MISSION TO MARS: A PERFORMANCE DRIVEN DESIGN APPROACH

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ABSTRACT

The research paper elaborates upon performance driven design experiments at the Faculty of Architecture, TU Delft, Netherlands for habitation and production facilities on Mars. The experiments focus on enhancing optimal multi-usability of interior space, 3d printable integrated structure and skin solutions and the effective usage of greenhouses and water infrastructure for radiation shielding and self-sustenance in the environmental conditions on Mars.

The paper, shall, apart from providing a concise overview on the implications of the participatory role of contemporary architects and designers in the space race, shall dive deeper into synergistic explorations pertaining to Human Factors, Environmental Engineering Material Systems, Biomimicry, Fabrication Logics and Computational Design. These, domains and their cohesive associations are deemed essential for generating holistic spatial solutions for the conducted experiments. The main goal of the experiments being: to develop new typologies of Space Architecture in the form of self-sustainable base stations capable of producing an environment suitable for long-term habitation.

Within the above-mentioned context, the paper shall elaborate upon two architectural experiments dealing with on-site production of resources, long-range mobility, novel structural assemblages (based on computational simulation techniques of fibrous and cellular aggregation) and cyclic infrastructural self-sustainability. The role of computationally driven spatial planning, continuity of topological geometry at the micro and macro scales (for ease of fabrication), its integration with distributed greenhouses for creating psychological associations and well-being of the inhabitants and Biomimicry driven real-time adaptation of space shall be intensively presented. Multimodal real-time interactive spaces, an area of expertise of the Hyperbody research group at the Hyperbody group, TU Delft shall also be elaborated upon, in order to provide creative insights into fully customizable, embedded sensing, actuation and control mechanisms driven spatial solutions.

In conclusion, the research paper operates as an inter-disciplinary vehicle for experimenting and showcasing novel spatial solutions for habitations on Mars while suggesting the benefits of integrating architectural designers at the process and conceptual development phases for the Mission to Mars.
Contents

ABSTRACT .................................................................................................................................................. 1
INTRODUCTION ........................................................................................................................................ 4
RESEARCH UNDERPINNING .................................................................................................................. 6
  a. Biomimicry ........................................................................................................................................... 7
  b. Human Factor ..................................................................................................................................... 8
  c. Computational Design ....................................................................................................................... 9
  d. Environmental Engineering ............................................................................................................. 10
    Environmental Conditions and Requirements ...................................................................................... 10
    In-Situ Resources on Mars .................................................................................................................. 12
  e. Materials and Technology .............................................................................................................. 14
    Polyethylene - PE ................................................................................................................................. 14
    Polypropylene – PP ............................................................................................................................... 14
    Glass fiber – reinforced polymer – GFRP ............................................................................................ 14
    Carbon fiber – reinforced polymer – CFRP ......................................................................................... 14
    Graphene ............................................................................................................................................... 15
    Aerogel ................................................................................................................................................... 15
    Phase-changing materials ..................................................................................................................... 15
    Electroluminescence (EL) Displays ..................................................................................................... 15
  f. Sustainable energy usage .................................................................................................................. 15
g. Fabrication Logics .................................................................................................................................. 16
    Flexible Textile Structures .................................................................................................................. 16
    D-Shape ................................................................................................................................................ 17
    Material .................................................................................................................................................. 18
    4D Printing .......................................................................................................................................... 18
    Mark One ............................................................................................................................................ 19
    Advantages of 3D printed structures ..................................................................................................... 20
Conclusion and Overview Map ........................................................................................................... 20
Research Questions ................................................................................................................................... 20
EXPERIMENTAL PREMISES ................................................................................................................... 21
  Crew composition ................................................................................................................................. 21
  Functional Requirements ...................................................................................................................... 21
  Structural & Technical Requirements .................................................................................................... 22
  Research Experiments .......................................................................................................................... 23
  Common Construction Scenario ........................................................................................................... 23
EXPERIMENT A – RE_MOVE (A BIOMIMETICS INSPIRED MOVABLE HABITAT STRUCTURE FOR RESEARCH AND EXPLORATION PURPOSES).....24
  Underpinning........................................................................................................24
  Biomimetics and movement..................................................................................25
  In-situ atmospheric harvesting and resource production system........................28
  Architectural Form Finding...................................................................................29
    Cellular Aggregation Form-finding ....................................................................29
  Functional distribution and spatial qualities.........................................................30
  Computational optimization...................................................................................33
    Monocoque geometries......................................................................................33
    Solar and structural optimization........................................................................34
  Integrated design...................................................................................................36
  Conclusion..............................................................................................................36

EXPERIMENT B – MARS CONTINUUM (ONE SKIN - ONE STRUCTURE FOR EFFECTIVE USAGE OF GREENHOUSE AND WATER INFRASTRUCTURE FOR RADIATION SHIELDING) ..................................................40
  Biomimicry............................................................................................................40
    Understanding the Cacti make-up.....................................................................40
    Understanding Bone porosity – the case of the femur bone............................42
  Minimal surface condition ..................................................................................42
  Program network and distribution .....................................................................43
  Geometry and computational optimization.........................................................44
    Solar analysis......................................................................................................45
    Structural analysis..............................................................................................46
  Section..................................................................................................................50
  Conclusion..............................................................................................................50

GENERAL CONCLUSION......................................................................................55
APPENDIX ..............................................................................................................56
REFERENCES.......................................................................................................59
INTRODUCTION

Current approved prediction models such as Hubbert Peak Theory\(^1\) or Limits to Growth Model\(^2\) estimate that given our current resource needs, we will soon reach a resource saturation point, followed by a sharp global decline of civilization. **Fig. 1** Moreover, this is not the only threat facing us, albeit it represents the most urgent to tackle. Humanity has to extend its reach beyond Earth to ensure the survival of our civilization and species.

The Cold War that started the Space Race and propelled space exploration programs created technological advancements that influenced human society. During the 70’s and 80’s, the general up-lift, “If we conquered the Moon, we can do …”\(^3\) attitude produced a lot of proposals from different fields of interests for outer Earth colonies and space stations. The 1975 NASA Summer Study\(^4\), which saw many projects that implemented both engineering and architectural solutions remarkably are a proof of this interest. **Fig. 2**
Although the architectural community was rarely involved in such projects, the last 10 years show a renewed interest from architectural praxis as well as academia for envisioning space architecture. Studio Lynn in Vienna\(^5\) \textit{Fig. 3} focuses on spatial perception and formal experiments in outer space while Foster + Partners together with ESA\(^6\) are working on developing 3D printing techniques and in-situ materials for a Moon base. \textit{Fig. 4} Also, we can find numerous projects and competition entries that tackle the subject, such as the recent entries for the eVolo architectural competition\(^7\). \textit{Fig. 5}

\textit{Fig. 3}: Greg Lynn Studio Vienna - Space Study

Source: http://spacecollective.org/jiri

\textit{Fig. 4}: Moon Base proposal by European Space Agency (ESA) and Foster + Partners

Source: http://www.esa.int/spaceinimages/Images/2013/01/Multidome_base_being_constructed

\textit{Fig. 5}: eVolo competition - Ring of Mars: Proposed Cities in Outer Space

The authors believe that current architectural practice and new technologies enable us to shift from current trends of technically driven design approaches that usually lack spatial qualities towards a new generation of inclusive spatial solutions for space habitats that are based on synergizing human psychology, technical innovativeness, long term performance and adaptation in time, novel structural qualities deciphered from material properties (based on computational simulation techniques of fibrous and cellular aggregation) and infrastructural self-sustainability.

The role of computationally driven spatial planning, continuity of topological geometry at the micro and macro scales (for ease of fabrication), its integration with distributed greenhouses for creating psychological associations and well-being of the inhabitants and Biomimicry driven real-time adaptation of space are a few characteristics of such spatial solutions, which the authors have been involved with. The role of inter-disciplinary research driven design, which, delves into establishing a relational linkage between multiple domains to generate multi-performative solutions is put forth via this paper. The experiments detailed in this paper, shall outline the pros and cons of such investigations and showcase spatial solutions, which are defendable from sociological, technical, spatial and sustainable perspectives.

RESEARCH UNDERPINNING

Coming from an architectural background, the authors’ purpose is to establish a relational linkage between the domains of Biomimicry, Human Factors, Computational Design, Environmental Engineering, Material Systems and Fabrication Logics in order to decipher performance-driven architectural designs for self-sustainable habitats. These findings are then cumulated in a visual reference map Fig. 6 to understand the underlying relationship between each of the aspects studied as to be able to ensure a solid footing for the proposed formal experiments. The mapping, thus acts as a visual support for inter-disciplinary research that can be further expanded while narrowing down and maintaining control of the evolution of the experiments.

Fig. 6: Visual representation map
Credits: Authors
Concise research findings per domain/research component are elaborated upon in the following sections. These findings specifically relate to the experiments, which we elaborated upon in the experiments sections of the paper.

