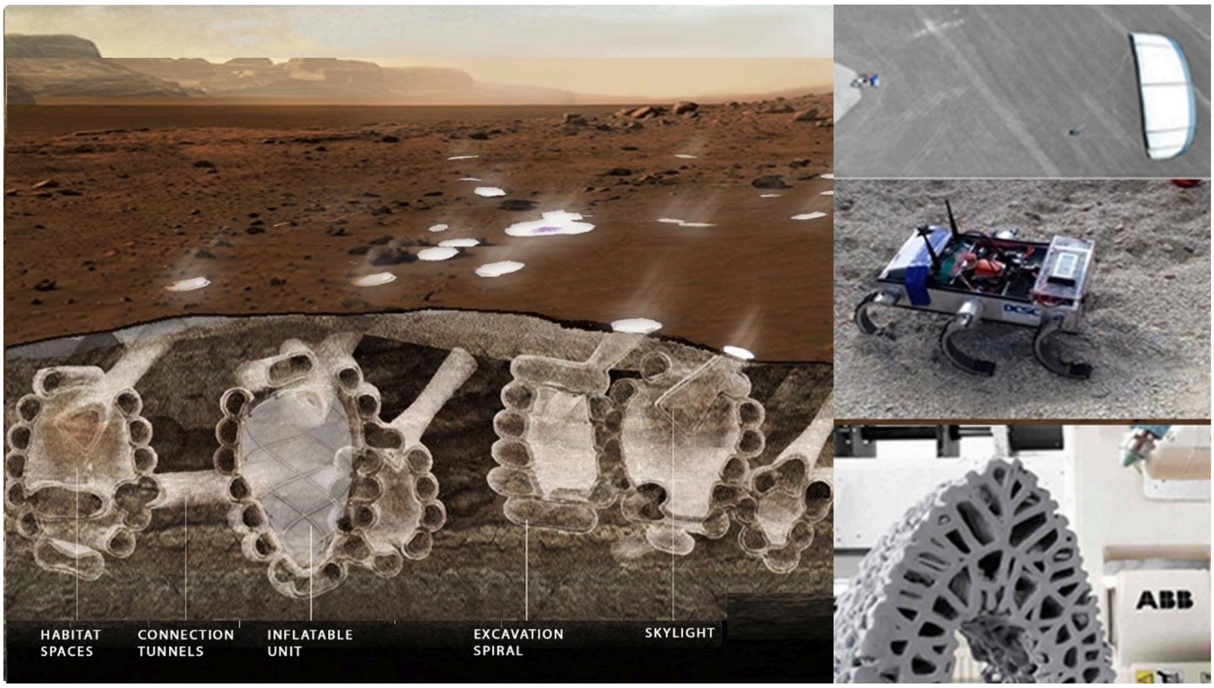

Idea I-2020-00916: Rhizome: Development of an Autarkic Design-to-Robotic-Production and -Operation System for Building Off-Earth Habitats

IDEA ABSTRACT

In order for off-Earth top surface structures built from regolith to protect astronauts from radiation, they need to be several meters thick. The Technical University Delft (TUD) proposes to excavate into the ground of Mars to create subsurface habitats. By excavating not only natural protection from radiation can be achieved but also thermal insulation because the temperature below ground is more stable. At the same time through excavation valuable in situ resource utilization (ISRU) is implemented. The idea is that a swarm of autonomous mobile robots developed at European Space Agency (ESA) and/or TUD excavates the ground in a sloped down- and back up-wards spiral movement. The excavated regolith is mixed with liquid sulphur to create Martian concrete, which is then sprayed and/or 3D printed to create a structure supporting the excavated tunnels. As soon as the tunnels are reinforced, the material in-between the tunnels can be removed to create a larger cavity that can be inhabited. Spraying and 3D printing relies on Design-to-Robotic-Production and -Operation (D2RP&O) technology developed at TUD. The rhizomatic structure is a structurally optimized porous shell structure with increased insulation properties due to its porosity. To regulate the indoor environment a pressurised inflatable structure is placed in the cavity. This inflatable structure is made of materials, which can also be at some point reproduced on Mars through ISRU. The production and operation/use of the habitat are powered by a renewable energy system which combines an automated kite-power system with solar panels in a microgrid. The ultimate goal is to develop an autarkic D2RP&O system for building off-Earth subsurface autarkic habitats from locally-obtained materials.

