in the mission structure.

The arrival of the first Cargo Starship is scheduled for January 2032. Once the landing has taken place, all the machinery necessary for the preparation and exploration of the site is deployed on the surface before the arrival of the crew, which will happen three years later. First of all, the Spider Explorer surveys the designed construction area to provide detailed information about the site to the construction rovers, such as the presence of water in the subsoil. Subsequently, the Flattener rover will level the terrain and free the area from the rocks that can`t be processed. In the second phase, the Bee Excavator and Bee Transporter rovers will dig the foundation's area and collect the regolith for the transport to the ISRU area, where it will be processed, and where the activities of water extraction, production of oxygen, and propellant take place.

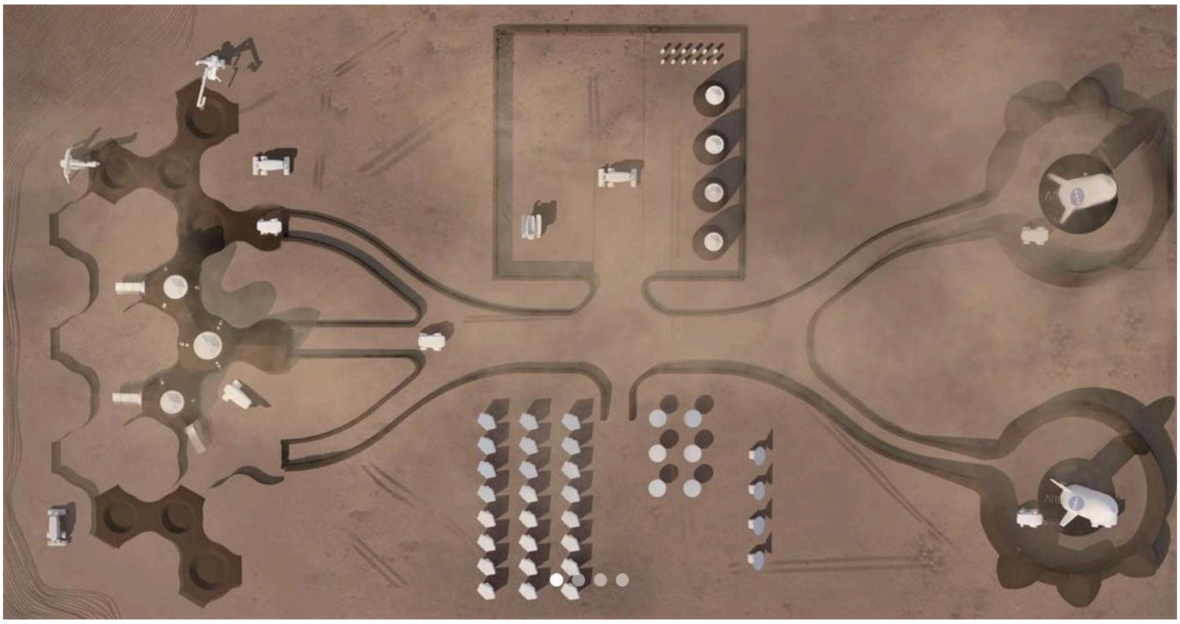


Fig.23 HiveMars Masterplan, PoliBa 2021

Once the regolith is processed, it's transferred to the 3D Printer rover, which will print the protective wall of the primary landing pad, the rover pathway, and the shell of the habitat. The Kilopower reactors and solar panels are placed robotically within the energy production area, and the electric cables are laid down until the habitat area, at 300m of distance. Just after the construction of the first habitat module, the site will be ready to host the first crew which will land on Martian soil with the SLS BLOCK 1B vehicle in 2036. Upon its arrival, the astronauts will find the Archimars Pressurized Rover waiting at the landing pad to take them to the habitat. The first nucleus consists of three multifunctional units, one main and two secondary, and an unpressurized hangar to protect the vehicle during sandstorms and solar events.

- **Landing Area:** The first area to come in contact with the human spaceships will be the landing pads. The area chosen as the landing area must comply with some technical and physical requirements such as the adequate solidity of the ground considering an underlying paved surface, the scarce presence of rocks on the ground to avoid any accidents during the descent of the vehicle, the conformation preferably flat, less than 10% slope, the low ground level to allow the spacecraft, which uses the Martian atmosphere for its deceleration, to descend in complete safety. Each of the two landing pads will be 100m in diameter and surrounded by a protective wall of printed 3d regolith. The wall is critical to stop the sandblasting effect on the structures of the Starship propulsive landing. The whole landing area must comply with a distance of at least 500m from the habitat area, and served by the main road to minimize the dust circulation and enhance crew safety. The landing pad will need to sustain more launches with minimal maintenance time. Within the area, it is necessary to consider the presence of other buildings such as maintenance bay and emergency shelters for radiations, micrometeoroids, and sandstorms or to store the unloaded cargo.
- **ISRU Area:** As human capability for long-range missions evolves, the In Situ resources utilization and manufacturing will become increasingly important. The ISRU area is dedicated to the collection, processing, and storage of materials produced from the mars soil. Breathable air, clean water, metals, rocket

propellants, building materials, and more. All these elements can be extracted through chemical and mechanical processes such as electrolysis. The selection of the Area is based on the presence of ice and some other basic mineral elements, such as basalt. Other elements such as propellant can be extracted directly from the atmosphere rich in carbon dioxide or even from the regolith itself. From raw materials such as ice, regolith, sulfur, and basalt, through processing methods like sintering, hot pressing, and liquefaction, other materials would be produced, such as glass and fiberglass, polyethylene, plastic, iron, and steel. The energy production will be progressively excavated like lithic mining sites on Earth.

- **Power production Area:** The energy production area is dedicated to servicing the power needs of Habitat and the ISRU Area. The most important power source is the Sun from which ultraviolet rays propagate and constantly hit the surface of Mars. Through lightweight, super-efficient photovoltaic panels. Solar power will be used as the main source of the outpost, refilling the accumulators of the outposts. The panels will need constant cleaning and maintenance, which will be mostly done robotically. The actual transformation efficiency is about 30%, but it will grow in the next future. Furthermore, solar panels have a fairly long useful life, especially considering that on Mars they would be subjected to much milder weather events and more favorable temperatures. which turns them into a long-term renewable energy source. A considered solution to integrate panel production is the use of multiple Kilopower reactors. The kilo power uses a solid core of molten Uranium-253 to provide a constant flow of energy, at any hour, that can protect the outpost from malfunctioning events and prolonged sandstorms. It is a very reliable solution with a high Technology Readiness Level (TLR) [71]. Some form of algae bioreactor has been also considered.