**a. Biomimicry**

Nature and organisms, over the course of billions of years, have been able, through evolution, to dynamically adapt to their environment. Biomimicry, as a field of research, can provide optimal solutions for various problems. As Petra Gruber states:

"It is therefore the principal goal of biomimetics to provide an in-depth understanding of the solutions and strategies having evolved over time and their possible implementation into technological practice." 8

From Petra Gruber’s teachings, the authors also distilled that Biomimicry, as a domain, can be split into 3 general subfields: structural bionics, (structure, materials and construction in nature), procedural bionics (nature’s procedures or processes) and informational bionics (principles of development, evolution and information transfer).9 Self-sustenance via real-time adaptation, self-organization, cellular aggregation, self-similarity, information regulation and novel topologies are some of the vital principles, which the authors extract from the research into Biomimicry.

Combining the field of interaction design and new media with such findings has also lead to interesting architectural installations, such as “Hyozolic Ground” installation by Philip Beesley Fig. 7. The project recreates a hierarchical artificial ecosystem that integrates movement, sensing and production into a multi-layered complex gesture. The designer states:

"[…] with an immersive, interactive environment made of tens of thousands of lightweight digitally-fabricated components fitted with meshed microprocessors and sensors. The glass-like fragility of this artificial forest is built of an intricate lattice of small transparent acrylic meshwork links, covered with a network of interactive mechanical fronds, filters and whiskers. The environment is similar to a coral reef, following cycles of opening, clamping, filtering and digesting."10

Fig. 7: Hylozoic Ground by Philip Beesley
b. Human Factor

The human factor component not only includes spatial perception and basic ergonomic requirements but also psychological impact on the users of the designed habitats. Architectural space and its parameters such as scale, density, porosity, color, depth etc. have the quality of influencing psychological and physical well-being of its users.

Serious psychological effects that appear from confinement and isolation are currently observed in current low-orbit habitats and Earth analogues experiments\(^\text{11}\). This is due to the fact that the design is strictly technical and utilitarian. The next generation of habitats is one where familiar spatial organization and objects can be found as a way to provide psychological relief\(^\text{12}\). While we cannot discern any architectural input from the presented NASA proposals, we can observe they take into consideration the notion of “familiarity”.

Spatial layout configurations are another major issue in creating psychological issues. Fig. 8 shows a diagrammatic view of the layouts in the ISS and other proposed habitats Fig. 9. What can be observed is that due to the use of simple layouts (linear on the ISS, circular on the MEDUSA\(^\text{13}\) project) a number of problems appear, such as: low private space, monotony in daily cycles, high noise areas, no appropriate common areas, highly technical appearance and no familiar configuration in the design of spaces and hygiene is difficult to maintain due to scarcity of water. Moreover, limited living conditions lead to serious socio-psychological issues on long-term missions.

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Another serious issue that has been observed on Earth analogues such as the HI-SEAS in Hawaii is the slow installment of boredom. As Kate Green suggests, this is due to the lack of variety in sensory input coupled with the daily routine participants are having. Green proposes that mitigation of the issue of boredom can be achieved through a more attentive interior design that stimulates the senses and creativity.

Some methods of minimizing psychological issues should thus include: more generous private spaces, mitigating sources of conflict (personal hygiene, noise, and work versus rest areas), lowering feeling of fear, contact with a natural environment and establishing a natural circulation inside the habitat with more interesting spatial configurations.

c. Computational Design

The relationship between digital tools and architectural design has entered a new age. The paradigm shifts that have occurred in the last two centuries, since developments in science and technology have influenced architecture and produced the transition from mechanical production to digitalized design and fabrication. Computational design encompasses both advanced fabrication techniques for non-standard geometries and new dynamic and adaptive modes of spatial operation. The Hyperbody research group at the TU Delft, under the guidance of Dr. Nimish Biloria, investigates such design methodologies via challenging research initiatives for understanding the informatics-oriented behavior of natural systems. Experiments in performance driven design, multi-performative spatial systems as well as architectural robotics involving sensing, actuating and control systems constitute such experiments. The role of kinematics for real-time adaptation of structural, spatial and facade elements according to the dynamic change of outside and inside context is a feature, which shall also be deployed in the two experiments. For instance, real-time protection from solar flares can result in building components to be actuated and operate as shielding material in as and when needed throughout the surface of the proposed habitat, given the direction from where the particles come.

Besides the kinetic behavior of the spatial system, multi-parameter optimization shall also be vital during the design process. This involves testing and experimenting with the following software throughout the design cycle:

- Autodesk® T-splines® plug-in for Rhino® and Grasshopper® - This tool is used to design organic geometries, and allows for complex form modeling
- Weaver Bird® plug-in for Grasshopper® - This tool is used to generate a structural mesh of the developed 3D model as well as for preparing meshes for rapid manufacturing processes such as 3d printing and CNC milling.
- Millipede®/Karamba® plug-in Grasshopper® - This tool is used to verify, analyze and optimize the created structures.
- Ladybug® plug-in for Grasshopper® – This tool is used to simulate insulation and solar radiation exposure.
- Kangaroo® plug-in Grasshopper® – This tool is used to simulate real-time physical interactions with its built in physics engine.
- Galapagos® for Rhino and Grasshopper® – This evolutionary solver is used to find optimum genomes.

**d. Environmental Engineering**

**Environmental Conditions and Requirements**

Mars presents harsh environmental conditions that require careful consideration when designing habitats to ensure not only comfort but also a high degree of structural and technical protection. Research was conducted on the following environmental aspects: influence of gravity, atmospheric composition, temperature variations and specific surface characteristics.

Gravity on Mars is 1/3rd that of Earth, measured at 3 m/s^2. Specifically, for a habitat, that would imply the possibility of developing lighter structures with greater spans. Moreover, it affects how circulation through the habitat will be developed as lower gravity permits having stepper ramps, for example\(^{16}\). Atmospheric composition measurements (taken from Curiosity rover in October 2012\(^{17}\) show a mixture of 95.9% CO2, 2% AR, 1.9% N, 0.14% O and traces of other gases such as CO. Atmospheric pressure is 0.6 of that of Earth (101kPa), measured at approximately 600Pa.

As the habitat in such environmental conditions will need to be artificially pressurized for optimum living conditions, the thin atmosphere poses another interesting problem. A study published on Marssetlement.org suggests that rather than pressurizing the hub at 100kPa (thus equal to the pressure on Earth), optimal living conditions could be reached with pressures as low as 60kPa. The direct implications are, as the author notes: lower habitat mass, less air to be processed and produced, reducing strain on life-support systems and less structural stress\(^ {18}\).

Surface mean temperatures at the equator vary between -50°C to -60°C and a summer midday maximum of 0°C, although daily temperatures can have a difference of almost 60°C\(^ {19}\). These low temperatures can affect electronic equipment and structures. Special care thus needs to be taken in how the habitat is insulated and different materials perform at low temperatures.

Special surface characteristics include the fact that due to low atmospheric pressure and temperatures, water can’t exist in liquid conditions on the surface. As water transportation from Earth is difficult due to high mass, solutions could include harvesting water from the atmosphere or from the soil\(^ {20}\). Moreover and most importantly, due to the lack of a magnetic field and thin atmosphere the surface faces strong bombardment from radiation. The main
sources of radiation are GCR (galactic-cosmic rays) and short term exposures to SEP (solar-event particles), associated with coronal mass ejections and solar flares\textsuperscript{21}.

This poses a challenge for human exploration and habitat design. Average measurements for a 500-day stay on Mars exposes astronauts to a dose of approximately 1SV that would increase fatal cancer risk with about 5\%\textsuperscript{22}. Fig. 10 shows comparative radiation levels for different mission scenarios. Therefore, radiation shielding represents an important aspect to be taken into consideration for any habitat design. This would imply the need for radiation shielding materials and shading devices to protect the habitat.

