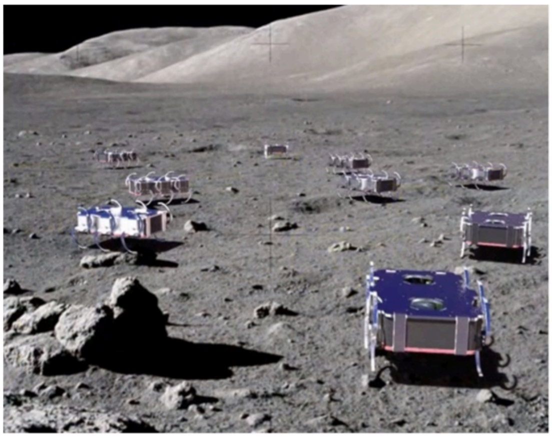 

FINAL REPORT

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

BUDGET

100k€

DURATION

12 +1 months

STATE OF THE ART / 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 aim to address these challenges as follows:

A. The Mars Ice House and the National Aeronautics and Space Administration (NASA) feasibility study ICE Home use ice as main construction material as it is more effective against radiation than regolith-based constructions. To keep the ice from sublimating into the air, the use of inflatable plastics is proposed.
B. Foster and Partners autonomous habitation sintering study uses regolith as main construction material, but instead of printing it they fuse the layers together using an autonomous swarm of robots.
C. Apis Cor's X-House is a 3D printed habitat that uses Martian concrete reinforced with basalt fibres and expandable polyethylene foam.
D. AI Space Factory's MARSHA is a 3D printed habitat and uses a biopolymer basalt composite material for 3D printing. Which is effective against stress and to some degree against radiation as the material has a high hydrogen concentration.

All these examples are submissions to the NASA 3D printed habitat challenge and all of them are top surface design proposals. NASA stated that excavation into any off-Earth location would require large and heavy equipment making it not feasible. However, the Technical University Delft (TUD) team investigated possibilities to 3D print subsurface habitat using autonomous and /or semi-autonomous swarms of robots while also considering the restraints of interplanetary space travel and challenges of energy generation. Four areas of research have been explored and integrated:

AUTARCHIC HRI SUPPORTED D2RPA&O

D2RPA&O methods have been developed at TUD for on-Earth applications (inter al. Bier et al., 2018). While Design-to-Robotic-Production and -Assembly (D2RP&A) focusses on embedding robotic approaches into production processes, Design-to-Robotic-Operation (D2RO) embeds robotic systems into the built environment. Both facilitate advanced production and operation of buildings. On Mars, the D2RP&A methods facilitate the construction of subsurface habitats via robotic 3D printing and Human-Robot Interaction (HRI) supported assembly.

In situ obtained regolith mixed with cement is used to 3D print inhabitable structures. The structures are equipped with a life support system that requires D2RO methods, facilitating the integration of sensor-actuator networks into the built environment. These were though only marginally addressed in this project as the focus was in addition to D2RP&A, energy generation, which is harvested from sun and wind and system integration. Various technical requirements were identified and addressed during the project.

TECHNICAL REQUIREMENTS

The technical requirements for this study were derived from the following functional items:

1. Manufacture payload: This function includes all actions necessary to ensure a safe and up-to-quality manufacturing process of the payload (from safety equipment to collecting resources to manufacturing and assembling of the parts).
2. Transport payload: The payload is transported to Mars, including the rovers equipped with specialised tools, the life-support system and the energy system. This function covers the preparation and execution of the launch, the flight from Earth to Mars, and the landing at the target site.
3. Implement energy system: First, a basic energy system that has been used to create the parts required for the complete energy system is established. Then, the complete energy system, wherein the structures, PV modules, kite power system and energy storage are combined into

a micro grid and a final pre-operational system check is performed before activating the complete energy system.
4. Operate energy system: The operation is adapted to the local environmental conditions to ensure a safe, reliable and efficient energy harvesting, storage and distribution according to the usage profile. This function also includes maintenance of the energy system.
5. Deploy swarm of rovers equipped with Swarm Intelligence (SI) and HRI features: This function includes all actions required for deploying the swarm to implement excavation and/or reinforcement of underground structure. It includes activities such as mapping Mars surface and identifying site, defining deployment strategy, identifying number of rovers per type, defining technical specifications of rovers i.e power required, power source, payloads, robot size.
6. Manufacture/produce and construct underground structures: This function focuses on the construction of the habitat using in-situ materials and includes all actions required for harvesting materials as well as producing and constructing the underground structures.
7. Integrate life support system: The habitat is completed by integrating the LLS with the underground structures and the energy system.
8. Operate habitat: This function covers all actions required for operating the habitat, including sensors that monitor the environmental conditions in the habitat and specific functions of the integrated laboratories, as well as actuators that ensure that all requirements are met.
9. Perform communication: The last functional item is about communication, including the communication of the habitat with Earth and communication between subsystems. Both types of communications are used at various points throughout the mission.

RESEARCH DESCRIPTION

This research explores the potential of several technologies developed at TUD for off-Earth manufacturing and construction. It builds up on multi-disciplinary expertise developed in architecture, civil, mechanical, and aerospace engineering.