ESA ENTITY CODE

1 000 000 815

BUDGET

100k€

DURATION

12 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 and -Operation (D2RP&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 meters thick to sufficiently protect the astronauts. Furthermore, regolith can not 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 pressurized 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 that 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 sees an opportunity to investigate possibilities of how autonomous and /or semi-autonomous swarms of robots could drill into and/or excavate off-Earth and 3D print a subsurface habitat while also considering the restraints of interplanetary space travel. The advantages of building below ground are manifold: While thermal insulation and protection from radiation are facilitated, in-situ resources utilisation (ISRU) is implemented.

OBJECTIVES

Main objectives of the proposed activity is to develop technical designs for:

(a) an autarkic data-driven Design-to-Robotic-Production and -Operation (D2RP&O) approach heavily relying on in-situ resources utilisation (ISRU) and employing

(b) semi-/ autonomous rovers and

(c) renewable energy generation.

Next to the technical design, several tests will be implemented in laboratory conditions:

(1) Excavation with shotcrete reinforcement,

(2) subtractive and additive D2RP, and

(3) human-robot collaboration.

D2RP&O methods have been developed at TUD for on-Earth applications (inter al. Bier et al., 2018). While Design-to-Robotic-Production (D2RP) focusses on embedding robotic approaches into production processes, D2RO embeds robotic systems into the built environment. Both facilitate advanced production and operation of buildings. On Mars, the D2RP methods facilitate excavation into the ground to produce subsurface habitats and robotic 3D printing to reinforce the excavated underground cavities. Subsurface habitation has the advantage of natural protection while also being less affected by thermal stresses because the temperature is more stable underground. At the same time through excavation valuable in situ resource utilization (ISRU) is implemented. The use of locally obtained materials through excavation and the naturally obtained shelter represent the advantage over other design proposals. D2RP&O methodologies are restricted by the method of production and the materials available.

The process of excavation is implemented by a swarm of semi-/autonomous mobile robots, which excavate the ground in a sloped downwards spiral movement until they reach the lowest point from where they excavate in an upwards spiral movement. The excavated regolith is mixed with liquid sulphur to create Martian concrete (Wan et al., 2016), which is then used by the spraying and 3D printing robot to create a structure that reinforces the excavated tunnels. As soon as the tunnels are stable, the material in between the tunnels can be removed to create a larger cavity that can be inhabited. For that, the cavity is equipped with a life support system that requires Design-to-Robotic-Operation (D2RO) methods, facilitating the integration of sensor-actuator networks into the built environment. All involved processes require energy, which is harvested from sun and wind.

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.
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https://doi.org/10.1016/j.conbuildmat.2016.05.046

TECHNICAL REQUIREMENTS

The technical requirements for this study will be 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 specialized 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. Integrate energy system: First, integrate a basic energy system that will be used to create the parts required for the complete energy system. Then, integrate 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 Human Robot Interaction (HRI) features: This function includes all actions required for deploying the swarm to implement excavation and 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 life support system 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.

TASKS DESCRIPTION

This proposal 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.