Dust storms and wind events also occasionally occur on the surface, with average speeds of 10m/s as measured by the Viking Landers\textsuperscript{23}. The only risks associated with dust storms are the direct impact on exposed mechanical components and abrasion with exposed surfaces, although more experimental data needs to be acquired\textsuperscript{24}. 

\begin{center}
\includegraphics[width=\textwidth]{Fig_10_Radiation_Levels.png}
\end{center}

\textbf{Fig. 10: Radiation Levels}
In-Situ Resources on Mars

It has for some time been accepted by the scientific community that a group of meteorites came from Mars. As such, they represent actual samples of the planet and have been analyzed on Earth by the best equipment available. In these meteorites *Fig. 11*, called SNCs, many valuable elements have been detected. Magnesium, aluminum, titanium, iron, and chromium are relatively common in them. In addition, lithium, cobalt, nickel, copper, zinc, niobium, molybdenum, lanthanum, europium, tungsten, and gold have been found in trace amounts. It is quite possible that in some places these materials may be concentrated enough to be mined\textsuperscript{25}. The Mars landers Viking I, Viking II, Pathfinder, Opportunity Rover, and Spirit Rover identified aluminum, iron, magnesium, and titanium in the Martian soil. *Fig. 12*

\textbf{Fig. 11:} Nakhla Meteorite found on Earth  
Source: [http://upload.wikimedia.org/wikipedia/commons/c/c1/Nakhla_meteorite.jpg](http://upload.wikimedia.org/wikipedia/commons/c/c1/Nakhla_meteorite.jpg)

\textbf{Fig. 12:} Mars Regolith  
Source: [http://rt.com/files/news/20/92/80/00/1.jpg](http://rt.com/files/news/20/92/80/00/1.jpg)

In December 2012, these results were compared with the one of Curiosity Rover. The *Fig. 13* indicates the elemental composition of typical soils at three landing zones on Mars: Gusev Crater, where NASA's Mars Exploration Rover Spirit traveled; Meridiani Planum, where Mars Exploration Rover Opportunity landed; and Gale Crater, where NASA's newest Curiosity rover is currently investigating. The data from the Mars Exploration Rovers are from several batches of soil, while the Curiosity data are from soil taken inside a wheel scuffmark called "Portage" and examined with its Alpha Particle X-ray Spectrometer (APXS)\textsuperscript{26}.

\textbf{Fig. 13:} Diagram showing elements discovered by Spirit, Opportunity and Curiosity Rover  
Opportunity found small structures, named "blueberries" which were found to be rich in hematite, a major ore of iron. These blueberries could easily be gathered up and reduced to metallic iron that could be used to make steel. In addition, both Spirit and Opportunity Rovers found nickel-iron meteorites sitting on the surface of Mars. In December 2011, Opportunity Rover discovered a vein of gypsum sticking out of the soil. Tests confirmed that it contained calcium, sulfur, and water. Apart from this, dark sand dunes are common on the surface of Mars. Their dark tone is due to the volcanic rock called basalt. The basalt dunes are believed to contain the valuable minerals chromite, magnetite, and ilmenite. Since the wind has gathered them together, they do not even have to be mined, merely scooped up. These minerals could supply future colonists with chromium, iron, and titanium.

As we can see, the data provided by the rovers until now and the following missions like the Mars Atmosphere and Volatile Evolution Mission (MAVEN) helps us decide what kind of materials can be harvested from Mars in order to reduce the dependence of Earth. This means...
that the necessary materials that have to be brought from Earth to establish a permanent base will be reduced. Also the number of the crewmembers can significantly grow, as the spaceship could host more basic needs for the trip to Mars and the time needed for establishing the permanent base.

e. Materials and Technology

Extensive research was conducted on material systems and their properties, considering how useful and applicable would they be in the experiments. The following are some of the findings:

Polyethylene - PE

Research conducted by NASA on materials and structural characteristics provide valuable insight on performance issues. The capacity of polyethylene to be an effective radiation shield, while maintaining flexibility and low mass can permit the development of light and protective composite material. Polyethylene is usually produced from petrochemical sources, which cannot be found on Mars, but recent research shows that it could be harvested from the Martian soil and atmosphere. In this paper, the authors show a method how to create the needed hydrocarbons for obtaining PE, in order to simulate a composite material based on Martian regolith and PE as a binding source.

Polypropylene – PP

Polypropylene is a hard and flexible material. Its only side effect is that if it is exposed to heat and UV radiation it starts to degrade. This property makes it usable as a primary material for furniture, cups and other house appliances.

Glass fiber – reinforced polymer – GFRP

Behaves well under stress condition, having good tensile strength properties. Fiber makes good thermal insulation, with a thermal conductivity of the order of 0.05 W/(m·K). Thin strands of silica-based formulation glass are extruded into many fibers, obtaining the necessary filaments. Glass-reinforced plastic (GRP) – FRP – fiber reinforced plastic act together, each overcoming the deficits of the other. Whereas the plastic resins are strong in compressive loading and relatively weak in tensile strength, the glass fibers are very strong in tension but tend not to resist compression. By combining the two materials, GRP becomes a material that resists both compressive and tensile forces well. The two materials may be used uniformly or the glass may be specifically placed in those portions of the structure that will experience tensile loads.

Carbon fiber – reinforced polymer – CFRP

In the case of carbon-reinforced plastic, the reinforcement is carbon fiber that provides the strength. The matrix is usually a polymer resin, such as epoxy, to bind the reinforcements together. Unlike isotropic materials like steel and aluminum, CFRP has directional strength properties. The properties of CFRP depend on the layouts of the carbon fiber and the proportion of the carbon fibers relative to the polymer. Despite its high initial strength-to-weight ratio, the fatigue failure properties of CFRP are difficult to predict and design for. As a result, when using CFRP for critical cyclic-loading applications, engineers may need to design in
considerable strength safety margins to provide suitable component reliability over its service life.

**Graphene**

The development of composite materials such as graphene creates materials with multiple properties. It is remarkably strong for its very low weight (100 times stronger than steel) and it conducts heat and electricity with great efficiency.40

The onset temperature of reaction between the basal plane of single-layer graphene and oxygen gas is below 260 °C and the graphene burns at very low temperature ~350 °C. Electrical resistance in 40-nanometer-wide nanoribbons of epitaxial graphene changes in discrete steps. The ribbons' conductance exceeds predictions by a factor of 10. In copper, resistance increases in proportion to length as electrons encounter impurities.42

**Aerogel**

A silica based material that is ultra-porous and weighs almost 15% more than air, it is one of the best solution for thermal insulation, because of so many microscopic air pockets.43 Its lightweight, transparent and stiff properties gives the freedom of creating any desired architectural solution, without ever having the problem of thermal bridges. Also another feature of this material is the resistance against fire, creating a safe environment.

**Phase-changing materials**

Phase changing materials have the ability to change their state from hard to soft, according to structural needs. A research done by MIT shows small-scale test models being currently developed. These types of materials are suitable for robotic parts or structural parts that have to move or adapt to certain conditions.

**Electroluminescence (EL) Displays**

The light-emitting substance is usually a doped luminescent crystal (phosphor). Depending on the dopant, different colors can be achieved according to the needs and functionality of the spaces, in order to create a suitable psychological environment. EL displays can be fabricated using screen-printing techniques, which allow a great reduction in material usage, less costs and bring speed and adaptability to the fabrication process.

**f. Sustainable energy usage**

Energy requirements for the habitats will be primarily supplied through self-contained fusion reactors and solar panels. Fusion reactors function on the principal of heating up gas and splitting it up into ions and electrons. When the ions reach a high enough temperature, they overcome their mutual repulsion and collide, fusing together. At this point, high amounts of energy are released, up to 3-4 times as conventional fission reactors using a fraction of the required fuel. The main advantage of a fusion reactor is the fact that there is little to none radiation emitted and there is no risk of having a meltdown, as the reaction can be turned off at any moment. Another advantage is that hydrogen isotopes that can be easily extracted from waterpower fusion reactors.48 Although no test has reached breakpoint until now (when the
energy output is larger than the energy input), Lockheed Martin suggest that they can build a functional fusion reactor that could fit in a shipping container in around 5 to 10 years.\(^{49}\)

Solar panels are a good and tested solution to provide energy. Implementation for the habitat could range from powering non-critical systems and providing additional back-up energy for the fusion reactors. Carbon aerogels can be used in concordance with the solar panels as the material exhibits low reflection values. Specifically, only 0.3% of radiation between 250 nm and 14.3 \(\mu\)m is reflected, making them efficient for solar energy collectors.\(^{50}\)

As back-up systems, a small-scale generator as found on the Mars Curiosity rover can thus effectively be used mainly for life support systems and emergency procedures. The Curiosity generator is called The Multi-Mission Radioisotope Thermoelectric Generator, or MMRTP, an energy source that relies on the heat generated by decaying plutonium. Risks associated with radiation emissions can be mitigated by enclosing the reactor with radiation shielding materials.\(^{51}\)

\textit{g. Fabrication Logics}

Most of the above-mentioned materials can be fabricated as fibers, which then can be further produced as filaments for the use of 3D printing logics. This section deals with exploring possibilities of 3D printing material technologies.

\textbf{Flexible Textile Structures}

A collaboration initiative between DREAMS Lab Virginia Tech and Negar Kalantar and Alireza Borhani, has been researching and developing Flexible Textile Structures \textit{Fig. 18} that has potential application in medical, textile and fashion industries.\(^{52}\) They have developed some prototypes using Rhino, Grasshopper and SolidWorks CAD software to generate geometries and use two additive manufacturing approaches: Powder Bed Fusion Process and Fused Deposition Modeling Process for the 3D printer machine.\(^{53}\)

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Flexible-Textile-Structures-3d-printed-1.png}
\caption{Flexible Textile Structure}
\end{figure}

Source: http://www.3ders.org/images/Flexible-Textile-Structures-3d-printed-1.png
D-Shape

Is a new robotic building system that uses a manufacturing process similar to an additive manufacturing based printing process, with the difference being that it has the capacity to create full-size sandstone buildings. Fig. 19. In addition, the major advantage of this fabrication process is that it can lower time, labour and transportation costs.