5.8 Scalability

The configuration of the single habitat module allows three points of connection, corresponded with the three airlocks placed at 120° from each other, disposed of radially. This arrangement makes it possible to connect the single unit with others, of different sizes and shapes until a hexagonal shape is achieved. The hexagonal geometric figure allows the outpost area to be divided into modular tiles, favoring a future expansion of the outpost while procedurally increasing the hosting capabilities of the system. The ISRU and energy production areas will grow consequentially until the reach of the minimum safe distance from the habitat and landing pad areas.

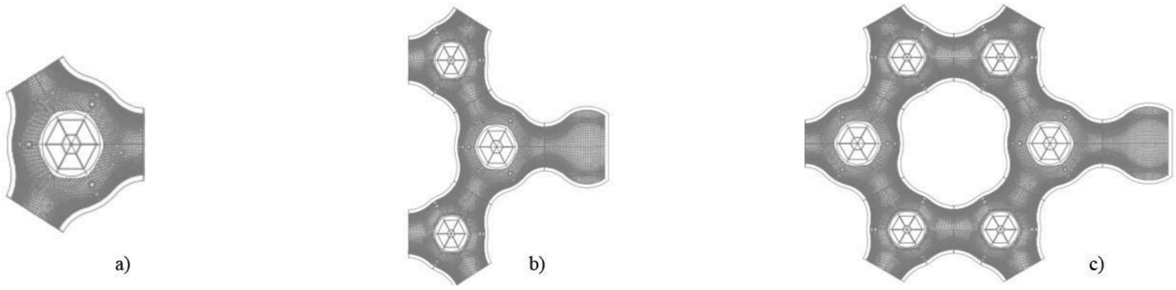


Fig.24 HiveMars Scalability three phases plan, PoliBa 2021

5.9 Moonfiber: A lunar lava tube outpost using regolith-composite fibers

The recent efforts to return to the lunar surface embodied by the development of the Artemis program include the concept of achieving a permanent stay, enabled by ISRU technologies that didn’t exist at the time of the Apollo Program; This paper present

Moonfiber, a project derived from a competition designed by Young Architects Competition (YAC) for the construction of a settlement located in a lunar Lava Tube. This choice is determined by the need to exploit a place with characteristics suitable for human permanence in the long term, achieving a balance between safety and construction complexity. The Moon is a hostile environment, seemingly devoid of blatant resources, subject to the most destructive events in the solar system, such as the constant bombardment of both micrometeorites and radiation, as well as occasional solar storms. The project finds full realization, in its working and living functional divisions, below the lunar surface, while the areas used for ISRU, 3D printing, payload unloading, and energy production operations are located near the entrance of the Lava Tube, to which they connect via a main logistic axis. The main structure, built in the Lava Tube, is made up of a series of inflatable modules held suspended in the center of the gallery by a mesh of composite material fibers obtained through extrusion and winding of regolith fiber. The weaving technique of the supporting structure becomes the turning point regarding the architectural composition of the settlement because it makes everything light and parameterized based on the morphology of the place, which is subject to an automated preliminary scan by robots performing as an avant-garde fleet, extrapolating the optimized topology underlying the definition of the framework of the system. This structure is initially defined by its anchorages to the Lava Tube walls, to which the upper and lower load-bearing fibers are connected, on which rests a mesh, also in fiber, which performs the function of a suspended base for the inflatable modules. The construction technique is based on the processing of the fiber filament. the goal is to obtain the filament from the lunar regolith, adaptable in composition with different quantities and types of yarn, from glass to carbon fiber; the production process of such coils of fiber is described in detail in this paper, along with its installation in a notional Lava Tube.

Even before the beginning of spaceflight in the mid-20th century, long duration missions and permanent settlements, either in space or on other celestial bodies, have always been at the center of the conceptual ideal pushing the concrete effort in space. Space stations orbiting the Earth, lunar and martian bases have been considered logical and sequential objectives, instrumental to the colonization of space, with the idea that man would eventually have been able to call the solar system his home by means of these infrastructures. The practical translation from conceptual design to finished product is however much more difficult and littered with obstacles than the average sci-fi writer would imagine, as the progress towards such ideal goals is always a compromise between the shareholders’ objectives, the current technological progress and, in particular situations, the limited resources and shortcuts that an unforgiving environment like space and other planets offer; on this latter instance, if the settlement is set to be built on the Moon or Mars, particular locations on such celestial bodies would offer a particularly attractive solution, in light of a potential reduction of shielding and overall protection requirements of the given design, a burden which would almost entirely rest on the shoulders of the indigenous Lunar or Martian Lava Tubes. These geological formations, according to scientists, have been formed by the flow of magma leading it to excavate large caverns left empty as the flowing materials continued their passage. Lunar Satellite recognition resulting in the observation of the would-be entrances of some of those geological features have led experts theorize the existence of several of these Lava Tubes, albeit more research has to be performed to assess their actual sizing, in light of a possible human colony to be established there as the booming space industry claims new space and calls for achievements, chief among which a sustainable human presence. Space Architecture is the leading technical discipline aiming to lead such progress, gathering the best technologies and design practices to achieve such goals; while Lava Tubes are still notional and their actual potential is still far from actual estimation, the proactive effort of the group writing this research paper, along with a comparable growing literature on the subject, has been to design a possible lunar settlement to be built in a notional Lunar Lava Tube. Our context of work has been a competition that was run by the YAC in the first months of 2023. The challenge, albeit called by an Italian organization like the YAC of Bologna, was open to students and young architecture professionals from all over the world. At the end of the competition in June of 2023, our design was nominated among the Honorable Mentions, testament to its quality. From the start the focus of the group was to achieve a design which greatly relied on existing or close to be launched space hardware that could be modified and implemented in this scenario, achieving an overall economy leading to the construction of the novel system on the Moon [84]. The favored approach based on a cautious examination of existing and in-development technologies has led the group to the definition of the overall settlement, along with its construction facilities, vehicles, and systems in general, fulfilling the need for a comprehensive design complying with the Space Architecture practice. The overall design output is the main subject of the paper, comprising both the construction phases along the relative equipment forecasted to support it, and the final settlement.

5.10 Relevant Technologies

Lidar Scanners: [83]Lidar technology expanded our sensing capabilities for space exploration by providing precise and detailed three-dimensional models of celestial bodies. It works by emitting laser pulses and measuring the time taken for them to return after hitting a surface. This technology is invaluable for space exploration because it can penetrate atmospheres, map surface features, and create high-resolution topographical models.