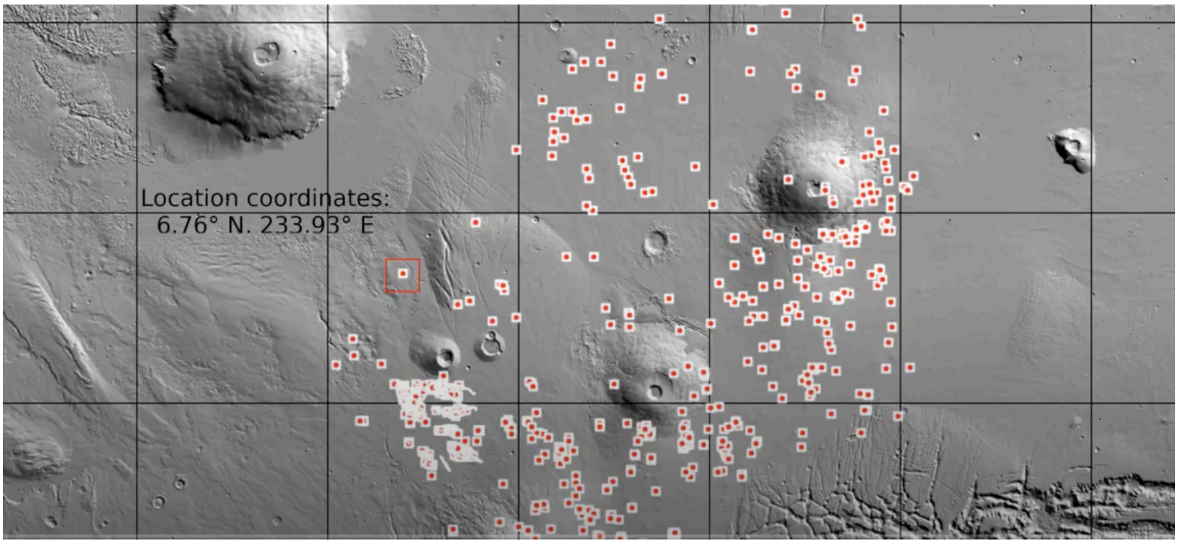

Figure 1: Location of the habitat has been identified in Arsia North in the Tharsis bulge

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

[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

Tharsis bulge (Fig. 1) 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 (see deliverable D8).

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

Data-driven D2RPA&O is implemented at the Faculty of Architecture and the Built Environment (ABE). It integrates advanced computational design with robotic techniques to produce and operate architectural structures. This implies that design is directly linked to building production and operation (inter al. Bier et al. 2018). The overall design of the habitat relies on data-driven simulation, production, and assembly of the inhabitable rhizomatic structure (see cover image). The first case study is for a 60-80 m^2 habitat that can be extended in time. Subtractive and additive Design-to-Robotic-Production (D2RP) have been employed in the following sequence:

2.1 Subtractive D2RP

Excavation for ISRU is implemented with rovers similar to the rovers developed at TUD. Expertise in subtractive D2RP developed by the Robotic Building (RB) lab, as well as expertise in underground structures developed at CEG have been employed mainly to identify suitable locations for building the habitat underground such as the Tharsis bulge (inter al. Sauro et al, 2020). 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].

2.2 Additive D2RP

Additive approaches explored in RB's laboratory setup using clay, silicon and thermoplastic elastomers as well as prototyping implemented with concrete by Vertico represent the basis for the 3D printing approach with regolith-based concrete developed in the project. The printing system is connected to a mobile rover that is depositing material. 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. 2) that facilitates all functionalities (see deliverable D5).

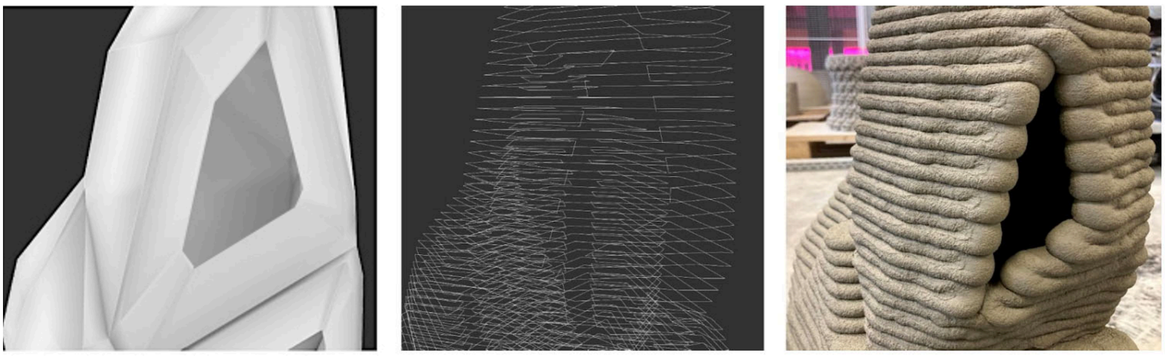

Figure 2: Voronoi-based design for D2RPA&O

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 assessed and justified by implementing numerical simulations and experimental testing[5]. Knowledge on available simulants developed at TUD has been applied to identify and formulate

_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

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

processing and design constraints with respect to manufacturing of porous insulating materials proposed in this project (see deliverable D5).

Particular challenges of the 3D printing approach have been material printability, robot reachability, and digital-physical synchronisation. These were addressed in collaboration with industrial partner Vertico where the components were printed. They were assembled with support of HRI technology and use of rovers. 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. 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. The rovers' swarm design builds up on technology developed at Aerospace Engineering (AE) and is described in the AE section of the report.

2.3 Design-to-Robotic-Assembly (D2RA)

D2RA involves the assembly of components into a habitat and has been implemented with HRI support and is described in the HRI section.

2.4 Design-to-Robotic-Operation (D2RO)

This D2RO process has been employed for embedding the environmental control and life-support system, which supplies air, water and food and relies on filtration systems for human waste disposal and air production. These systems require an average power of 1600 W for a habitat on Mars for a crew of 6 people (Santovincenzo, 2004). Water needs to be stored, used, and reclaimed (from wastewater), although Mars missions may also utilise water from the atmosphere or ice deposits. Oxygen comes from electrolysis, which uses electricity from solar panels or kite-power to split water into hydrogen gas and oxygen gas. Temperature regulation is achieved using both passive and active systems, which protect from overheating, either by thermal insulation and by heat removal from internal sources (such as the heat emitted by the internal electronic equipment) or protect from cold, by thermal insulation and by heat release from internal sources. Furthermore, shielding against harmful external influences such as radiation and micro-meteorites is necessary. This is achieved by placing the habitat below ground level. In addition, an inflatable structure is proposed to counteract Mars's low atmospheric pressure, which is a threat to human health. The inflatable structure that regulates the indoor pressurised environment is placed in the structure that is reinforced with concrete. This inflatable structure consists of materials such as neoprene, vectran, kevlar or dyneema. The advantage is that the range of required materials can also be reproduced on Mars through in situ resource utilisation (ISRU) of silicon, which is proven to be in abundance on Mars. The inflatable structure relies on ESA's current development for Lunar habitation with Foster and Partners. Alternatively, the TUD team envisions to 3D print a sealing layer (Bier et al. 2018) on top of the supporting concrete structure (Kim et al., 2000), which is, however, outside of this project's scope.