This method has already demonstrated its potential in the Space Industry via a collaboration between the European Space Agency (ESA) and architects Foster + Partners by testing the feasibility of 3D printing using lunar soil. Using Enrico Dini’s D-Shape printer, they managed to print a brick out of simulated lunar regolith. Fig. 20
Material

The result of the collaborative research between Petr Novikov, Saša Jokić from the Institute for Advanced Architecture of Catalonía (IAAC) and Joris Laarman Studio, is a highly advanced robotic arm that can 3D print on any given surface without a need of additional support structure. Fig. 21 The main advantage of this technique is its extrusion capacity that can create 3D curves that can follow exact stress lines of a custom shape unlike the 2D layer technology that uses a horizontal plane as a building step.56

![Fig. 21: Mataerial robotic arm](http://blog.tecnospazio.org/mataerial-una-nuova-stampante-3d-per-oggetti-curvi-e-multi-cromatici-15647)

4D Printing

A cross-disciplinary research lab at MIT, the Self-Assembly Lab57 in collaboration with Stratasys’ Education58 is innovating a new method of construction and manufacturing. They managed to invent a self-assembly and programmable material technology that adapts to certain condition and needs Fig. 22. As the Self-Assembly Lab Director, Skylar Tibbits describes:

"Self-Assembly is a process by which disordered parts build an ordered structure through only local interaction. In self-assembling systems, individual parts move towards a final state, whereas in self-organizing systems, components move between multiple states, oscillate and may never come to rest in a final configuration."59

"Programmable Matter is the science, engineering and design of physical matter that has the ability to change form and/or function in a programmable fashion. 4D Printing, where the 4th dimension is time, is one recent example of PM that allows objects to be printed and self-transform in shape and material property when submerged in water."60
Mark One

Uses a 3D printing technology that enables to print continuous fiber carbon⁶¹ Fig. 23. With this technology the possibilities of creating any given geometries extend beyond the reach of today’s technologies. Its application can improve Spaceships structure as well as future outer Earth base, by making them more safe and lightweight.
Advantages of 3D printed structures

- Makes use of Martian materials
- Allows free forms and larger open spaces
- Remains rigid in case of pressure loss
- Hold weight of radiation protection
- Are lightweight structures
- Use small amount of details - repetitive details
- Can be transported anywhere
- Can be tested on Earth

Conclusion and Overview Map

The research components elaborated upon above are finally cumulated in a visual reference map Fig. 6 for understanding the underlying relationship between them. This ensures a solid footing for the proposed formal experiments.

![Visual representation map](image)

The investigations in the domains of material systems and 3d, 4d printing also shows promising directions for what can be accomplished on Earth. For instance, pushing the boundaries of 3D/4D printing with multi material prints, for example, can have huge impacts for the building industry. Real time adaptive environments and self-sustainable habitats can present a paradigm shift in how we perceive and interact with our built environment.

Research Questions

In order to synthesize the research component explorations into a generative form finding system for the habitats, the following research questions have been formulated to further narrow down the scope of the experiments and ensure the validity of the experimental output.
How can architecture contribute in creating an optimal living environment considering the harsh environmental requirements?

What would the relationship between humans, machines and architecture be in such a scenario?

What kind of formal topologies can be developed, which are multi-performative as regards being lightweight, radiation proof as well as efficient in terms of material usage and speedy fabrication?

What is the importance and the necessity of integrating kinetics and real-time adaptability for an exploration mission on Mars and what are the most efficient ways to do it?

EXPERIMENTAL PREMISES

As a general guideline for developing the experimental premises, we focused on the design brief and technical requirements for an architectural design project "Transformative Structure/Space" put forth in the summer term of 2004 by space architect Barbara Imhof and Petra Gruber. As Gruber notes:

“It was announced as a set of experimental concepts to investigate the overlapping areas of the two architectural fields of biomimetics and space system design.”

Crew composition

This section was developed and adapted by the authors of the paper, as a guideline from Georgi Petrov’s proposal for a first permanent habitat on Mars.

The total initial population is considered as 14 crewmembers which are divided according to their specializations: 5 engineers + 2 farmers + 4 scientists + 1 commander/administrator + 2 doctors/psychologist.

Each specialization is further investigated in order to formulate functional requirements and understanding their daily activities cycles. Moreover, psychological and social interaction patterns were also considered.

- Engineers – Establish and maintain life support and insure technical functionality.
- Farmers – Work mainly in maintaining the greenhouses and food production.
- Scientists – Rotate on roving trips. Analyze samples in lab space.
- Commander – Leads and coordinates work at base. Rotational role.
- Doctors/Psychologist – Keeps the crew physical and mentally healthy.

Functional Requirements

The functional requirements have been developed taking into account the average space needed for a long-term mission plus subsequent deposit and technical spaces. The total area considered is approximately 2000m². A summary of required spaces together with their areas can be found in Fig. 24.
For safety reasons, each space is provided with a series of life support nodes:

- Each node has complete capability of recycling water, air and nutrients
- Each node has an airlock to isolate in case of emergency.
- Redundancy - if one unit fails, demand can be covered by adjacent units

**Structural & Technical Requirements**

Different uses/functions require different structural conditions and spatial characteristics. Some generic parameters to be considered are as follows:

- Strength
- Stiffness
- Static vs dynamic systems,
- Mass
- Resistance to corrosion and other environmental factors
- Thermal properties
- Reliability
- Radiation degradation
- Manufacturability
- Availability and cost
- Inflatable airlocks,
- Docking ports
- Speed of transformation
- Optimized actuation systems
- Structural performance (mechanical)
- Protection (Solar Radiation)
- Material properties for technical applications
- Complexity
- Scalability
**Research Experiments**

The research experiments methodology focuses on the development of initial geometric case studies. Each experiment involved the production of a number of topological models using either a single or a combination of the presented computational tools and inter-disciplinary research structure. The initial selection of the candidate geometries, that have been further developed, are based on human factors, structural, technical and geometrical criteria. Options are gradually narrowed down via collaborative brainstorm and critiquing setting within a design studio. 3D printed models and virtual presentations constituted an important part of the design development.

The iterative research methodology involves the following steps:

- Identification of relevant models from nature
- Identification of space application for infrastructure or habitat
- Development of candidate geometries
- Evaluation and selection of the candidate geometries, considering technical and engineering aspects, necessary technology and geometry
- Design proposals
- Development of architectural working models
- Mechanical issues and constructive concepts

The approach focuses on a bottom-up emergent design process including some initial top-down decisions for setting computational environments. The above-mentioned methodology is applicable for both experiments A & B.

**Common Construction Scenario**

Continuing to rely on materials brought from Earth is an unsustainable strategy unless truly revolutionary advances in transportation technology are made. Therefore it is imperative to maximize the use of Martian materials and use revolutionary building techniques.

In-situ resources found on Mars will thus be heavily used in the construction scenario. Light materials that do require technology intensive production processes will still be delivered from Earth. As a construction technique, multi-material phased 3D printing will be implemented. These are expanded upon in the Fabrication Logic section of the paper.

A multi-step scenario, as a shared construction logic for both experiments is subsequently created and involves the following:

**Step 1:** Send highly equipped robotic equipment and lightweight materials to start harvesting resources and processing materials needed for 3D printing. These resources will be stored in temporary units. To power these, send power plants; Energy will be first provided through nuclear reactors with the plan of creating solar power plants and implementing fusion reactors.

**Step 2:** Send human crew that will have temporary inflatable structures for the habitat as long as the construction process is ongoing. Moreover, the required 3D printing technology will be sent along with the crew.

**Step 3:** Start 3D printing of the constructions under crew surveillance. Meanwhile, the crew can start producing necessary food, water and oxygen.
Step 4: Finish construction and start 3D printing interior appliances. Initial safety and systems tests.
Step 5: Phased crew transition in the habitat. Secondary safety and redundancy system tests to be performed.
Step 6: Temporary structures will be maintained as back-up solutions in case of critical emergency.
Step 7: Full use of habitat capabilities.

The extensive findings, per research component, coupled with the proposed design methodology and the experimental premise are deployed and tested via two design-research experiments, elaborated upon in the following sections.

EXPERIMENT A – RE_MOVE (A BIOMIMETICS INSPIRED MOVABLE HABITAT STRUCTURE FOR RESEARCH AND EXPLORATION PURPOSES)

The premises for the first experiment are the advantages of providing a movable structure as opposed to a static habitat for research and exploration. The concept focuses on the following 3 aspects: movement and adaptability, in-situ resource production & harvesting and architectural form finding. Specific attention is placed on earning from Biomimicry for developing movement mechanisms and for the iterative generation of the interior structure and outer shell as multi-performative solutions. Moreover, real-time structural adaptability is also featured as a way to extract maximum resource harvesting potential from the external skin system.