Lidar is used in various applications in space exploration. One major application is surface mapping, where Lidar scanners create detailed maps by measuring the distance between the spacecraft and the surface. These maps help scientists understand the geology and morphology of celestial bodies and select landing sites for rovers and landers, ensuring a safe touchdown and meaningful scientific exploration. Lidar technology also plays a vital role in autonomous navigation and obstacle avoidance. Spacecraft equipped with Lidar sensors can autonomously navigate and avoid collisions with debris or hazardous terrain during descent and landing, especially for missions to celestial bodies with unknown or uneven surfaces where traditional imaging systems may not be sufficient. Its applications continue to expand, contributing to our understanding of the universe and ensuring the success and safety of space missions.

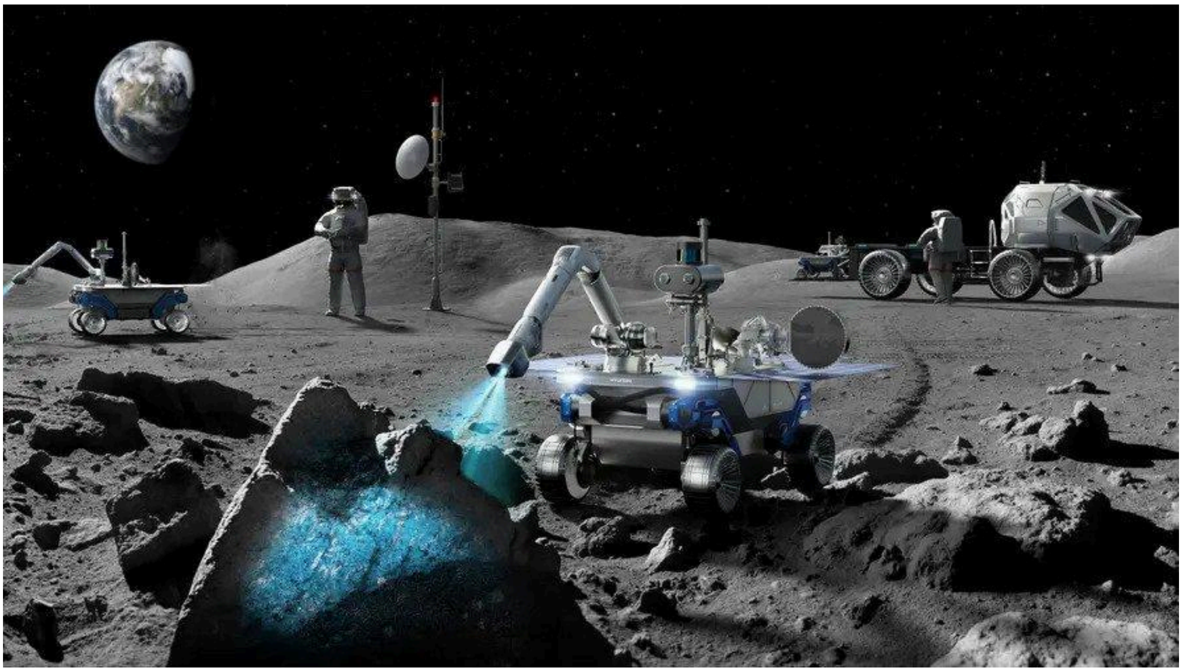


Fig.25 Toyota Lunar Rover equipped with Lidar Scanners, 2018

Regolith collection (RASSOR): The NASA Regolith Advanced Surface Systems Operations Robot, or RASSOR, represents a pioneering advancement in space exploration technology, specifically designed for the collection and excavation of regolith, the layer of loose, fragmented material covering solid rock on planets like the Moon or Mars. Design and Structure: RASSOR is engineered as a compact, lightweight robotic system featuring dual digging drums, inspired by the principle of a mechanical bucket-wheel excavator. This innovative design allows RASSOR to efficiently scoop and collect regolith in a low-gravity environment. The robot's low mass and high mobility are essential features, ensuring its ability to navigate challenging terrains while effectively gathering surface materials.

- **Scientific Relevance:** The primary purpose of RASSOR is to collect regolith samples for scientific analysis. Regolith, being the uppermost layer of planetary bodies, holds vital clues about the geological and compositional history of these celestial objects. By excavating and collecting regolith samples, scientists gain insights into the body's surface properties, mineralogy, and potential resources [88]. These samples are invaluable for understanding the origin and evolution of planetary bodies, as well as for identifying resources that could support future human settlements.

- **Resource Utilization and Sustainability:** One of the key objectives of RASSOR's development is to support the concept of In-Situ Resource Utilization (ISRU). By extracting resources, such as water ice or rare minerals, from regolith, future human missions can lessen their reliance on Earth-based supplies. This approach significantly enhances the sustainability of long-duration space missions.

