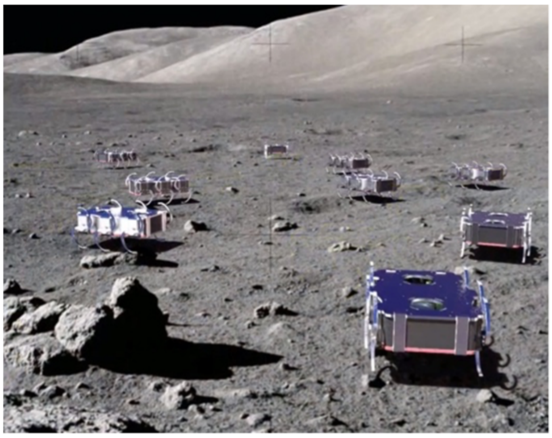


EXECUTIVE SUMMARY

Rhizome: Development of an Autarkic Design-to-Robotic-Production and -Operation System for Building Off-Earth Habitats

ABSTRACT

In order for off-Earth top surface structures built from regolith to protect astronauts from radiation, they need to be several metres thick. With support from European Space Agency (ESA) and Vertico, the Technical University Delft (TUD) advanced research into constructing habitats in empty lava tubes on Mars in order to create subsurface habitats. By building below ground level not only natural protection from radiation is achieved but also thermal insulation because the temperature below ground is more stable. A swarm of autonomous mobile robots developed at TUD scans the caves, mines for in situ resource utilisation (ISRU), and with the excavated regolith that is mixed with cement constructs the habitat by means of automated and Human-Robot Interaction (HRI) supported Design-to-Robotic-Production-Assembly and -Operation (D2RPA&O) methods developed at TUD. The 3D printed rhizomatic habitat is a structurally optimised porous structure with increased thermal insulation properties due to its porosity. To regulate the indoor environment a Life Support System (LSS) is considered, which is, however, outside of the scope of the presented research. Instead, the production and operation of the habitat are explored by combining an automated kite-power system with solar panels in a microgrid with the goal to develop an autarkic D2RPA&O system for building off-Earth subsurface autarkic habitats from locally-obtained materials.

ESA ENTITY CODE

1 000 000 815

BACKGROUND

Building off-Earth habitats requires acknowledging three interconnected aspects: First, a different design methodology is needed as opposed to many Earth-based design methodologies. Second, the understanding of location, climate, available materials and local hazards all play a major role in the Design-to-Robotic-Production-Assembly and -Operation (D2RPA&O) process. And third, the understanding of the limits in terms of mass and volume for interplanetary space travel and identification of what needs to be transported from Earth and what can be produced off-Earth.

Currently, Moon and Mars are suitable and within reach for interplanetary habitation based on the current and expected level of technology readiness likely to be reached in the near future. According to previous research, regolith, crushed rock and dust can potentially be used as construction materials. Regolith constructions can potentially protect astronauts from large amounts of radiation. However, galactic cosmic rays would require a regolith layer of several metres thick to sufficiently protect the astronauts. Furthermore, regolith cannot endure the thermal stresses that occur from large temperature variations during the day-night cycle on both, Moon and Mars. And the absence of an atmosphere with high density could further increase stresses in the building envelope when creating a pressurised environment or could make a surface printing process challenging.

Precedent case studies such as the Ice House, X-House, and MARSHA aimed to address these challenges, with top surface design proposals. The Technical University Delft (TUD) team investigated possibilities to 3D print subsurface habitats using autonomous and /or semi-autonomous swarms of robots while also considering the restraints of interplanetary space travel and challenges of energy generation. It explored the potential for transfer of several technologies developed at TUD for on-Earth manufacturing and construction to off-Earth applications. It relied on multi-disciplinary expertise developed in architecture, civil, mechanical, and aerospace engineering. The following tasks were were successfully implemented:

1. Identification of the underground lava tube

The Geoengineering section of the Faculty of Civil Engineering and Geosciences (CEG), the Architecture (A), and Aerospace Engineering (AE) teams identified lava tubes location for the habitat based on discussions with experts and review of existing literature on caves, approaches to access[1] (inter al. Viudez-Moreira, 2021), and repurpose them for the habitat[2]. Arsia North in the Tharsis bulge has been identified as suitable location mainly because the lava tube satisfies diameter requirements for lowering equipment to the bottom of the lava tube and winds have highest speed and density[3] for generating energy (D8).