Underpinning

Movement and adaptability are intrinsic features of any living organism. We need only to look at examples of human colonization and the complex system that their movement patterns create. As a species, we see stability in static environments, but human dominance and rapid expansion would have not been possible without the aid of exploration. Adaptability and self-sustainability are features that emerge through constant collision with various situations and conditions. While on Earth we have managed to tame our surroundings and enjoy to a certain measure the stability offered by static habitation, for Mars a new kind of colonization scenarios where being able to move and adapt rapidly should be considered.

As current Mars bound scenarios are limited to static, small habitats due to the inherent difficulty of landing habitats and infrastructure in multiple missions close to one another for the safety of the crew and various technical limitations (mass that can be transported, etc.), we have to consider a way to maximize each landing opportunity on the planet.

The foundation of the project is to provide a movable spatial system that can accommodate a full crew of researchers, engineers and farmers whilst being able to harvest natural resources found on-site and lay infrastructure for future expansion. Thus, as we can observe in Fig. 25, the initial design goal for the habitat is laid out: to propose an adaptive and movable base that can facilitate the creation of a Mars-wide infrastructure to minimize dependency on Earth. Fig. 26 also shows possible movement and production patterns in such a scenario.
Biomimetics and movement

Biomimetic studies also explore optimum kinetic systems found nature and how technical large-scale solutions can be derived. While conducting research within this domain, the following cases were studied: Fig. 27 showcases the initial research done. Arachnids were chosen for inspiration as they utilize a combination of hydraulics and muscles with extremely good lifting power. Also, the mechanism utilized for achieving movement is relatively simple and scalable. Fig. 28 illustrates a simple analysis of a spider’s movement mechanics with its basic principles.
Besides this, novel biomimetic solutions have also been investigated, in NASA for proposing robust solutions for arachnid-like actuator systems such as the ATLAS system\textsuperscript{65}. Another good example of biomimetic adaptation that is used for such nature inspired hydraulic systems is the Disney Fluid Actuators research\textsuperscript{66} Fig. 29, which provides for low mass, fluid motion and high output power without the use of special hydraulic fluids. Also, a group of researchers\textsuperscript{67} showcased novel plastic actuating joints that mimic the movement system of the spider as shown in Fig. 30. The system is based on expandable elastic joints that are pressurized.
The system described also uses water for pressurization, thus avoiding the need for special hydraulic fluids. As one of the researches states the advantages:
"We realized that the characteristics of spiders' hydraulic systems fit the need of great miniaturization and high force/mass ration required by space actuators."

The presented technical solutions, while of biomimetic inspiration, are still at an early stage of development but present clear advantages in term of efficiency and safety. The experiment will integrate the principles of arachnid movement system made possible through fluid-actuators and elastic joint system on a larger scale as a solution for movement issues. The design proposal is centered on a 4 leg system as a basic premise.

**In-situ atmospheric harvesting and resource production system**

The production part integrates an ISRU system as described in Fig. 31. The proposed system can provide not only life-support elements such as air and drinkable water but also enough material for processing and research. The system is based on research done various researchers into atmospheric harvesting and resource production, with some technical liberties by the authors.

![Fig. 31: Proposed ISRU system for integration.](image)

Credits: Authors

From a design integration perspective, the presence of an on-board ISRU system influences the aesthetic appearance of the outer shell. As resources will be transported around the skin of the habitat (water for protection and greenhouses or oxygen for the crew for example), the outer shell reflects this through its geometry, as further illustrations will show. Moreover, the ISRU system is of capital importance, as the movement of the habitat requires the ability to be self-sustainable in terms of production and material processes as opposed to having to rely on static production facilities.
Architectural Form Finding

The architectural form-finding section represents the crux of the project as a generative solution for integrating afore-mentioned aspects and to highlight the importance of involving designers from an early stage in concept generation for Mars habitats. Biomimetics and computational optimization play a key part in developing an integrated adaptive solution. Human psychological and physical issues mitigation concepts are also integrated while developing topological conditions for the habitat.

The constraints outlined for the movement scenario requires investigation in novel spatial and structural techniques. The spatial and structural design solutions demand the generation of a lightweight adaptive structure that can be efficiently fabricated. Structural efficiency, in this case implies finding solutions that have low mass but have a distinct architectural expression and could host a variety of functions.

Cellular Aggregation Form-finding

For the experiment, cellular aggregation as a computational strategy for clustering self-similar cells to form stable spatial networks has been experimented with. By studying the work of Ernst Haeckel and D’Arcy Thompson into non-random form and allometry, a clear strategy for developing the cellular morphologies emerged. The studied cellular aggregation principle in the case of this experiment, applies to both, the macro (overall shaping) to the micro scale (detailing).

As mentioned in the research experiments section of the paper, several initial geometric candidates were developed for further analysis. These candidates are inspired by the work of Lars Spuybroek, who made a formal classification of cellular radiolarian and other cellular organism depending on their morphology and geometrical generative phases. 2D DLA (Diffuse Limited Aggregation) algorithms have been used to check the potential of forming basic cellular structures. Subsequently additional evaluation criteria of: topology, lightness, porosity, scalability and spatial quality are introduced in order to identify and select a set of candidates to further develop.

Fig. 32 shows the selection of candidate geometries. We have to mention that all the candidates follow the same steps in geometrical morphological evolution. All of the role models start from one basic geometric shape (cube, sphere, dodecahedron). Subsequently, a number of geometrical modifications are applied such as extrusions, bridging, etc and various types of smoothing algorithms are applied (Duo-Sabine, Catmull-Clark) to check for variations on the topological level. The role models are intended for multi-use, as shown in Fig. 33. The hybrid cell concept involves the merging of the selected candidates in one cellular structure, including the interior and exterior shell. Another aspect to consider is that while cellular aggregation structures tend to form monotonous spatial configurations (as in same scale of the cells and thickness of elements), for spatial design intents a system needs to be implemented to control the spatial quality of the structure. Thus, the idea of a porosity gradient based on functional and structural requirements is presented that influences the final cellular structure both in density of elements and thickness/connection radius.
Functional distribution and spatial qualities

For functional layout design, a bottom up approach has been used due to the benefits of assuring an emergent system that combines all necessary conditions. Initially, spatial requirements have been graphed as shown in Fig. 34 based on a binary combination of sound/privacy, light/ventilation and mobility/connectivity factors.
This graphical mapping evolved into a definitive functional connectivity scheme as shown in Fig. 35. Using Grasshopper TM and Kangaroo TM (physics simulation engine), the relationship between the functions have been translated computationally. The developed algorithm permits multi-factorial optimization based on the graphed conditions and general structural conditions.

A process of self-organization and self-adaptation is thus put in place for attaining 3d functional placements. This emergent output defines a 3D spatial layout informed by the afore-mentioned factors. Fig. 36 illustrates the output of the algorithm, including the position of the movement mechanisms.
The general concept for spatial development strives to maintain fluid visual and physical communication between the spaces throughout the habitat to minimize isolation while offering generous spaces for various activities. All programs are organized around a central greenhouse that filters sunlight indirectly throughout the habitat. A functional separation can thus be observed, with all private quarters and social functions placed in the front, separated from the working areas as to avoid noise and respect privacy issues. Each section can also be closed off in case of emergency, whilst not impeding circulation within the habitat, since each section affords multiple connections in the chosen layout.

Subsequently, a 3D prototype study was modeled to showcase specific qualities and systems to be further developed, as seen in Fig. 37. The figure outlines the principal adaptive qualities of the skin, as in adaptive skin surfaces that can be used to capture and process the atmosphere and react to light levels and the integrated ISRU system. The skin also acts as a sensing mechanism to provide environmental information to the crew. Moreover, the integrated skin structure will also host multiple components such as water and air transportation systems. On the previous figure, 3 varieties of components are proposed: a system that captures the atmosphere for use in the ISRU system, an adaptive skin system that can close or open depending on insolation levels and finally, throughout the skin, a transport system for the various products of the ISRU system. The transport system, for example, uses water on the skin to cool various areas and to provide radiation protection. Also, after the oxygen is synthesized and mixed to form a breathable atmosphere, by using the skin as a distribution system, in case of an emergency it is easier to isolate specific areas of the habitat without affecting air circulation in unaffected areas.
**Fig. 37:** Initial 3D prototype of the experiment featuring all required skin qualities.
Credits: Authors

### Computational optimization

The initial concept, while following the general guidelines of the design, presented several problems. The shell was fractured in 4 elements, also, no structural analysis or solar analysis had been performed for its optimization.

### Monocoque geometries

Going back to the initial 3D functional layout, a new development strategy was hence devised. The aim was to generate an optimized monocoque outer shell that can have both, structural and aesthetic qualities. Using monocoque structures, for instance, in Formula 1 cars, implies geometrical continuity with no break points in the shell. Furthermore, monocoque structures are static and stable on their own, requiring no interior structural support.