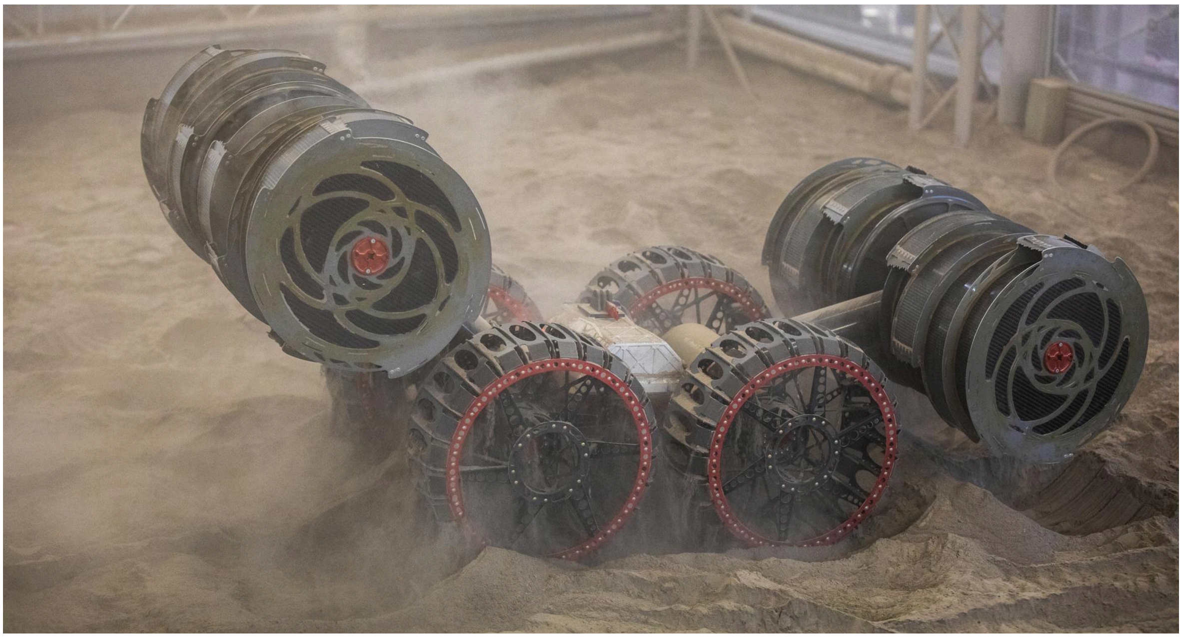


Fig.26 NASA RASSOR on testing ground, NASA 2019

Athlete : The NASA ATHLETE rover (All-Terrain Hex-Limbed Extra-Terrestrial Explorer) represents a cutting-edge robotic system designed for extraterrestrial exploration. Developed by NASA's Jet Propulsion Laboratory (JPL), ATHLETE is a versatile and highly adaptable robotic platform specifically engineered for lunar and planetary missions. Its design features six multi-jointed limbs, each equipped with wheels, allowing it to traverse diverse terrains with remarkable agility and stability.

- **Structural Design:** ATHLETE's hexapod configuration consists of six limbs, resembling insect legs, each with six degrees of freedom. This design grants ATHLETE exceptional flexibility in movement, enabling it to climb steep slopes, navigate rocky landscapes, and surmount various obstacles. The rover's legs terminate in wheels, which provide mobility on flat surfaces and enhance its overall versatility.
- **Mobility and Navigation:** ATHLETE's mobility system allows it to walk, roll, or use a combination of both, enabling seamless transitions between different modes of movement. Its autonomous navigation capabilities, coupled with a suite of sensors, including cameras and LIDAR (Light Detection and Ranging), enable it to navigate and map its surroundings with precision. This advanced sensor array facilitates obstacle detection and avoidance, ensuring the rover's safe traversal across challenging extraterrestrial terrains.
- **Payload Capacity:** One of ATHLETE's significant features is its impressive payload capacity. Its modular design allows for the attachment of various payloads, scientific instruments, and tools. This versatility makes ATHLETE an ideal platform for transporting and deploying equipment on the lunar or planetary surface. Its ability to carry substantial payloads enhances its utility for scientific exploration and construction tasks.
- **Potential Applications:** ATHLETE's adaptability and mobility make it suitable for a

wide range of applications, including geological exploration, sample collection, and infrastructure development. Its ability to access challenging terrains, transport heavy loads, and collaborate with human explorers positions it as a crucial asset in the exploration and potential colonization of other celestial bodies.

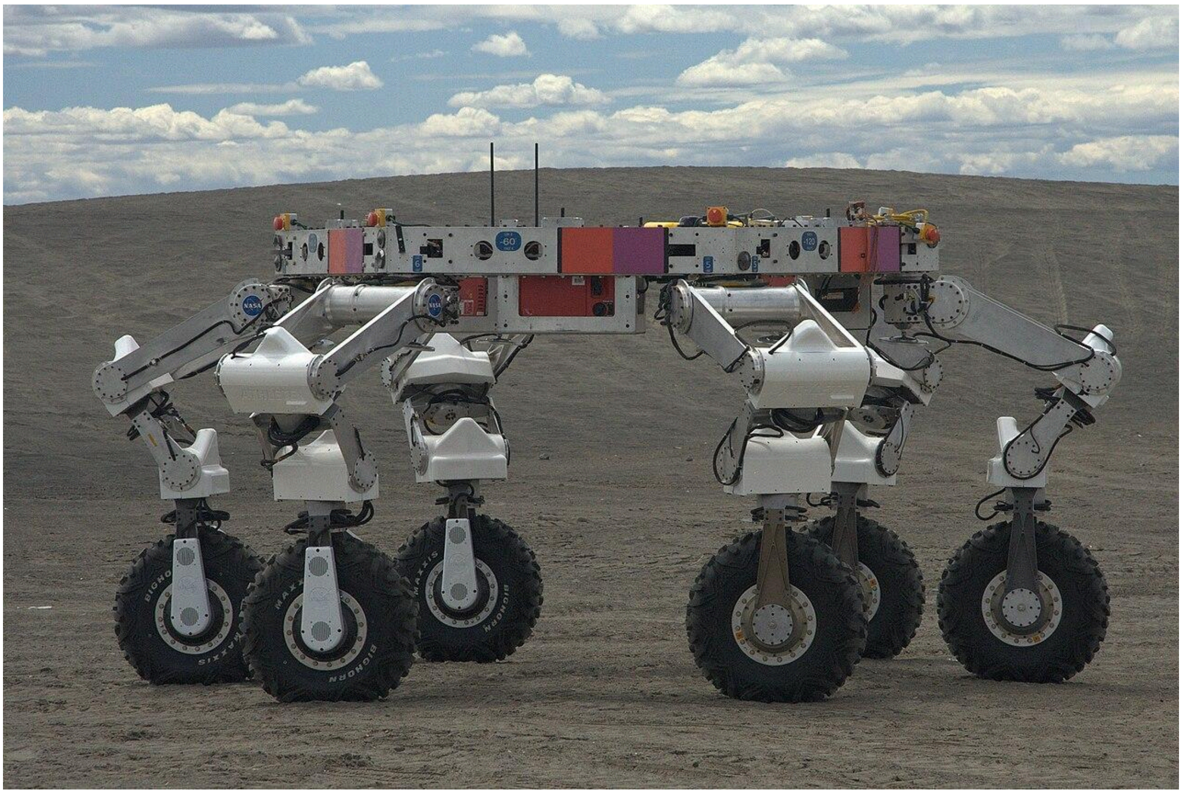


Fig.27 NASA ATHLETE v1 during a DESERT RATS Mission, 2017

5.11 Fiber Production and Winding

The production of lunar regolith fibers [73] presents a novel approach to using resources available on the Moon for construction, habitat manufacturing, and even 3D printing [79, 82]. The process involves extracting and processing regolith, the layer of loose, fragmented material covering the Moon's surface, to create durable and versatile fibers that can be incorporated into building materials and other industrial products. The process includes several steps:

Collection and Beneficiation: Firstly, robotic or automated systems would be used to excavate lunar regolith, with digging tools equipped to collect and process the surface material effectively. The collected regolith would be transported to a processing facility where impurities, such as dust, rocks, and other contaminants would be removed through sieving, magnetic separation, and chemical treatments. Such processes, albeit not discussed in detail in this paper as they are considered to be future assets within the MoonFiber regolith processing system, have been extensively investigated within the topic-related literature of the last few years, with an increasing degree of detail and accuracy about such processes. One of the crucial aspects that the analysis of such papers highlights is the need for such workflows to be standardized, along with the concurrent need for the enabling-machines to be designed; this corresponds to the requirement to obtain systems which can be proved sustainable from an economical standpoint. The ATHLETE-based and RASSOR-based architecture we propose aims at such a philosophical premise, to create a relatively small and self-contained set of tools to be implemented in the creation of those economies of scale.