The life-support system could include a plant cultivation system, which could also regenerate water and oxygen. Such a system could reuse nutrients via composting waste, which is then used to fertilize crops. For instance, research of the Micro-Ecological Life Support System Alternative (MELiSSA), an ESA led initiative, which aims to understand the behaviour of artificial ecosystems to develop technology for a future regenerative life support system, have been conceptually integrated in this project. The preliminary design of the life-support system includes considerations related to redundancy and maintenance aspects. However, Reliability, Availability and Maintainability (RAMS) studies will be implemented at later stages.

Similar to earlier studies implemented with students in the Spring semester 2020, the technical design of the habitat and respective D2RP&O processes aim at taking all aspects into account, while testing is implemented exemplarily on a fragment. The studies involved inter al. the integration and overlay of piping and the challenges concerning both with respect to implementation and maintenance (see deliverable D16). While overlaid piping is easier to access, it requires regular cleaning, which needs to be further investigated in the future with respect to advantages and disadvantages of both. Furthermore, used materials and approaches emulated the ones implemented in-situ. In order to achieve a high level of accuracy, material design and testing have been implemented in collaboration with Structural Mechanics (A). Furthermore, the construction of the habitat relied on printing technology developed in collaboration with Vertico and on Human-Robot Collaboration technology developed by Cognitive Robotics (3ME).

2.5 Material Engineering

Relevant experience on processing of regolith simulant has been acquired by characterization of initial regolith powders, optimization of 3D-printing process, relating processing parameters to materials microstructure and functional properties (mechanical and thermal isolation), post-processing for possible improvement of properties.

Concrete samples with various % of regolith simulant have been tested for compression strength and other properties. The test results show that concrete based on artificial Martian regolith has mechanical properties at least comparable to terrestrial concrete. It has better ductility leading to safer failure behaviour. Thermal properties are also good. Since critical properties are comparable to known terrestrial concrete, thus, 3D printed concrete based on Martian regolith should provide a suitable and safe structural material (see deliverable D5).

3. Human-Robot Interaction / Collaboration

One of the key challenges of space exploration is limited resources and agents available to perform various tasks. While on-Earth specialised tools and robots efficiently perform specific tasks, off-Earth each agent must be able to perform a variety of tasks. Working without complex machinery often requires multiple agents to team up in order to be able to perform certain tasks. For example, lifting and moving heavy objects, performing assembly that requires more than two hands etc., all require at least two agents and good coordination between them. While humans can team up, their numbers are limited in off-Earth scenarios and therefore robotic agents have to team up with them instead.

Robots may not be as smart and adaptable as humans yet, but they have some advantages over the humans, such as precision, speed and payload capacity. In this project these advantages have been exploited by establishing smart human-robot teams for an off-Earth habitat construction task, where 3D printed components have to be assembled together at the building site. Four key sub-tasks for the given construction task have been identified. First, the component pick-up sub-task requires human cognitive capabilities to physically guide the robotic hand for successful grasping and lifting (see Fig. 3A and B). Second, during the carrying sub-task, the human should control the motion on the trajectory, while the robot should carry most of the component weight along that path (see Fig. 3C and D). Third, the component's orientation must be aligned to fit the appropriate place in the structure (see Fig. 3E). Finally, when the human must temporarily attend to other tasks, such as inspection of the building progress, the robot must remain in a fixed position and orientation (not shown).

A B C D E

Figure 3: HRI supported D2RA of components

The physical interaction controller was based on our previous work (Peternel, et al., 2018). Several control modes tailored for solving specific sub-task were designed. These control modes had various robot stiffness settings in order to accommodate the collaborative human-robot movements. The *main mode* is used for the carrying stage (Fig. 3C and D), the *lift and low mode* is used for lifting and lowering the 3D printed component (Fig. 3B and E), the *orientation mode* is used to orient the component before and after carrying (Fig. 3B and E), the *free mode* is used during the grasping where the human guides the robotic hand to the correct pose (Fig. 3A), while the *locked mode* enables the human to temporarily fix the robot in a given pose (not show on this Figure). To allow the human to switch between the modes, a voice interface that detects language commands has been developed. Besides for switching modes, the interface is also used for other actions, such as close/open the robotic hand (see deliverable D5 report).

To make the robot learn new skills from the human demonstration, a method has been developed based on Machine Learning (ML) and optimization that can incorporate human preferences while learning new skills from the collaborating human. The method uses human demonstrations to infer the preferences, which are extracted from the measured data (position, velocities, etc.) using the inverse reinforcement learning (IRL) approach (Jain, et al., 2015). Four main preferences that are fundamental to the construction task considered in the project were identified: carrying velocity, height from the ground during the carrying, minimum distance to obstacles during the carrying, side on which the obstacle is passed. These preferences are incorporated into the robot trajectory planner based on mathematical optimization, where each preference adds a specific term to the cost function that guides the optimization process. The optimization also enables generalisation to various conditions that were not directly demonstrated by the human, thus providing the robot with a significant degree of adaptability to new situations (see deliverable D5).

Since the existing experiment involved a fixed base robotic arm, a feasibility study for attaining the required robot mobility on the construction site was conducted. Three main aspects were considered: weight and carrying capacity of the robot, type of mobility (legs vs. wheels) and type of power supply (battery vs. cable) (see deliverable D5).