A convex hull, which represents a geometrical approximation, was thus generated over the functional layout for optimization and modeling. Solar and structural optimizations are subsequently conducted and these findings are presented below. **Fig. 38**
Solar and structural optimization

Solar optimization is usually used for optimizing the geometric logic to protect a built form from direct solar radiation. Alternatively it can also be used to decipher the shape and size of opening patterns to regulate the amount of sunlight entering a building. For the case of this experiment, solar simulation for the habitat was conducted, using the Atacama Desert in Chile as an Earth Analogue for Mars conditions as it shares similar conditions to Mars (high UV radiation, relatively low atmospheric pressure, high temperature variations per day)\textsuperscript{72}. The analysis is done to decipher the total average radiation on the shell over the course of one terrestrial year. The results of the solar analysis map are used to decide where possible openings in the shell could be placed and how to model the habitat itself as to have maximum exposure on the top surface compared to the side surfaces that need protection from direct radiation.

Structural simulation was done using Milipede and Karamba, Grasshopper plug-ins for the modeling software Rhinoceros. An interior pressure of 100KN/m\textsuperscript{2} was applied on all normal directions of the surface. As mentioned before, in Mars conditions, minimum required atmospheric pressure for the crew’s well-being should be at least 60KPa. An additional 40KPa has been added as a safety coefficient\textsuperscript{73}. The simulation assumes a material with the properties of steel and gravity is calculated at 3.2N. Initial thickness of the structure was considered at 30cm. Fig. 39 shows the initial simulations results. The deflection for the structural simulation is at 17 cm.
Additional wind tunnel simulations as seen in Fig. 40 have been conducted to identify areas of the shell, where atmosphere capture devices can be installed while maintaining a smooth aerodynamic geometry to minimize dust deposition and friction. The rebuilt shell can be observed in Fig. 41.

For the rebuilt shell, another set of structural and solar analysis has been performed. Fig. 42, reconfirms that the habitat is protected from direct solar exposure on the top surface while the open sides receive low values of sun exposure Fig. 43 represents the structural analysis with extracted stress lines. The stress lines outline compression and tension values around the surface and pinpoint exactly where structural development should occur. A script is subsequently written to develop cells on the surface in accordance with the density of the stress lines as described in Fig. 44. The solar insulation optimization is used to control the scale of
the openings of the cellular structure while maintaining a stable structure. The current structural analysis on the cellular structure shows a drop in the deflection to 6 cm, which can be acceptable considering the lack of any interior supporting structure.

**Fig. 42:** Insolation levels on re-built shell  
Credits: Authors

**Fig. 43:** Visualization of main structural stress lines on re-built shell  
Credits: Authors

**Fig. 44:** First iteration of cellular script based on stress line density and insolation values  
Credits: Authors

**Integrated design**

The front quarter of the habitat is subsequently further detailed. The formal expressive approach considers the use of ornamentation on the skin level serves performative as well as aesthetical causes. *Fig. 45* illustrates various geometric logics being deployed for integrating the interior and exterior spatial conditions into one continuous topological system. The habitat, owing to its real-time adaptive structure, can respond instantly to contextual environmental change.
The detailing of the skin is also inspired by cellular and fero-magnetic fluid formations as observed in Fig. 46. One can observe how the qualities of the skin change according to technical and functional needs. It is clear from the overall geometry how each shape hosts another function. The ecology and build-up of components that integrate in the skin follow
specific roles: one can observe the adaptive atmosphere intakes and the openings, while the accentuated structural cell splines play a double role: to provide extra support in areas where stress values are higher and to host various analysis tools and cooling areas. Also, the front opening presents an adaptive skin based on muscle-wires that can react to environmental parameters such as solar exposure.

The structure will be materialized via multi-material 3d printing. This makes it possible to integrate various technical dependencies inside the structure, while being printed. In this case, water circulation routes, to transport water around the hub and to be used as radiation protection, the electrical cabling, etc. are just a few of such technical dependencies. The structure thus becomes a complex multi-use system, which is capable of accommodating a plethora of infrastructural functions. A detailing principle that shows the integration of structure, cabling, water transport and openings in the skin has been detailed in Experiment B.

The propelling legs, can also be retrofitted for various functions, from greenhouse to additional research stations or resource storage. The end section of the legs acts as drills and resource processing units. The outer skin of the legs also contains a multitude of adaptive surfaces like retracting solar panels or different atmospheric analysis tools. The actuation mechanism integrates the before mentioned spider movement mechanism principles. Fig. 47 illustrates a section through the legs where the hydraulics and fluid actuators are integrated and the various components found on the skin. One can observe that there is sufficient space left to retrofit the legs with complementary functions as mentioned.

Interior spatial qualities highlight various routes to access the private quarters whilst by using the cell like structure large open spaces can be provided. The detailed quarter exhibits the crew cabins that feature adaptive furniture for customizing multiple spatial layouts and include a
common room. A part of the greenhouse is also detailed, pointing out the fact that it is not only used for research purposes but also acts as a good psychological relief tool, as all common spaces have a visual link with it. The meditation and Airlocks/Access areas are detailed in general, as focus has been on crafting an ideal interior for the common and private areas. Each of the cabins and common room also present a generous visual link to the outside, to further mitigate the sense of interior isolation. Moreover, each room contains a small interior garden to provide further psychological relief. Fig. 48 illustrates some of the principles mentioned for qualitative spatial design. Fig. 49 represents an impression from one of the private cabins.

Fig. 48: Circulation and interior layout concepts
Credits: Authors

Fig. 49: Interior impression of one of the cabins
Credits: Authors
At this stage, it is clear how the emergent approach naturally lead to an interesting spatial solution. Biomimetics provides clear inspiration for key parts of the experiment, whilst computational design helps with real-time optimization and continuous feedback. Real time adaptability delivers a responsive system and opens new possibilities of formal and technical expression. As seen in the detailed quarter, the aim of the experiment is to integrate a variety of concepts and transform the habitat from a static construction into a life-like organism that can react and respond in real-time while offering the crew members the psychological and physiological relief as and when demanded by them.

Conclusion

The theoretical benefits of adopting an adaptive and movable spatial system for habitats was explored through design iterations based on biomimetic principles and architectural design. The concepts investigated illustrate the potential of multi-disciplinary research where computational optimization and performance driven design are of paramount importance for establishing a solid option for the proposed habitat.

EXPERIMENT B – MARS CONTINUUM (ONE SKIN - ONE STRUCTURE FOR EFFECTIVE USAGE OF GREENHOUSE AND WATER INFRASTRUCTURE FOR RADIATION SHIELDING)

Because of the extreme environment of Mars, various precautions have to be taken against solar radiation, scarcity of water, and lack of breathable air, food and materials. An answer to these problems can be found in nature and in mathematics.

Biomimicry

When we look at nature, we can observe that it operates according to its environment and that it finds constantly new solutions to adapt. Biomimicry is not about finding the perfect solution to mimic nature, but is about studying the system in which nature operates. Nature protects itself mainly through geometry and structure.

Understanding the Cacti make-up

In order to reduce solar exposure and water loss during periods of water scarceness, cacti have found a solution to adapt via its geometric/morphological make-up, which has the property of operating as a self-shading mechanism. This mechanism can be seen in Fig. 50, where all the adjacent bulbs act like shading devices to its neighboring bulb. This implies more shaded areas and lesser surfaces exposed, to harsh solar radiation. The same logic can be applied to a

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**Fig. 50: Cacti shading**

Sources: ‘Cereus’ http://viverosvangarden.blogspot.nl/2012/02/cactus-cerebro.html,
‘Cerebro’ http://viverosvangarden.blogspot.nl/p/empresa.html,
building, where each componential module constituting the building’s façade can act as a shading device to its immediate neighbor.

Another adaptive feature of the Cacti morphology is the functioning of the tubercles Fig. 51. Usually if a barrel cactus is saturated with water, the tubercles can be merely seen through the areoles, having a smooth uniform surface. But when it starts to loose water, the tubercles become more prominent, creating a more irregular geometry. This process of continuous adaptation of the tubercle is aimed at creating more shade, thus minimizing the overall temperature in order to lower water loss, and ensuring the plant remaining healthy and hydrated.

![Fig. 51: Diagram tubercle](image1)

Credits: Authors

A clear explanation of the shading mechanism of the tubercles can be seen in Fig. 52. This diagram shows a comparison between a round geometry and barrel cacti like geometry exposed to sun. Both geometries though rounded show a big difference in the percentage of shaded areas due to the presence of tubercles (increase in shaded areas by around 16%).

![Fig. 52: Diagram shading comparison](image2)

Credits: Authors

This study was done in order to find a strategy to lower the total solar exposure as well as to make use of water circulation patterns (since water has large radiation shielding properties). At the same time, this logic of a self-shading geometry reduces the needs of additional shading devices while lowering the radiation risk inside the building. Consequently, this method has an impact on the human factor for reducing physiological damage, such as radiation poisoning while conferring psychological relief.
Understanding Bone porosity – the case of the femur bone

The study of Biomimetics unravels the manner in which nature optimizes material properties to create lightweight, robust and efficient structures. The usage of materials is no more, no less than the exact amount of materials needed in the exact position of maximal stress in order to keep the structure in an optimized balance.