Processing: Once the regolith is purified, it can be processed to create fibers. One method is to melt the regolith at high temperatures and then extrude it through fine nozzles, forming thin filaments. Another method involves using a process similar to the production of glass fibers, where molten regolith is drawn into fibers as it cools. These methods result in regolith fibers that are strong, lightweight, and potentially suitable for a variety of applications, to be manufactured by means of the tools and machines discussed in the previous point.

Mixing: Lunar regolith fibers can be incorporated into composite materials, such as polymers or resins, to create reinforced composites. These composites have enhanced mechanical properties due to the strength and stiffness of the regolith fibers. They can be used in the construction of habitats, infrastructure, and other structures on the Moon, providing strength and durability to the manufactured components.

Extrusion: Once mixed, the regolith fibers are extruded and winded onto spools. By combining regolith fibers with binders or resins, lunar 3D printing can fabricate intricate and robust structures. This technology has the potential to revolutionize lunar construction, enabling the creation of structures and infrastructures such as tensioning cables directly on the Moon's surface. The production of lunar regolith fibers offers a sustainable and innovative solution for utilizing local resources on the Moon. By extracting, processing, and incorporating regolith fibers into various applications, we can pave the way for cost-effective lunar exploration, colonization, and the establishment of a sustainable human presence on the Moon.

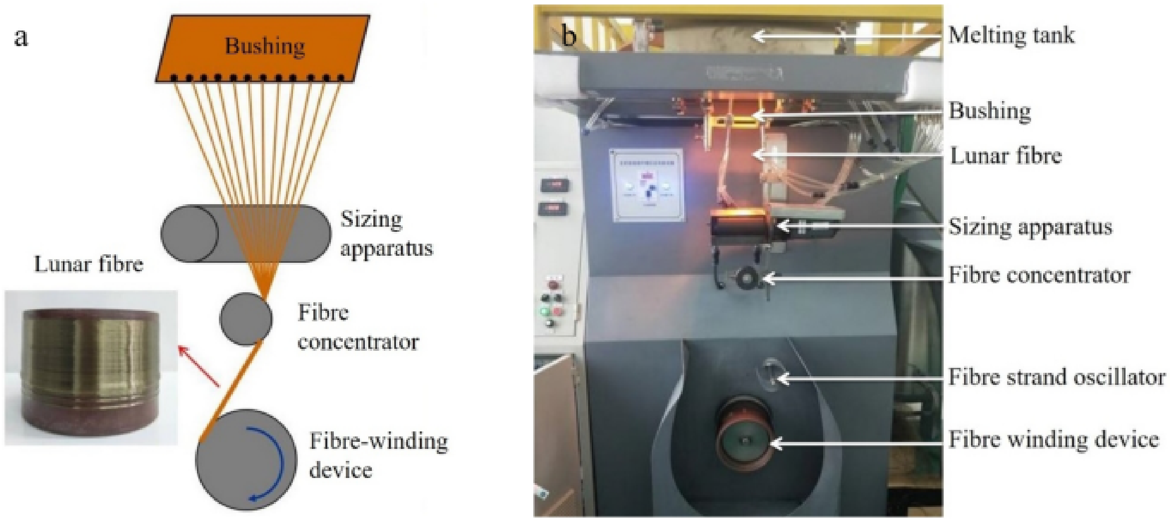


Fig.28 Regolith Fiber production process

5.12 MOONFIBER PROJECT

The YAC organization of Italy launched a design competition in the first part of 2023, which brief was the design of a settlement meant to be built exploiting the features of a Lunar Lava Tube, taking advantage of its convenient, albeit notional, protected enclosure from the Sun’s radiation and the micrometeoroids impact. The design and project rendering effort took about four months starting in early March 2023 with the conceptual design and the fundamental philosophy of the project being laid out as the requirements were concurrently determined. The project idea, as mentioned in the introduction, is based on the construction of a settlement located in a lunar Lava Tube, a requirement that was given to the team by the competition’s brief. This choice is determined by the need to exploit a place with characteristics suitable for human permanence in the long term, achieving a balance between safety and relative construction economy. The Moon is a hostile environment, seemingly devoid of overt resources, subject to the most destructive events in the solar system, such as the constant bombardment of both micrometeorites and radiation, as well as occasional solar storms.