4. Renewable energy, space systems and rover swarms engineering

The Aerospace Engineering (AE) faculty has been developing innovative wind energy systems and rover swarms that this project is taking advantage of. The expertise in space systems engineering is important to integrate the different components of the proposed solution.

4.1 Hybrid wind-solar energy system

Renewable energy sources on Mars substantially differ from those on Earth. Solar irradiance is lower and reduced further by strong seasonal dust storms (Fraser, 2009). The atmospheric density is less than 1% of that on Earth, while wind speeds can be higher, on average 10 m/s (Boumis, 2017). To mitigate the unavoidable variations of natural energy sources, the Mars base would ideally be powered by a combination of solar and wind energy systems (Bluck, 2001), supplemented by suitable energy storage. This project employs a hybrid wind-solar energy system to power the construction of the Mars habitat as well as its later use. Because conventional, tower-based wind turbines would have a prohibitive impact on the mass and volume budget of the mission, a lightweight and compact kite power system is used to generate wind energy (Silberg, 2012). 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 (Mersmann, 2015). 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.

As a first step of the project, the solar and wind resources on Mars have been assessed, using available data from existing studies (Delgado-Bonal, 2016). Based on this resource assessment and the geoengineering studies, the site of the habitat has been selected. As a next step, the automated kite power system developed at TUD (Fig. 4) has been used as a starting point for a redesign that can be operated on Mars. The design for terrestrial operation features an inflatable wing with very small packing volume and minimal weight, an 18 kW generator and produces an average electrical power of about 7 kW in good wind conditions which is sufficient to power about 14 Dutch households (Van der Vlugt, 2013). To account for the lower atmospheric density the wing surface area is increased. The system has a mass of 150-200 kg and a packing volume of about 2 m^3 and is combined with PV modules to buffer periods of low wind. For the sizing and design of the kite power system, a validated performance model has been used (Van der Vlugt, 2019).The preliminary design of the energy system for the Mars habitat was developed within two consecutive Design Synthesis Exercise (DSE) project at the Faculty of Aerospace Engineering. The final reports of both DSE projects have been published open access[6] and the energy system analysis has been published as a peer-reviewed journal article (Ouroumova et al., 2021).

[6] Links to reports: http://cs.roboticbuilding.eu/images/5/52/FinalReport_ARES.pdf and http://cs.roboticbuilding.eu/index.php/Shared:2021AEG2

In a second step, the work of the DSE teams has been combined in order to build a more accurate higher-fidelity energy system model. First, the pumping kite model developed based on Luchsinger theory has been revised to revise theoretical and modelling errors that were leading to an overestimation of the actual power output of the kite. Additionally, a more accurate theoretical version of the Luchsinger model, which incorporates the elevation angle, has been developed. For this, improved kite model, the wind resource information from the MCD has been used. 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 (see deliverable D6).

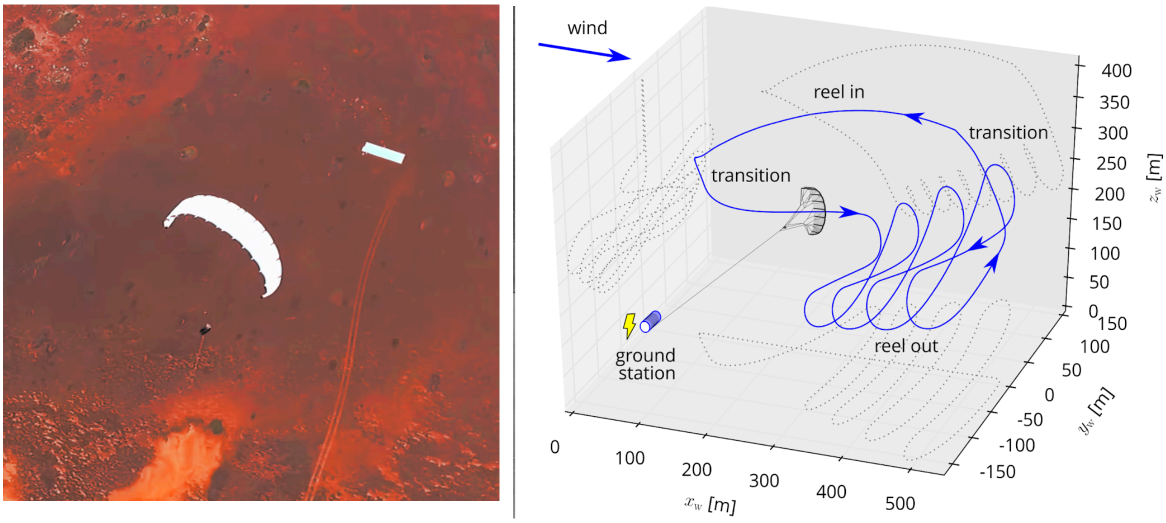

Figure 4: Image of the kite power system in operation on Aruba (left) and simulation (right)

4.2 Space systems
A number of systems engineering activities have been conducted in the framework of WP8. Systems engineering is not a trivial task for a futuristic, highly-visionary project such as Rhizome. Detailed technical information is not fully available at the current project stage, and a number of appropriate assumptions need to be made in order to derive a basic set of technical budgets (mass, volume, power) and an initial, general idea about the integration of all different subsystems and activities associated to the creation of the habitat.

To deal with these 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 proposed design for the transportation system has been adapted from the results of a work conducted by a group of students involved in an DSE project[7] running in parallel to the DSE project on kite power described in the previous section.

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.

The results can be summarised as follows:

1. The launch window opportunities allow for a first flight in November 2028 and a frequency of approximately one flight every 4-5 years, with at least one-year interval between the arrival back to Earth of the previous flight, and the departure of the next flight to Mars. In this way, the first 10 flights serving the habitat will span over a time frame of approximately 40 years.
2. It is possible to meet the requirements and needs of the Rhizome habitat by scheduling the first three flights as cargo missions (departure dates from Earth in 2028, 2033 and 2037), and a departure of the first crewed flight in October 2041. The habitat will be ready and fully operational by the arrival on Mars of this first crewed flight.