1. Excavation and reinforcement of the underground structure

The Geoengineering section of the Faculty of Civil Engineering and Geosciences (CEG) will work on the enhancement of specialist drilling techniques, such as used in the ExoMars mission, that are currently capable of achieving depths of 2m below ground level. Sensors will be added to allow automatic classification of regoliths using terrestrial soil classification techniques (Reale et al. 2018). This will allow the drill to act as a site location tool, identifying the optimal location to provide the depth required and allow for the determination of parameters necessary for sizing the support system for the underground space. Prototypes of the drill will be tested in the geotechnical centrifuge facility of TUD (see Fig. 1) where the g-level of fine sand samples (analogous to the regolith) can be controlled and mixing of the materials will be tested (Li et al., 2020). This mixing technique will be used to create a concrete-like material for the reinforcement of the generated underground cavity. The strength and stiffness of the concrete-like material generated with the in-place mixing technique will be tested in the controlled environment laboratories of the section, thus providing important information about the resilience of the structures.

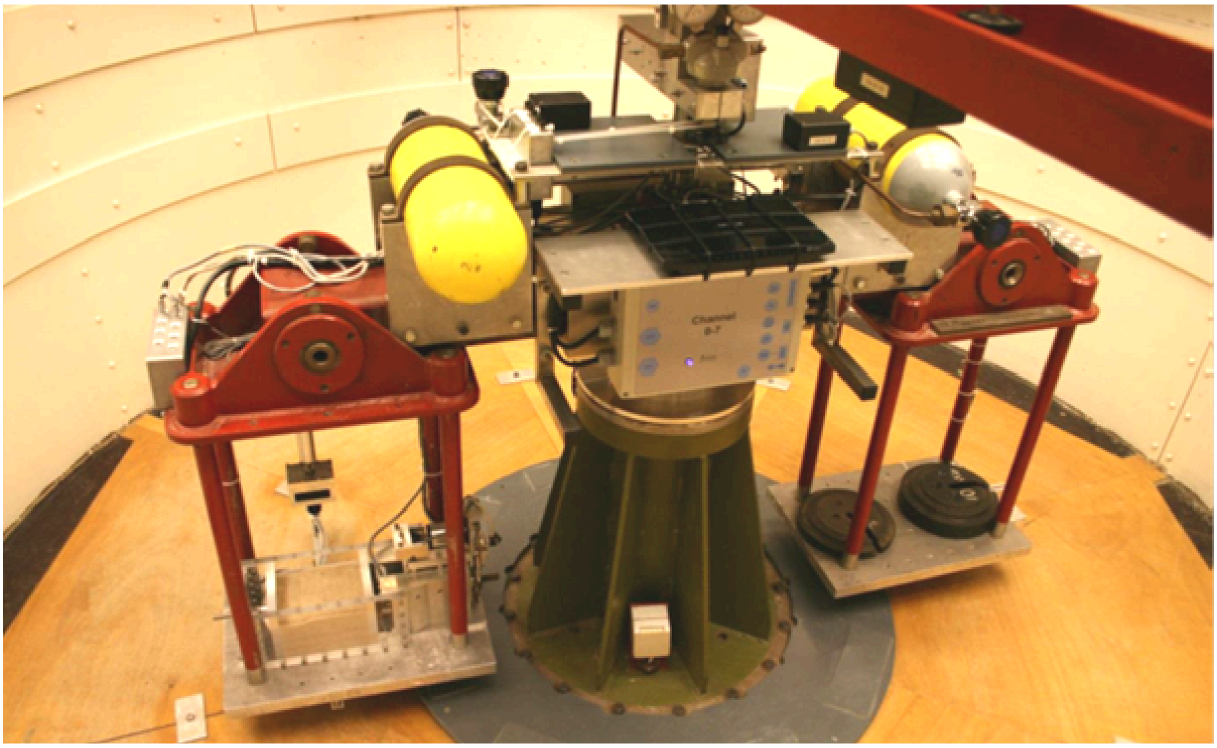

Figure 1: TUD centrifuge facility

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

Data-driven D2RP&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 of the underground inhabitable rhizomatic structure (see cover image). By analysing the composition of the terrain, suitable locations will be identified to excavate and 3D print habitats below ground by means of D2RP&O. 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) will be employed in the following sequence:

2.1 Subtractive D2RP

This process involves excavation following a regular mining approach. Excavation is implemented with rovers similar to the rovers developed at TUD in a controlled down- and upwards spiral movement. Excavation is followed up by reinforcement using shotcrete. Expertise in D2RP involving robotic milling, drilling, cutting (see Fig. 2) developed by the Robotic Building (RB) research group, as well as expertise in underground structures developed at CEG will be employed.