2. Data-driven Design-to-Robotic-Production-Assembly and -Operation (D2RP&O)

The overall design of the habitat relies on data-driven simulation, robotic production, and assembly of the inhabitable rhizomatic structure. The first case study is for a 60-80 m^2 habitat that can be extended in time. Excavation for ISRU is implemented with rovers similar to the rovers developed at TUD for the Moon. Since entrance to the lava tube has on average a 30m drop down to the bottom of the tube, use of a crane to bring material and equipment necessary to build access ramps and habitat developed by the University of Oviedo in Spain (2019) has been proposed[4].

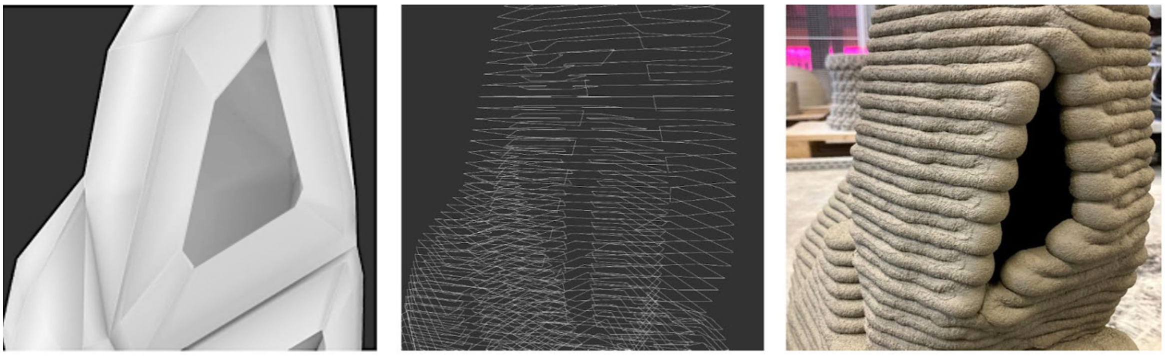


Figure 1: Voronoi-based design for D2RPA&O

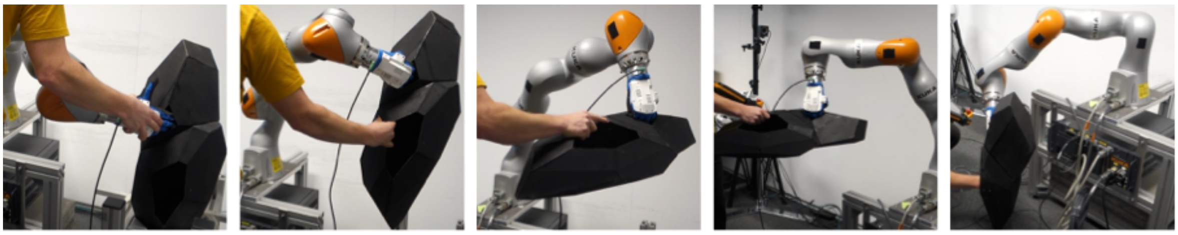
The 3D printing with concrete approach developed by Vertico represented the basis for the 3D printing approach with regolith-based concrete developed in this project. The printed structure is a structurally optimised porous structure, which has increased insulation properties and requires less material and printing time. It relies on a Voronoi-based material, component, and building design (Fig. 1) that facilitates all functionalities (D5).