[7] Link to the report: http://cs.roboticbuilding.eu/index.php/Shared:2021AEG1

3. Each cargo flight can bring to Mars surface a payload with mass of 45 tons and volume of 200 m^3, while each crewed flight can bring to Mars surface a payload with mass of 16 tons and volume of 50 m^3, plus 5 crew members.
4. The first three cargo flights will be used to bring to Mars the swarm of rovers serving the habitat construction, the robotic arms and other construction tools and items, the power generation system for the habitat (including redundancy) and the water and oxygen in-situ production plants (including redundancy). The landers of these cargo flights will not fly back to Earth. They will stay on Mars, where they will serve as telecommunications and power generation stations.
5. The crewed flights will bring to Mars surface the food and other raw materials necessary to sustain the life of all crew members, plus spare/replacement items for the swarm of rovers, the robotic arms and the construction tools.

The main conclusion that can be drawn from this part of the project is that an integrated systems engineering approach is possible for an off-Earth autarkic habitat such as Rhizome. Using currently available technology options, with their inherent performance and characteristics, a realistically feasible dedicated transportation system can be designed to serve the needs associated to building and maintaining the Rhizome habitat (see deliverable D10 and D12).

4.3 Autonomous multi-functional robots swarm

For this project, a swarm of mobile robots i.e. rovers developed at TUD have been considered for implementing tasks such as excavating, transporting, and processing materials. Since 2013, TUD has been actively working on small scale rovers Zebro Rover (Fig. 5). The rovers are especially built for swarming given they are built from the ground up for mass production and have an array of sensors such as stereo vision to detect and avoid obstacles and sensors for localization. These lightweight rovers (2kg to 5kg) are an ideal sensor mobile platform and can be retrofitted with any instrument like radar, drills, 3D printing systems to give them a specific use. The embedded swarm intelligence controls the overall behaviour of the swarm (>10 rovers) and as it has a decentralised architecture meaning that any number of rovers can be added to the swarm. To demonstrate the technology, TUD will launch the lunar Zebro to the Moon in 2022 with future plans of launching more rovers at once to build a lunar based radio telescope using swarm technology.

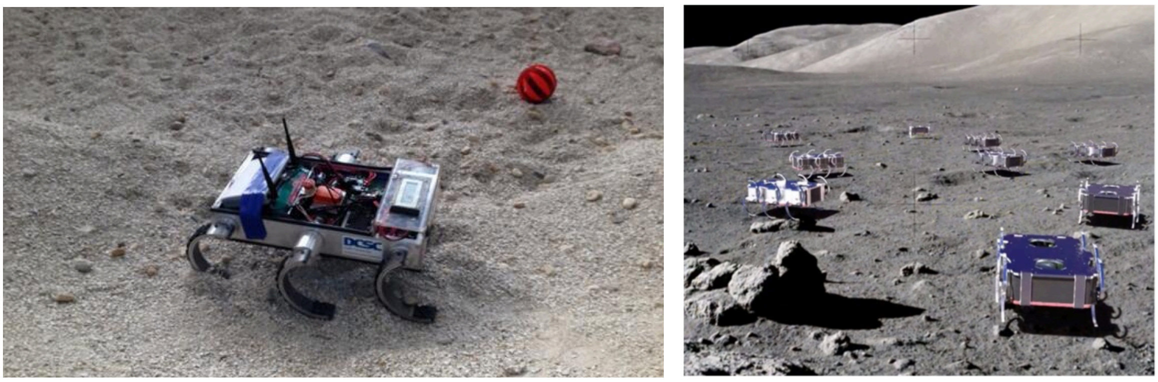

Figure 5: Zebro robot

The main tasks for the robot has been broadly divided into: (i) exploration/mapping implying that the surface and subsurface will need to be mapped for topology and composition before any type of mining takes place; (ii) mining implying that, once the areas of interest (AoI) are determined, robots will start to remove materials and safely transfer them to an alternative location for further processing; and (iii) construction implying that robots with specialised payloads will support building the structure. Hence, the swarm is carrying out various tasks in a specific order and uses various types of SI algorithms as there is no unifying SI at present. There are more than 30 known algorithms and most of them are nature inspired which are commonly known as metaphor-based metaheuristics. Out of these, two specific swarm behaviour algorithms have been selected for the swarm of robots serving the Rhizome habitat: Differential Evolution (DE) and Artificial Bee Colony (ABC). Furthermore, the interactions between robots and humans are also an important aspect of swarming, as most SI are developed to operate in full autonomous mode. On Mars, there are certain tasks which are not advised to be in swarm's control as for instance: (i) Maintenance, (ii) Decision making in unknown/unpredictable situations, and (iii) Teleoperation from an orbital platform. The concrete needs for human/robot interfaces have been identified during the project, and recommendations have been formulated on how to organise and design these interactions in the following project phases.The different types of robots proposed for each task are implementing specific tasks relying on various types of SI:

1. Exploration/mapping is implemented with ABC swarm algorithms (which spread out and randomly or orderly map for AoI).
2. Excavating/Mining is also implemented with ABC algorithms (specific locations are needed to be populated after exploration and mapping/prospecting).
3. Construction requires, instead, DE algorithms (train the robots to make construction fast and efficient).

Considering these three categories of operations, the Concept of Operations for the swarm robotics has been based on Scouting Rovers, Cargo Rovers and Precision Rovers.