Bones, such as the human femur display similar construction logic. They are subjected to stress moments (tensile and compressive) generated by the bending moment Fig. 53. These moments accounts for the distribution of collagen in cancellous and cortical bones. The cancellous bone is composed out of 2 distinct systems: one that follows the curved path from the inner side of the shaft and radiates outwards following the lines of maximal compressive stress and the second following the curved paths from the outer side of the shaft. These two intersect each other at right angles, following the lines of maximal tensile stress Fig. 54. Also, the thickness of these two rib structures varies and adapts in time depending on the magnitude of the stress.

Minimal surface condition

For another smart approach in terms of optimal material usage, minimal surface condition was studied. These are characterized as surfaces of minimal surface area for given boundary conditions. Such topological conditions synchronize with the aim of the design; to create “one skin - one structure” condition, which can only be achieved by ensuring a continuous topological surface condition Fig. 55. Also, this strategy simplifies detailing and labor, since the construction process is natural and in line with the degrees of freedom afforded by 3D printing technologies.
Using computational tools like Topmod®, Rhino®, T-Spline® and Grasshopper® variation of topological meshes reflecting Minimal surface conditions were thus created. These were further analyzed according to its properties of topological continuity, evolution, porosity, spatial quality and internal infrastructural flows. Based on the analysis 2 candidates, which reflected a suitable balance between the aforementioned properties was subsequently selected as starting point of the design Fig. 56.

Program network and distribution

The functions, akin to Experiment A, undergo a self-organization process (based on swarm simulations) and attain vertical and clustered configurations while addressing/computing and negotiating each functions position in 3d space to satisfy the following criteria: gradient of public vs private, noise levels, daylight need and occupancy of space in a cyclic time based routine, which the occupants shall follow on mars Fig. 57 and Fig. 58.
Two principles of circulation are proposed: one that allows for movement through the building from inside out, and another one, the other way around, from the outside of the building to the inside. This continuous circulation property offers direct (short) routes to be followed as well as indirect (longer) routes, which reach the same destination. The idea being to provide the occupants with an opportunity to physically exercise as well as to psychologically reduce the impact of living in closed/crammed conditions where they feel trapped.

The duration of possible solar radiation exposure also governs the positioning of the sleeping and working zones within the habitat. These are taken into consideration in relation with the biorhythms, which the inhabitants should maintain: Sleeping zones are the most exposed to the sun, but will at the same time be the most unused spaces during the day, thus decreasing the risk of solar radiation exposure. Also, the working areas, which are the most used space during the day, are positioned at the bottom of the building, in order to use the upper mass of the building for radiation shielding.

The clustering of spaces also allows for depressurized and shutting down one cluster, in case of an emergency without interrupting the primary infrastructure for circulation in and out of the habitat.

**Geometry and computational optimization**

According to the program, the resultant geometry Fig. 59 has several advantages. Mathematically, it has topological continuity, offering the possibility of creating an integrated skin and structure. The roof surface too is rounded in order to reduce sand deposition and thus avoid extra loading conditions.

Having to deal with only one third of Earth’s gravity makes big spans and steep ramps possible to create. These spans are conceptualized as connecting tubes, which from a physiological point of view, can be used as exercise ramps for walking and jogging, thus increasing the physical activity of people, the lack of which otherwise reduce bone density and muscle volume.
Solar analysis

At the macro level the cacti logic of self-shading mechanism found in biomimicry is applied to create larger shaded surface areas to provide protection against solar radiation. The results of deploying this strategy can be seen in a solar insolation simulation Fig. 60 and Fig. 61 that was created using Ladybug® plug-in for Grasshopper®. The analysis is done for a total average radiation of one year and one day period. The chosen location is Atacama Desert in Chile because it is most akin to a Mars like setting on Earth.
Structural analysis

For structural analysis and optimization, Millipede®, a plug-in for Grasshopper®, was used. For the simulation an interior pressure of 100KN/m² was applied on the normal direction of the surface area. The required minimum atmospheric pressure for human well-being is at least 60KPa, but for safety reasons, a coefficient of 40KPa was added. These safety coefficients were used in order to prevent destabilization of the structure, in case one module is shut down. For the self-weight of the building, a composite material with properties similar to that of steel (E=21+e10, v=0.29, ρ=7800 kg/m³) was calculated in relation with the acceleration force of 3.2N. The required minimum thickness of the shell to resist the stress moments is 30cm with a deflection of the elements around 23cm.

The resultant stress patterns, where the interior curves of the building are subjected to tension forces while the exterior ones are subjected to compression can be seen in Fig. 62.
This analysis helped in identifying which surface of the geometry could be cut out in order to minimize the load and material usage Fig. 63.

![Fig. 63: Cutout geometry](image)

Credits: Authors

Stress lines were thus extracted from the simulation for a better understanding of the flow of the forces Fig. 64.

![Fig. 64: Diagram stress lines](image)

Credits: Authors

We observed that the tensile forces intersect the compression forces at right angles, thus obtaining an optimum distribution of the load in the same manner as the force flows in the human femur bone Fig. 65. The structure thus possesses the ability to be stable using the minimum required materials.
Subsequently, two modules with similar stress lines were selected Fig. 66 and based upon the mean values calculated from both, another map, outlining the densest stress lines was generated Fig. 67. These stress line conditions denote the zones that need structural continuity for optimal load transfer and also outlines zones in the surface area that could be used for creating openings Fig. 68.
Fig. 67: Outlining the densest stress lines
Credits: Authors

Fig. 68: Geometry porosity of the two modules
Credits: Authors
Section

A small section out of the two modules was selected for further development. In this Fig. 69 we can clearly see how the selected stress lines are converted into a continuous structural profile system while at the same time serving the purpose for defining openings and acts as infrastructure hosts for the water pipes.

Fig. 69: Small section developed from the two modules
Credits: Authors

The role of the water pipes is exactly like the ones of the tubercles in the cacti, and help in creating micro level shading and to offer maximal protection against solar radiation Fig. 70.

Fig. 70: Plan and Section compared with the barrel like geometry
Credits: Authors
The pipes can expand and contract according to the sun position as well as during intense solar flares Fig. 71. They are thus made out of Electroactive polymers, which have the capacity to change their properties from a hard state to a soft state. Such real-time water flow regulation, to cater to solar radiation and exposure levels is bundled with a water recycling and reuse system, thus becoming extremely performative in nature.

![Fig. 71: Expansion of the water pipe tubercle](image)

The supporting skin is made out of performance specific materials, which are described in a detailed section Fig. 72. For instance, the surface coating is conceived as a composite material, made out of graphene fiber reinforced polymer. This covering serves as a protective coating against solar radiation.

![Fig. 72: Tubercle detail](image)

The openings are also an integrated feature of the structure. Being a continuous 3D multi-material printed skin; the openings are made out of polypropylene and a layer of transparent aerogel in between Fig. 73. As for the windows of the sleeping quarters, they are facing against the sun, in order to only permit daylight inside.
The internal spatial quality is characterized by diversity against monotony, openness against confinement. This is achieved through the dynamic of furniture, contrast between light and dark, open and closed, through opaque and porosity Fig. 74 and Fig. 75.
Being a controlled environment with a high coefficient of humidity, the greenhouse is separated from the sleeping cabins through a walkway that acts like a buffer zone. The greenhouse is based on aeroponic principles where the growing chambers are directly connected to the water pipes showcasing in Fig. 76.

Part of the wall between the greenhouse and the walkway is translucent. This is done with the intent of creating a green streets, a direct connection to the alleys of the parks on Earth, conferring a variety of view throughout the entire building, fighting against monotony and repetitively. Besides the food production, the greenhouse ensures psychological well-being. On one hand it is a place of relaxation and free activity, where everybody can grow its own plants, favorite vegetables and on the other one, it is a place of meditation and reminder of the home planet, reducing the stress and fear of loneliness Fig. 77, Fig. 78.
Conclusion

The potential of one skin – one structure system was demonstrated by working with models from mathematics and biomimicry. These concepts are joined as an inter-disciplinary vehicle with computational tools validates the feasibility and advantages of performance driven design.
GENERAL CONCLUSION

In conclusion, the inter-disciplinary theoretical and design framework developed in this paper proposes novel spatial solutions for Mars habitats. A relational mapping between multiple disciplines leading to the emergence of an inclusive design strategy outlines the possible benefits of working in a collaborative fashion to synthesize multiple knowledge streams. While doing so, the paper and its findings also raise awareness as regards the current gap between the hard scientific community and soft design specialists. A focused attempt to systematically extract relevant information per domain and to singularize the impacts of this synthesis via the language of architecture is what the paper professes.