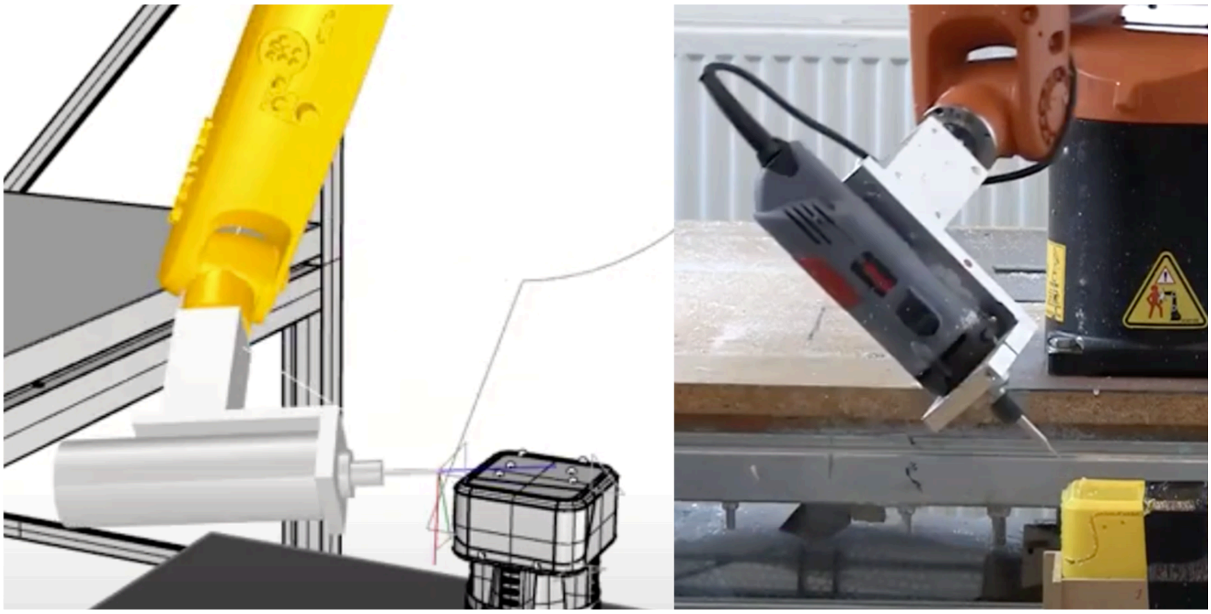

Figure 2: Simulated and prototyped subtractive D2RP

2.2 Additive D2RP

This process is currently explored in laboratory setup using clay, silicon and thermoplastic elastomers and represents the basis for the 3D printing approach with Martian concrete[1] (Khoshnevis et al., 2015; Wan et al., 2016) that is proposed in this project. The spraying/printing system is connected to a rover that is moving down- and upwards to deposit material. By mixing regolith with molten sulphur a mixture is formed that is stronger than usual concrete. The printed structure is, preferably, a compression only i.e. shell structure. It is a structurally optimized porous structure, which has increased insulation properties (see Fig. 3), requires less material, and minimizes the printing time. Particular challenges are material printability, robot reachability, and digital-physical synchronization. Also, considering that sulphur concrete material was reported to have worse radiation shielding properties than plain regolith simulant (Grugel, 2008, Toutanji et al. 2010) material studies and experiments need to be implemented. The excavation and reinforcement of the underground structure are implemented with rovers that are equipped with robotic tools. Rovers deployed for building the structures will have various sizes as specialized tools are needed for different types of tasks. Although, some robots might 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 drilling tool). The mobile

[1] Martian concrete is a mix consisting of 50% sulfur and 50% regolith and it has compressive strength of above 50 MPa.

platform will provide 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, will execute tasks by using Swarm Intelligence (SI). The SI is a decentralized, self-organizing algorithm which will manage the division of labour between different types of robots at different times. The rovers' swarm design builds up on technology developed at Aerospace Engineering (AE) and is described in task 3.