The first cargo flight will bring to Mars a large number of Scouting Rovers (50 in total), to allow for a thorough exploration of the environment and preparation for the construction phase. Scouting Rovers will explore the Mars surface to search for in-situ construction materials and life support resources. They will be followed, in the second and third cargo flights, by the Precision and Cargo Rovers. The scope of the Precision Rovers will be to provide support to the construction of all necessary infrastructures. This will start with the power generation system (after the second cargo flight), but the Precision Rovers will also be involved in the operations inside the lava tubes, to transfer fabricated parts from the fabrication site to the habitat building location. The Cargo Rovers are heavy transportation vehicles, which will have the scope of moving raw materials from their extraction site to the location where they will be used for printing and installation purposes. A total of 6 Precision Rovers and 5 Cargo Rovers will be brought to Mars by the second and third cargo flights. In the following crewed flights, it is expected that spare units for each type of rover are brought to Mars: per flight, this will be 10 Scouting Rovers, 1 Precision Rover, and 1 Cargo Rover. This relatively small number of rovers will still be sufficient for all required operations on Mars, thanks to their collaborative work in a swarm setting. Preliminary simulations have shown the feasibility of all mission tasks with this number of rovers. In these simulations, the exploration area and maximum range for transportation was set to 2250 km (radius) from the landing location.

In ABC simulations, rovers are represented as bees and point of interests are the food sources (Fig.6). The rovers (or bees) can be further classified as employed or unemployed depending on whether the point of interest meets the requirements for identifying in-situ resources. Therefore, the primary application/tasks for these simulations have been to: spread out the swarm, randomly locate areas of interest, find the best path to these areas of interest. Simulations have shown that every single Scouting Rover, even when acting separately (not in a swarm) is able to find the best possible path over time around obstacles, once the exploration phase is completed.

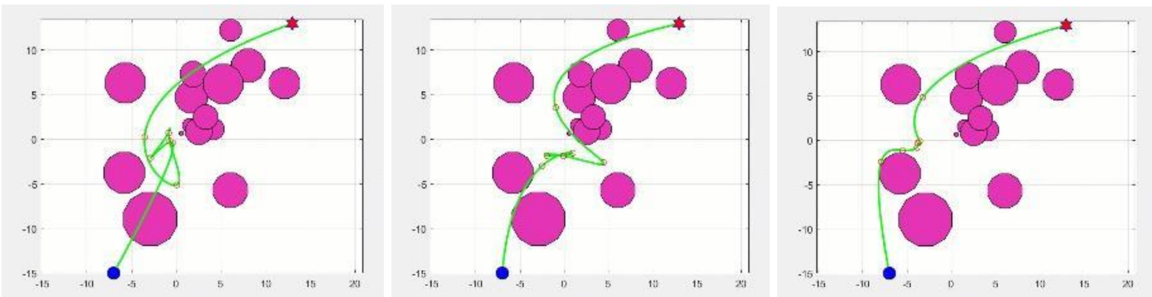

Figure 6: Final path of rover between point of origin and point of interest around obstacles using ABC algorithm

The neural network training based on Differential Evolution has been focused on the movement of Precision Rovers between 3D panel printer and habitat, and their arm movement to place the panels in their correct location. If the algorithm is correctly implemented, little or no human contributions will actually be needed to support the rovers in their operation. The idea behind this concept is that DE can be used to train the robots on Earth to cope with slightly different (updated) constructions, and then the robots on Mars will ‘evolve’ to make constructions faster and more efficiently. In the simulations performed for this study, it has been assumed that a Precision Rover must travel to four different habitat sites and circle back to the printer (origin). The simulations have shown that, while the initial path is quite rough, over time and with positive reinforcement learning, the rover optimises the best path possible with minimum energy and time required to reach all four assembly sites (see deliverable D12).

REFERENCES

Reale, C., Gavin, K., Libric, L., Jurić-Kaćunić, D. (2018) Automatic classification of fine-grained soils using CPT measurements and Artificial Neural Networks. Advanced Engineering Informatics, Vol. 36. https://doi.org/10.1016/j.aei.2018.04.003

Li, Q., Prendergast, L., Askarinejad, A., Chortis, G., Gavin K. (2020) Centrifuge Modeling of the Impact of Local and Global Scour Erosion on the Monotonic Lateral Response of a Monopile in Sand. Geotechnical Testing Journal, Vol. 43.
https://doi.org/10.1520/GTJ20180322

Bier, H., Liu Cheng, A., Mostafavi, S., Anton, A., Bodea, S. (2018) Robotic Building as Integration of Design-to-Robotic-Production and -Operation. In: Bier H. (eds) Robotic Building. Springer Series in Adaptive Environments. Springer, Cham.
https://doi.org/10.1007/978-3-319-70866-9_5

Khoshnevis, B., Yuan, X., Zahiri, B., Zhang, J., Xia, B. (2016) Construction by Contour Crafting using Sulfur Concrete with Planetary Applications. Rapid Prototyping Journal, Vol. 22, No. 5, pp. 848-856.
https://doi.org/10.1108/RPJ-11-2015-0165

Wan, L., Wendner, R., Cusatis, G. (2016) A novel material for in situ construction on Mars: experiments and numerical simulations. Construction and Building Materials, Vol. 120, pp. 222-231.
https://doi.org/10.1016/j.conbuildmat.2016.05.046

Grugel, R.N. (2008) Sulfur 'Concrete' for Lunar Applications – Environmental Considerations. NASA MSFC Technical Memorandum NASA/TM-2008-215250. Marshall Space Flight Center, Alabama. February 2008.
https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20080022947.pdf

Toutanji H.A., Evans S., Grugel R.N. (2010) Performance of "Waterless Concrete". 13th international Congress on Polymers in Concrete ICPIC 2010, Funchal, Madeira, Portugal, 10-12 February 2010.
https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20100026417.pdf

Santovincenzo, A. (2004) CDF Study Report Human Missions to Mars Overall Architecture Assessment. ESA Technical Report CDF-20(A), February 2004.
http://emits.sso.esa.int/emits-doc/1-5200-RD20-HMM_Technical_Report_Final_Version.pdf