[1] Links to Viudez-Moreiras' paper and other references: https://www.sciencedirect.com/science/article/pii/S0019103521003171?via%3Dihub and http://cs.roboticbuilding.eu/index.php/Shared:RhizomeReview2
[2] ESA studies: https://www.esa.int/Enabling_Support/Preparing_for_the_Future/Discovery_and_Preparation/ESA_plans_mission_to_explore_lunar_caves and https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/CAVES_and_Pangae
[3] AE report: https://docs.google.com/presentation/d/1VOeGwHE8JD4gm_3IFsW41H3aNSBkT8u2/edit#slide=id.p10
[4] Link to ESA project: https://www.esa.int/ESA_Multimedia/Images/2020/02/Robotic_crane_for_wireless_power_and_data_transmission_between_surface_and_cave

The assumption that porous materials have improved insulation properties is based on experiments implemented with ceramic clay at TUD. Expected increased insulation of porous concrete has been proved by implementing numerical simulations and experimental testing[5]. Printed components were assembled with support of Human-Robot-Interaction (HRI) technology and use of rovers.

3. Human-Robot-Interaction

Not only the assembly, which was the focus of the project, but the complete construction of the habitat is implemented with HRI support and rovers that are equipped with robotic tools. Rovers deployed for building the structure have various sizes as specialised tools are needed for different types of tasks. Although, some robots share a base design between themselves by having the same mobile platform on which different types of payloads are attached (for example, a robotic arm fitted with a milling or 3D printing tool). The mobile platform provides the payload with necessary basic environmental awareness, communications, power and navigational support to ensure its safety, and may allow the payload to command the mobile platform as needed to keep itself in sync with its swarm's task.



A B C D E

Figure 3: HRI supported D2RA of components

4. Swarm Intelligence and System Engineering

The swarm, composed of different types of robots, executes tasks by using Swarm Intelligence (SI). The SI is a decentralised, self-organising algorithm which manages the division of labour between various types of robots at different times. To deal with inherent uncertainties, the systems engineering approach chosen for this project has started with the definition and the preliminary design of an Interplanetary Transportation System serving the requirements and needs of the Rhizome habitat. The main scope of this design effort was three-fold: (1) define a concrete, realistic timeline and Concept of Operations for the transportation flights serving the habitat, during both its construction and operation; (2) establish how many materials, tools and people (including their necessary life support items) can be brought to Mars and back to Earth (when appropriate) per flight.

5. Renewable energy

This project employs a hybrid wind-solar energy system to power the construction of the Mars habitat as well as its later use. The aerodynamic force that a kite generates depends linearly on the density of the atmosphere, and linearly on the wing surface area. Since the power output of a kite power system scales with the cube of the wind speed, a speed increase of a factor of two leads to an eight-fold power output. This means that to some degree, the higher wind speeds on Mars compensate for the very low density on the red planet. Another factor that positively influences the flight operation of a kite on Mars is the lower gravity, such that a kite power system can harvest wind energy already at lower 'cut in' wind speeds. The wind resource has been evaluated based on the location (Arsia North) and the operational height of 127m. Weibull probability function has been evaluated for 16 equal periods of the year. The electrical power output for kite sizes ranging between 50-300 m2 given this resource availability has been calculated as ranging between 2.5-17 kW (D6).

CONCLUSION

The project has been implemented over the period of 12 +1 months in 2021-22 and involved expertise in robotic building, civil, material, and aerospace engineering, swarm and cognitive

[5] Link to A report: https://drive.google.com/file/d/1PHfDZb_je4lEVdYFkc_snuO_rwW-IM7X/view

robotics. There were in total ±10 experts, ±40 students, and 2 TAs involved at various stages of the project. These resources, 100k€, were sufficient for the proof-of-concept stage in which the team has been verifying the practical potential of the proposed idea, which involved the development of an autarkic Design-to-Robotic-Production and -Operation system for building off-Earth habitats. Future steps are considered involving 3D printing with cement-less materials and scaling up structure, integrating LSS, etc.

ACKNOWLEDGEMENTS

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