2.3 Design-to-Robotic-Operation (D2RO)

This process will be 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 are requiring 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 Martian concrete. This inflatable structure consists of materials such as neoprene, vectran, kevlar or dyneema, an ultra-high-molecular-weight polyethylene manufactured by Dutch chemical company DSM, whom the TUD team plans to involve in the project. The advantage is that the range of required materials can also be reproduced on Mars through in situ resource utilization (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).

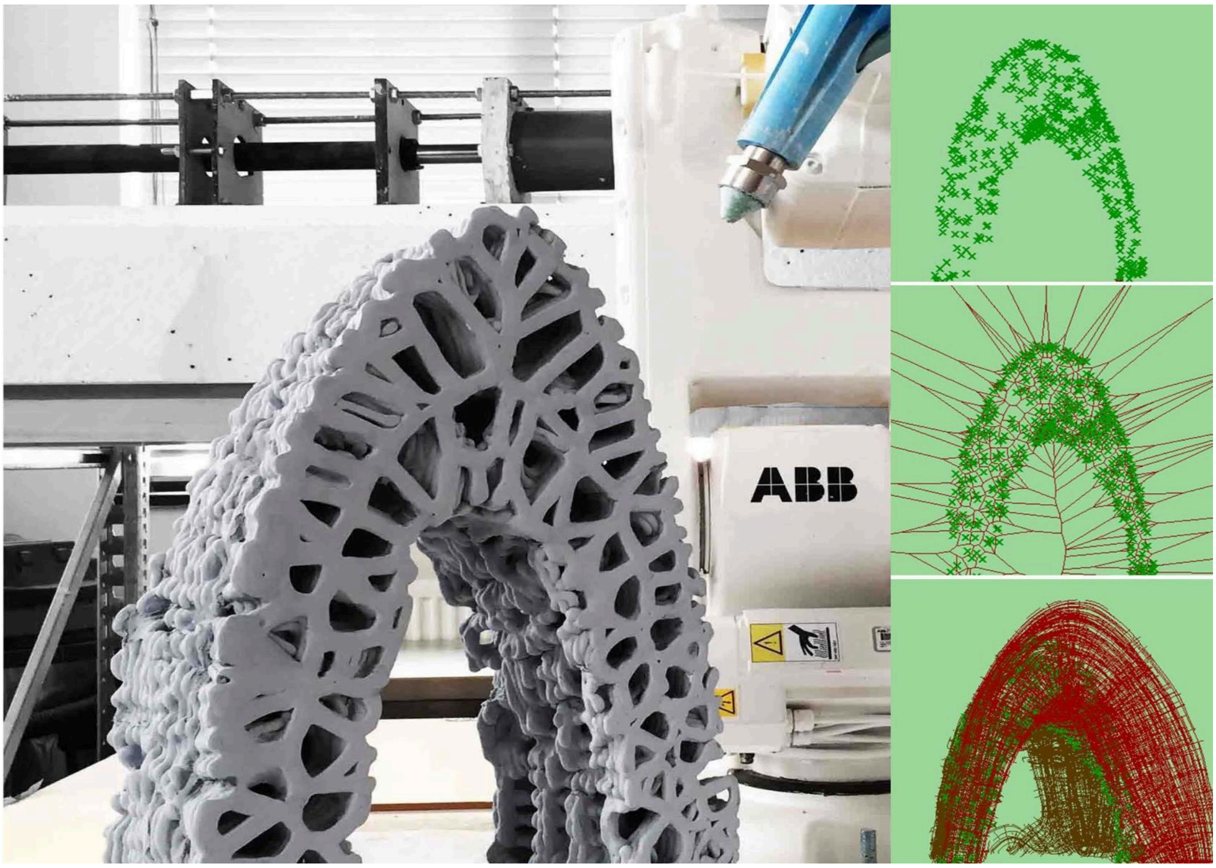

Figure 3: Additive D2RP using clay

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, is aiming to understand the behaviour of artificial ecosystems to develop technology for a future regenerative life support system, will be conceptually integrated in the proposed project.