Kim, M., Thibeault, S. A., Wilson, J. W., Simonsen, L., Heilbronn, L., Chang, K., Maahs, H. (2000) Development and Testing of in situ Materials for Human Exploration of Mars. High Performance Polymers, Vol 12, No. 1, pp. 13-26. https://doi.org/10.1088/0954-0083/12/1/302

Loopik, H., and Peternel, L. (2021) A Multi-Modal Control Method for a Collaborative Human-Robot Building Task in Off-Earth Habitat Construction. Workshop on Design, Learning, and Control for Safe Human-Robot Collaboration, ICAR 2021.
https://sites.google.com/view/safehrc-icar2021/home (Accessed 18 May 2022)

Fraser S.D. (2009) Power System Options for Mars Surface Exploration: Past, Present and Future. In: Badescu V. (ed) Mars: Prospective Energy and Material Resources. Springer, Berlin Heidelberg.
https://doi.org/10.1007/978-3-642-03629-3_1

Boumis, R. (2017) The Average Wind Speed on Mars. Sciencing.
http://sciencing.com/average-wind-speed-mars-3805.html (Accessed 14 May 2020)

Bluck, J. (2001) Antarctic/Alaska-Like Wind Turbines Could be Used on Mars. NASA Ames News Item.
https://www.nasa.gov/centers/ames/news/releases/2001/01_72AR.html (Accessed 14 May 2020)

Silberg, B. (2012) Electricity in the air. NASA Jet Propulsion Laboratory News Item.
https://climate.nasa.gov/news/727/electricity-in-the-air (Accessed 14 May 2020)

Mersmann, K. (2015) The Fact and Fiction of Martian Dust Storms. NASA Goddard Feature.
https://www.nasa.gov/feature/goddard/the-fact-and-fiction-of-martian-dust-storms (Accessed 14 May 2020)

Delgado-Bonal, A. Martín-Torres, F.J., Vázquez-Martín, S., Zorzano, M.-P. (2016) Solar and wind exergy potentials for Mars. Energy, Vol. 102, pp. 550-558.
https://doi.org/10.1016/j.energy.2016.02.110

Van der Vlugt, R., Peschel, J., Schmehl, R. (2013) Design and Experimental Characterization of a Pumping Kite Power System. In: Ahrens, U., Diehl, M., Schmehl, R. (eds.) Airborne Wind Energy. Springer, Berlin Heidelberg.
https://doi.org/10.1007/978-3-642-39965-7_23

Van der Vlugt, R., Bley, A., Noom, M., Schmehl, R. (2019) Quasi-Steady Model of a Pumping Kite Power System. Renewable Energy, Vol. 131, pp. 83-99
https://doi.org/10.1016/j.renene.2018.07.023

Speretta, S., Cervone, A. et al. (2019) LUMIO: An Autonomous CubeSat for Lunar Exploration. In: Pasquier H., Cruzen C., Schmidhuber M., Lee Y. (eds) Space Operations: Inspiring Humankind's Future. Springer Nature, Cham.
https://doi.org/10.1007/978-3-030-11536-4_6

Peternel L., Tsagarakis N., Caldwell D., Ajoudani A. (2018) Robot Adaptation to Human Physical Fatigue in Human-Robot Co-Manipulation. Autonomous Robots, Vol. 42, pp. 1011–1021.
https://doi.org/10.1007/s10514-017-9678-1

Jain, A., Sharma, S., Joachims, T., & Saxena, A. (2015). Learning preferences for manipulation tasks from online coactive feedback. The International Journal of Robotics Research, 34(10), pp. 1296-1313.
https://doi.org/10.1177/0278364915581193

PROBLEM AREAS

During the project several problem areas have been mitigated as follows:

1. Insufficient information about the composition of Mars and lack of materials from Mars limits technical design and prototyping to simulating and emulating conditions and material systems.
2. Unfamiliar conditions on Mars, such as different gravity, might affect the human performance during the physical collaboration with the robots (until proper adaptation is achieved). To alleviate this problem, on a real mission, the robots will have to adjust their collaborative behaviour (pace, working style, etc.) based on human performance.
3. There is a risk of potential damage to the robot equipment while working in unknown and highly unpredictable environments on Mars. To alleviate this problem, the humans are sufficiently trained to repair or replace the robot equipment.
4. The main systems engineering challenge envisaged at this stage for the project is represented by the lack of available information on similar systems or projects, since no similar off-Earth habitat construction projects have been conducted so far on-site. To mitigate the level of risk associated with the absence at the current day of an on-site demonstration of similar projects or technologies, preliminary data has been collected on Earth-based similar research and demonstrations have been used as a starting point for the calibration of the initial systems engineering budgets and assumptions. The main systems engineering trade-offs have been: existing vs. dedicated launcher solution for the transportation of materials that cannot be procured or produced on-site; communication to a relay spacecraft in orbit around Mars vs. direct communication to Earth; level of autonomy of the whole habitat building system from Earth commands (amount, extent and frequency of commands that must be received from the controls and operations on Earth).

RESULTS

Developed technology reached TRL 3/4, which implies that (3) analytical and experimental critical function and/ or characteristic proof of concept as well as (4) component and /or breadboard validation in laboratory environment have been successfully implemented. This technology can be transferred to on-Earth applications involving (a) 3D printing of structures with various functionalities, (b) constructing with HRI support, and (c) automating processes. The potential markets and customers are from the building industry that has been so far slow in adopting new technologies but is in zugzwang because of skilled labour shortage, more fatalities than any other sector in the EU, and low productivity.

The principal features of technology that would be required in a technology demonstrator for automated and HRI supported non-space construction are (i) development of alternative printing method using cement-less concrete, (ii) development of scaling up approach (with the structure providing access to rovers to move up and down and construct a large scale habitat), and (iii) integration of environmental control. The resources in time and money that would be required to achieve this are estimated as follows: 2-3 years and the costs range between 3-4K for a 3/4/8m structure.