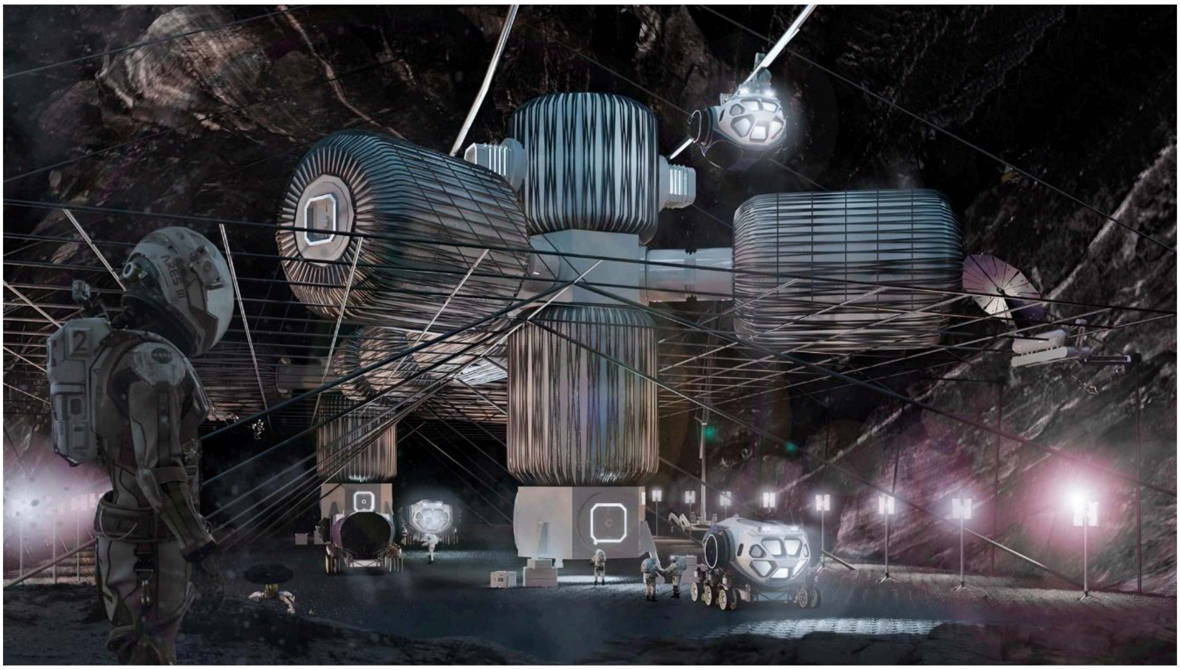


Fig.29 MoonFiber outpost, Poliba, 2023

The project finds full realization, in its working and living functional divisions, below the lunar surface, while the areas used for ISRU, 3D printing, payload unloading and energy production operations are located near the entrance of the Lava Tubes, to which they connect via a main logistic axis. The construction technique is based on the processing of the fiber filament. The goal is to combine technological innovation, computational design and structural performance, optimizing in-situ fiber production. In particular, the goal is to obtain the filament from the lunar regolith, adaptable in composition with different quantities and types of yarn, from glass to carbon fiber, obtained from the regolith. Once the coil has been produced, the filament is impregnated in two-component epoxy resins in order to be woven and intertwined according to a precise algorithm on the surface of the modules, and once the weaving is finished, the fiber takes shape and acquires its formidable resistance. This process of extraction, production and installation is made possible by a series of ad hoc robots, covered in detail in the project.

5.13 Mission Architecture

The settlement is located, at least for what pertains to the inhabited portion, in the Lava Tube where the support structure is built by means of additive manufacturing technologies combining initial topology optimization and subsequent ISRU. The objective of the preliminary topology optimization is to enable a considerable flexibility in terms of the structure to be built to obtain the best performance regardless of the geometry of the Lava Tube; this is due to the inherently notional nature of the site, a consequence of the lack of reliable information about it, resulting in an adaptability requirement informing the design. The resulting support structure can therefore substantially differ from the one shown in the renderings, adapting itself to the particular topology of the site. Such topology investigations are performed before any construction by pioneering automated systems doing the analysis; such a proactive approach is another key enabling factor to the adaptability of the overall architecture. After the topology of the Lava Tube and its geological features have been investigated, the following step deals with the construction process, performed by the combination of pioneering and new incoming systems. Among these new assets, key to the construction process, are ATHLETE-based and MMSEV-based rovers and machinery used in the ISRU processes leading up to the final materials employed in the construction. ATHLETE-based rovers, given their adaptability, scalability, lightness, and overall flexibility, are used to correctly position the structural components of the support net that enables the inflatable modules to be lifted from the ground, hence creating a useful segregation between habitable systems and regolith-filled environments. ATHLETE-based assets vary depending on the payload, mounted on the common moving architecture made of six spider-type legs. MMSEV-based assets are used to make the transportation system of the mature infrastructure, either in their original NASA design or in a different interpretation of the same: the idea in this case is to remove the bottom chassis with the rover's wheels, taking the pressurized module and making it into a cable car, creating a suspended transportation system that connects the equally suspended facilities in the Lava Tube and the remainder of the infrastructure outside, with a system that goes all the way to the Landing Pads were cargo supplies are meant to be unloaded.

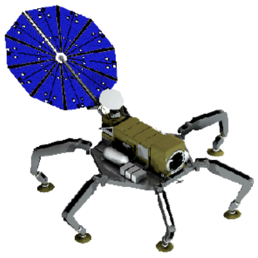
5.14 Mobile Assets

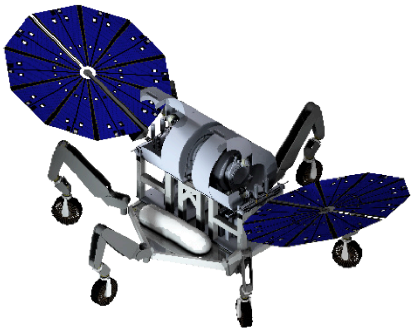
Here's an overview on the particular mobile assets envisioned so far:

SpiderExplorer: These small robots are built on top of a small version of the ATHLETE platform and are designed to inspect the Lava Tube site first, and then to support the construction phases.

SpiderCrane: based on the large ATHLETE chassis, with a lunar crane on its top, meant to be used as a lifting and moving tool for cargo, modules, and most importantly the fibers for the Lava Tube support structure.

SpiderGatherer: a combination of ATHLETE and RASSORS systems with a large container for the lunar material, it's a robot conceived to gather the lunar regolith to be used as a building material through ISRU processes.





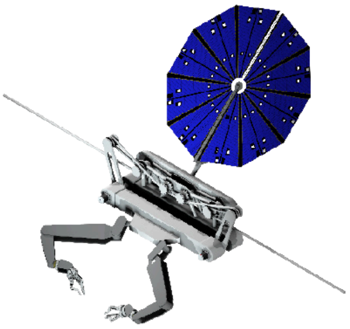


Fig.30 SpiderExplorer, SpiderWinder and ShuttleWeaver rover, Poliba, 2023

SpiderWinder: after completion of the ISRU phase leading up to the final construction material, the fiber is winded on large spools mounted on an ATHLETE base, enabling its transportation to the installation site.

CrewShuttle and PayloadShuttle: To ensure a constant separation from any dust contamination, preserving the same segregation and cleaness of the settlement in the Lava Tube, a system of cable cars has been developed. Based on the MMSEV rover body and on the ShuttleWeaver cable system, it is composed of a crewed and an uncrewed version, both of which can dock using their two hatches to safely transfer crews and cargo.

ShuttleWeaver: a robotic climber which is used to arrange the fiber in the tunnel, working like the shuttle of a loom. It’s brought to the Moon with the first lander and on subsequent missions.

5.15 Construction Processes

The project built in the Lava Tube is made up of a series of inflatable modules detached from the dirty lunar surface and held suspended in the center of the gallery by a mesh of composite material fibers [86]. The weaving technique [74] of the supporting structure becomes the turning point in the architectural composition of the settlement because it makes the support structure light and parameterized based on the morphology of the Lava Tube. This constructive flexibility makes the project adaptable to several potential sites, subject to an automated preliminary scan by robots performing an avant-garde function, inspecting the morphology of a given site and extrapolating the optimized topology underlying the definition of the framework of the system.