Towards the materialization of the design outcomes, what can also be observed is that the field of multi material 3D printing, which can prove to be a valuable asset, is still in its infancy. A first step, towards realizing the proposed multi-performative habitats would ideally be to develop real-time collaborative robotic manufacturing systems as well as the development of real-time robust and accurate multi-material 3d printing technologies. What is promising though, are progressive companies like HP, which is currently developing a new method of 3d printing, called “HP Multi Fusion Jet” where they can control the local properties of material (density, friction, conductivity) by mixing with specialized agents. If successful, this can be considered as a big boost for real-time multi-material fabrication. However, such technology and the resultant prototype, which are tested on Earth, must also be developed in an analogous process for Mars conditions. During such testing, human psychology should also be considered as an integral part of the experiment in order to fully understand the implications of the spatial prototypes on Mars.

Advantages of real-time interaction at both micro and macro scales for enhancing and aiding performance abilities of the habitats has been expanded upon in the paper. Kinematics at a macro scale, involving biomimetic principles can be effectively utilized for large-scale mobility with minimal energy consumption, while micro-level skin based adaptations can be successfully deployed for controlled atmospheric regulation. Besides this, form-finding strategies, which lead to the optimal generation of the tubercles also couples aspects of real-time water flow regulation for reducing solar radiation. Such integrated approaches could be vital for deriving integrated design solutions for habitats on Mars.

Such performance driven design solutions, which integrate technical, spatial and environmental concerns can also provide vital clues to develop sustainable solutions on Earth: for instance, the tubercle logic can be used in combination with geothermal sources to cool/heat an entire building effectively; at the same time, the idea of phase changing material applications can also be used in urban infrastructure projects to control the flow of resources (water, gas etc.); an adaptive mobility system such as the mechanical legs is also applicable in the heavy industry sector; movable self – contained habitats can also be used in hazardous areas.

Conducting this inter-disciplinary research helped the authors in building a springing board for realizing the merits of inter-disciplinary research approaches towards making space colonization possible. Rather than dwelling upon popular science fiction scenarios of the “Armageddon”, we, as avid researchers and designers we rather adhere to Elon Musk conclusions:

“I really think it’s important that we’re on multiple planets and a spacefaring civilization so that sort of preserves the future of humanity, it’s sort of life insurance collectively.”
APPENDIX

Fig. 1: Huber Peak diagram

Fig. 2: NASA 1975 Summer Study - Torus cutaway
Credits: http://www.nss.org/settlement/space/stanfordtorus.htm

Fig. 3: Greg Lynn Studio Vienna - Space Study
Credits: http://spacecollective.org/jiri

Fig. 4: European Space Agency (ESA) and architects Foster + Partners Moon Base proposal
Credits: http://www.esa.int/spaceimages/Images/2013/01/Multidome_base_being_constructed

Fig. 5: eVolo competition - Ring of Mars: Proposed Cities in Outer Space

Fig. 6: Visual representation map
Credits: Authors

Fig. 7: Hylozoic Ground by Phillip Beesley

Fig. 8: International Space Station (ISS) - Section
Credits: http://www.esa.int/var/esa/storage/images/esa_multimedia/images/2001/11/columbus_laboratory/9201199-8-eng-GB/Cutaway_view_of_Columbus_laboratory.jpg

Fig. 9: MEDUSA by Liquifer

Fig. 10: Radiation Levels

Fig. 11: Nakhla Meteorite found on Earth
Credits: http://upload.wikimedia.org/wikipedia/commons/c/c1/Nakhla_meteorite.jpg

Fig. 12: Mars Regolith
Credits: http://rt.com/files/news/20/92/80/00/1.jpg

Fig. 13: Diagram showing elements discovered by Spirit, Opportunity and Curiosity Rover
Credits: http://photojournal.jpl.nasa.gov/catalog/PIA16572

Fig. 14: Blueberries
Credits: http://www.3ders.org/images/Flexible-Textile-Structures-3d-printed-1.png

Fig. 15: Heat Shield Rock, Sitting meteorite on Mars

Fig. 16: Vein of Gypsum on Mars

Fig. 17: Dark Sand Dunes on Mars
Credits: http://upload.wikimedia.org/wikipedia/commons/d/dc/Dunes_Wide_View.jpg

Fig. 18: Flexible Textile Structure
Source: http://www.3ders.org/images/Flexible-Textile-Structures-3d-printed-1.png

Fig. 19: Egg-shaped structure printed by Enrico Dini with a D-Shape 3D printer
Credits: http://www.dezeen.com/2013/05/21/3d-printing-architecture-print-shift/

Fig. 20: 3D printed lunar brick
Credits:
http://www.esa.int/spaceinimages/Images/2013/01/1.5_tonne_building_block-produced_as_a
_demonstration

*Fig. 21*: Mataerial robotic arm
Credits: http://blog.tecnospazio.org/mataerial-una-nuova-stampante-3d-per-oggetti-curvi-
multi-cromatici-15647

*Fig. 22*: Stratasys + Self-assembly Lab 4D printed material
Credits: http://www.selfassemblylab.net/4DPrinting.php

*Fig. 23*: Mark One 3D printer

*Fig. 24*: Table Function requirement
Credits: Authors

*Fig. 25*: Brief overview of the main conceptual tenets of the experiment
Credits: Authors

*Fig. 26*: Movement and production patterns
Credits: Authors

*Fig. 27*: Biomimetic inspired kinetic systems analysis and criteria for movement system.
Credits: Authors

*Fig. 28*: Spider movement system
Credits: Authors

*Fig. 29*: Disney Fluid Actuator
Credits: http://spectrum.ieee.org/automaton/robotics/robotics-hardware/beautiful-fluid-
actuators-make-soft-safe-robot-arms

*Fig. 30*: Inflatable Elastic Actuator

*Fig. 31*: Proposed ISRU system for integration.
Credits: Authors

*Fig. 32*: Selection of candidate geometries for development
Credits: Authors

*Fig. 33*: Hybrid cell and porosity gradient concepts for candidate geometries integration
Credits: Authors

*Fig. 34*: Graphed visualization of comfort parameters
Credits: Authors

*Fig. 35*: Functional connectivity scheme
Credits: Authors

*Fig. 36*: Computationally derived functional layout
Credits: Authors

*Fig. 37*: Initial 3D prototype of the experiment featuring all required skin qualities.
Credits: Authors

*Fig. 38*: Convex hull approximation of the functional layout
Credits: Authors

*Fig. 39*: Initial insolation and structural deflection analysis
Credits: Authors

*Fig. 40*: Wind tunnel simulation for further geometrical optimization
Credits: Authors

*Fig. 41*: Re-built monocoque shell
Credits: Authors

*Fig. 42*: Insolation levels on re-built shell
Credits: Authors
Fig. 43: Visualization of main structural stress lines on re-built shell
Credits: Authors

Fig. 44: First iteration of cellular script based on stress line density and insolation values
Credits: Authors

Fig. 45: Illustration of the various geometric logics being deployed for developing one continuous topological system
Credits: Authors

Fig. 46: Close-up of the outer shell showcasing the different levels of components present
Credits: Authors

Fig. 47: Legs component ecology and schematic section
Credits: Authors

Fig. 48: Circulation and interior layout concepts
Credits: Authors

Fig. 49: Interior impression of one of the cabins
Credits: Authors

Fig. 50: Cacti shading

Fig. 51: Diagram tubercle
Credits: Authors

Fig. 52: Diagram shading comparison
Credits: Authors

Fig. 53: Diagram stress distribution in femur bone
Credits: Authors

Fig. 54: Diagram stress distribution in femur bone
Credits: Authors

Fig. 55: Klein bottle surface and Mobius strip

Fig. 56: Design exploration
Credits: Authors

Fig. 57: Function network
Credits: Authors

Fig. 58: Program distribution
Credits: Authors

Fig. 59: Geometry proposal
Credits: Authors

Fig. 60: Solar insolation for an average of one year
Credits: Authors

Fig. 61: Solar insolation for an average of one day
Credits: Authors

Fig. 62: Stress map
Credits: Authors

Fig. 63: Cutout geometry
Credits: Authors
Fig. 64: Diagram stress lines  
Credits: Authors

Fig. 65: Diagram stress lines comparison with femur bone  
Credits: Authors

Fig. 66: Two modules with similar stress lines  
Credits: Authors

Fig. 67: Outlining the densest stress lines  
Credits: Authors

Fig. 68: Geometry porosity of the two modules  
Credits: Authors

Fig. 69: Small section developed from the two modules  
Credits: Authors

Fig. 70: Plan and Section compared with the barrel like geometry  
Credits: Authors

Fig. 71: Expansion of the water pipe tubercle  
Credits: Authors

Fig. 72: Tubercle detail  
Credits: Authors

Fig. 73: Section through the greenhouse and detail of a window  
Credits: Authors

Fig. 74: Interior impression  
Credits: Authors

Fig. 75: Interior impression  
Credits: Authors

Fig. 76: Diagram showing aeroponic system  
Credits: Authors

Fig. 77: Interior impression  
Credits: Authors

Fig. 78: Interior impression  
Credits: Authors

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