FUTURE STEPS

Further development activities to reach TRL 5/6 include: (i) development of alternative printing method using cement-less concrete, (ii) development of scaling up approach (with the structure providing access to rovers to move up and down and construct a large scale habitat), and (iii) integration of LSS with the goal to achieve (TRL 5) component and /or breadboard critical function verification in a relevant environment and (TRL 6) model demonstrating the critical functions of the element in a relevant environment. In this context, the relevant environment is envisioned to be a cave on Earth. The duration of these activities are estimated to be 2-3 years and the costs range between 3-4K for a 3/4/8m structure built in a cave on Earth.

BACKGROUND

Relevant existing concepts/products relevant to the activity and/or to be used third party's concepts/products relevant to the activity and/or to be used background of the company(s) are as follows:

CEG: Research in Foundations and Underground Space in the Geotechnical Engineering section has been focusing on foundation systems, complex structures, and large-scale field testing. CEG identified the potential of caves and has facilitated connecting with experts involved in off-Earth cave studies in order to identify location of the habitat.

ABE: D2RPA&O processes have been developed at ABE since 2014 and build up on expertise in numerically controlled processes developed since 2004. Of particular relevance is the robotically 3D printed chaise longue made of recyclable thermoplastic elastomer is proof of concept for smart material design. It involved gradient pattern differentiation allowing for a gradient from high to low density of cells for achieving variable stiffness. If additive D2RP has been developed for materials such as concrete (a.o. with 100% replacement of aggregate/ sand with regolith-simulant), ceramic clay, silicon, and recyclable plastics, subtractive D2RP techniques involve robotic milling and cutting of wood, cork, upcycled plastic, and expanded polystyrene. D2RO has been mainly implemented with WSAN for environmental control and spatial reconfiguration (inter al. Bier et al. 2018). D2RP&O processes have facilitated in this project the development from building (schematic) to component and material (developed and materialised) design.

For material and structural engineering, the Structural Mechanics at ABE has been contributing with knowledge in structural and thermal material testing.

AE: Wind Energy: An experimental 20 kW kite power system has been in test operation since 2010, demonstrating automatic energy harvesting in 2012. This system has been adapted to meet requirements on Mars.

AE: Space Systems Engineering: Through the Space Systems Engineering chair of the Aerospace Engineering Faculty, TUD plays a leading role in the European research on space systems engineering, distributed space systems and nano-satellite design, as well as miniaturised satellite systems (radio hardware, analogue and digital circuit design, micro-propulsion). This expertise in space systems has been employed in Rhizome mainly to define timeline and concept of operations for the transportation flights serving the habitat, during both its construction and operation.

AE: Lunar rovers have been developed to explore the lunar surface for the first time and carry out on-ground imaging around the lander, studying the effects of landing on the lunar surface as well as test its power system and durability of the system. For Rhizome the rovers are adapted to Martian conditions.

3ME: For this project, in particular 3ME's expertise in learning and autonomous control (intelligent control, cognition), robot dynamics (dynamic motion control, motor control), and human-robot interaction has been of relevance.

Vertico: Material and 3D printing system are basis for D2RP approach.

Exolith: Regolith simulant replaces to various percentages up to 100% the aggregate in Vertico's concrete recipe.

TEAM

The team consisted of experts in robotic building,civil, material, and aerospace engineering, swarm and cognitive robotics. There were in total ±10 experts, ±40 students, and 1 TA 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.

The core TUD team consisted of: Dr. Henriette Bier, Ir. Max Latour, Ir. A. Hidding, and Dr. Fred Veere (Architecture and Architectural Engineering), Dr. Luka Peternel (Mechanical Engineering:

Human-Robot Interaction), M. Verma (Aerospace: Swarm Robotics), Dr. Roland Schmehl and L. Ourouvoma (Aerospace: Wind Energy), and Dr. Angelo Cervone (Aerospace: Space Systems Engineering). Supporting technicians V. Laszlo, S. Jones, and students. Consultants such as Dr. K. Gavin, (Civil Engineering: Subsurface Structures), Dr. V. Popovich (Mechanical Engineering: Material Science), and Dr. Y. Tang (Aerospace Engineering: Material Science) and partners such as ESA (Advanced Manufacturing) and Vertico (3D Printing) have contributed with expertise at various stages of the project. Material suppliers were Vertico (concrete) and Exolith Lab (regolith simulant).

PLANNING

The duration of the project has been 12 months (excluding public holidays and vacation periods). An extension of 1 month has been granted to finalise documentation and some of the dissemination activities.

DOCUMENTATION

In addition to this final report, detailed documentation of the whole project is available on the CS-wiki.[8]

DISSEMINATION

The project has been and is being in process of being published in various media[9] as well as on scientific platforms such as TUD's Spool Cyber-physical Architecture[10] and Springer's Adaptive Environments book series. It has been presented and discussed at the symposium organised by ESA where 23 activities that ESA's Discovery programme is supporting came out of an Open Space Innovation Platform (OSIP) campaign for ideas for technologies that could enable off-Earth manufacturing and construction[11].

TAGS/ KEYWORDS

Underground habitat, 3D printing, D2RPA&O, HRI, robot swarm, sustainable energy generation

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This project has profited from the contribution of TUD students at all stages from ideation to proof of concept. It could not have been implemented without funding and regular review sessions from and with ESA as well as co-funding, expertise, and technology from industrial partner Vertico.

APPENDIX

1. Deliverables[12]

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[8] Link to CS-wiki: http://cs.roboticbuilding.eu/index.php/2019MSc3
[9] Link to CS-wiki: http://cs.roboticbuilding.eu/index.php/Shared:RhizomeReview2
[10] Link to Spool: https://journals.open.tudelft.nl/spool/issue/view/787
[11] Link to ESA: https://www.esa.int/ESA_Multimedia/Images/2020/02/Robotic_crane_for_wireless_power_and_data_transmission_between_surface_and_cave
[12] Link to deliverables: http://cs.roboticbuilding.eu/index.php/Shared:RhizomeReview6