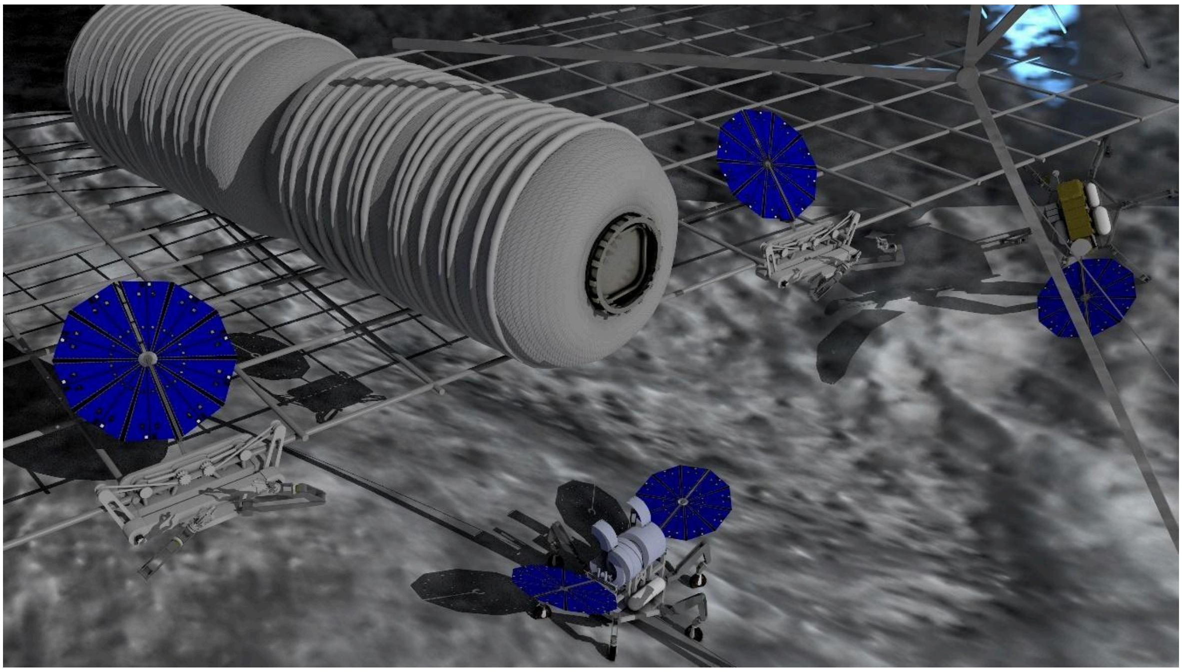


Fig.31 MoonFiber outpost construction process, Poliba, 2023

This structure is initially defined by 3d printed anchorages to the Lava Tube walls, where the upper and lower load-bearing fibers are connected, on which rests a mesh, also in fiber, which performs the function of a suspended support grid for the inflatable modules. The same technique is also used to reinforce and stabilize the inflatable modules, according to a parametric algorithm that generates a weave over the entire surface of the module. It creates protection, reinforcement, while integrating the housing modules with the main structure.

5.16 Outpost Functions

The entire complex consists of 8 inflatable modules with each specific dimension such as by competition line guides:

- Gym 60 mq
- Guest accommodation (2 levels - 6mq)

- Staff accommodation (2 levels - 6mq)
- Common areas (2 levels - 150mq)
- Dashboard 40 mq
- Hydroponics module 80 mq
- Work area 130 mq
- Infirmary 30 mq

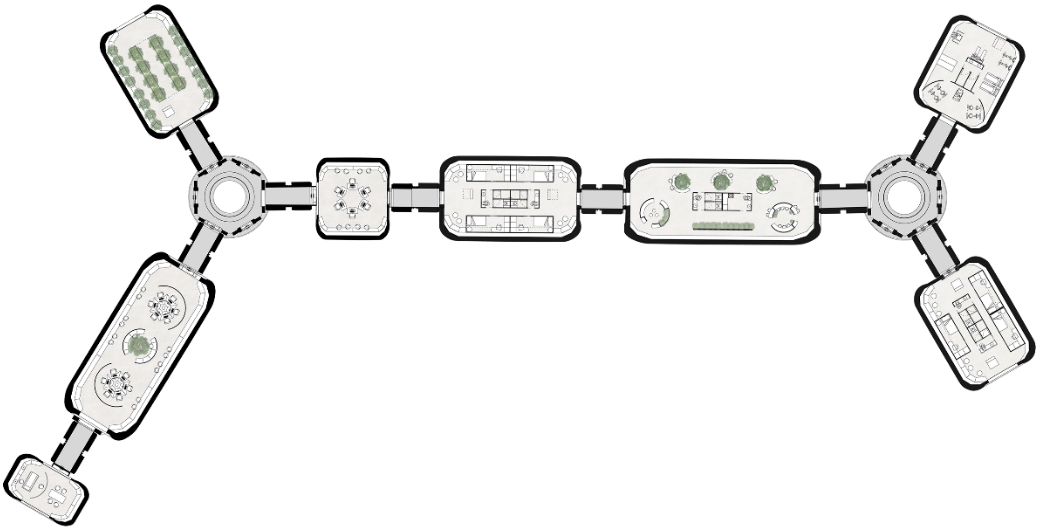


Fig.32 MoonFiber outpost module Plan, Poliba, 2023

5.17 Other Surface Assets

ISRU: All the elements that aren't brought from the Earth are collected and used directly in situ [77], exploiting all the local resources currently trapped within the soil of the Moon. The crew members will need oxygen to breathe, water and energy to power their habitat. Instead of bringing everything they need from Earth, they will use in situ resources. This way is self-sufficient, economically and environmentally friendly.

The use of Lunar regolith, with other surface minerals such as basalt, sulphur and ice, can be processed to obtain new materials to be used during construction. For example, fiberglass or lunar ink for the 3d printing process for some components. The production of the material in situ is closely linked to construction technologies that see new applications and new experiments already on Earth. Additive manufacturing, 3D printing, and the production of the fiberglass or basalt fiber can reduce the amount of material transported from Earth, construction costs, time, and even environmental impact, using less material and generating less waste.

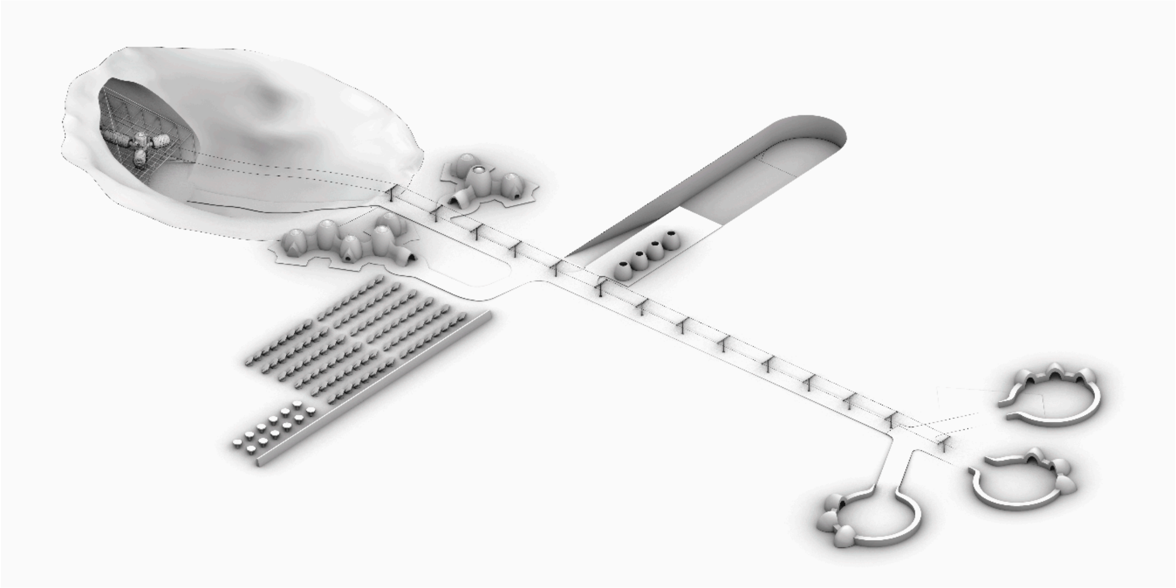


Fig.34 MoonFiber outpost MasterPlan, Poliba, 2023

Power Production: The lunar habitat needs the system of structures that can't be made in situ and must be brought from the Earth. These infrastructures are prefabricated elements capable of making human settlement self-sufficient and are collocated in two specific areas, and Power area, these areas play the role of:

- Energy production, entrusted to solar panels and kilopower;
- Storage made by prefabricated elements which allow water, oxygen and fuel storage.

Observatory: Located outside the Lava Tube, on the edge that delimits its morphology, the

Lunar Observatory is designed to be a unique structure of its kind: the lack of any atmosphere on the Moon allows images of the Universe to be obtained without those atmospheric disturbances that torment their terrestrial counterparts. The habitable and pressurized core of the Observatory consists of a two-level inflatable module and a central core: this module is inserted inside a 3D printed casing based on lunar regolith, in order to obtain maximum protection from micrometeorites and from radiation. But the real piece-de-resistance of the Observatory is the upper geodesic sphere, which houses the two telescopes, one optical and one infrared. This geodesic sphere, not pressurized and to which it is not necessary to access for normal operations, rests on the underlying structure through bearings, which combined with its shape, allow it to be orientated in any direction; this feature also fulfills the protective function of the telescopes and internal mechanical parts, since in the event of an emergency, due to micro meteoric rain or solar storm, the sphere can rotate 180 degrees and hide the openings from which the telescopes look out.

Logistics and Infrastructure: The main communication route is made up of two ideal levels, designed to guarantee a constant separation between activities on the ground and activities “in mid-air”: the former, in fact, being affected by the interaction with the lunar regolith and therefore being “dirty” areas , must be segregated from “clean” areas, where the life and work of future inhabitants can take place in safety. The need for this separation is due to the characteristics of the lunar dust, potentially harmful to human health, despite being the main resource for the construction of the structure itself; while the dirty areas are served by the classic MMSEV rovers on the ground, the clean areas are connected to the landing pads via a gondola lift, designed for both payloads and crews.

The suspended vehicles, which travel along this “lunar cable car”, allow the safe transport of both cargo and personnel from the vehicles that land at the opposite end of the settlement in the landing pads. The complementary function of the cable car and the underlying lunar “Main Street” is to guarantee the constant and efficient supply of resources, both those coming from the Earth and those in-situ [80].

This project has introduced a new model of habitat, in particular the class two and the new technology. The priority of the competition and also the design of this project was to protect the health and safety of the crew and support their sustainable productivity through good construction for habitability and human factors. So as to reduce mission costs and launch cargo from Earth, ollowing the exploration of the chosen area, these machines deal with the construction of infrastructures, the production of resources useful for life such as water, energy, oxygen, and the production of construction materials. This configuration allowed us to connect all the inflatable modules on the fiber grid in a continuous way. This settlement is characterized by the first housing system capable of protecting humans from radiation because it is in the Lavatube. In conclusion, if inhabiting the Moon is one of the objectives humanity would like to achieve, many factors must be considered, including the adaptability of the human species to extreme conditions, economic and human factors. These latter aspects of the analysis have only been touched upon in this paper, as the inherently design-focused nature of this article is meant to provide a general vision of a possible outpost to be built in a Lunar Lava Tube; the enabling economical considerations pertain to further analysis and investigations to be done as a follow up to the main vision expressed in the paper; however, this article would not be complete if some generic considerations were not to be laid out, serving as a compendium for the future. The central leitmotiv of this research was the reliance on existing and/or foreseeable assets like ATHLETE and the RASSOR, a choice that is the best representation of the foundational aspects of the paper, chief among which the relative self-contained nature of such assets and the scalability of the products that those assets can deliver. The first aspect is related to one of the most constraining requirements in spaceflight, which is the exponentially smaller payload fraction of any launch vehicle, when compared to the overall fuel and rocket size used to deliver such payload. This strict requirement prompts the viability of machines capable of ISRU and manufacturing, which lead to the consequent scalability character of the overall venture, as opposed to an incrementally growing outpost relying only on Earth-launched supplies, let alone a one-off mission carrying the entire system to the location. As a conclusive argument regarding our work we can then state that this work can only be a design effort which can only be the prelude to further similar ventures, of which this article attempts to be a reliable literature starting point. For the group that has laid this work down during the early months of 2023 the design effort has been a one of a kind attempt to merge idealistic visions with technical feasibility of the project, in accordance with the philosophy of the Space Architecture discipline.

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