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. Used materials and approaches emulate the ones implemented in-situ.

3. 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 will take advantage of. The expertise in space systems engineering is important to integrate the different components of the proposed solution.

3.1 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, a Mars base would ideally be powered by a combination of solar and wind energy systems (Bluck, 2001), supplemented by suitable energy storage. This project will employ 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 will be 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.

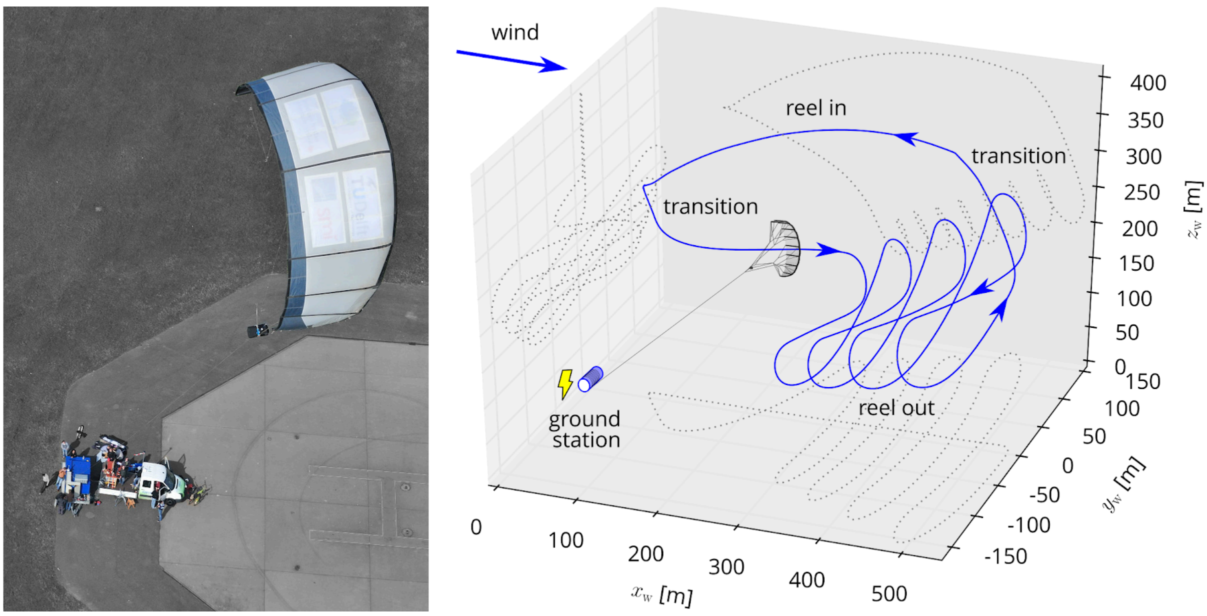

Figure 4: Kite power system of TUD in operation (left), simulated energy harvesting cycle (right)

As a first step of the project, the solar and wind resources on Mars will be assessed, using available data from existing studies (Delgado-Bonal, 2016). Based on this resource assessment and the geoengineering activities described in task 1, the site of the habitat will be selected. As a next step, the automated kite power system developed at TUD (see Fig. 4) will be used as a starting base for a redesign that can be operated on Mars. The current 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 will be increased. The system will have a mass of 150-200 kg and a packing volume of about 2 m^3 and will be combined with PV modules to buffer periods of low wind. For the sizing and design of the kite power system, a validated performance model will be used (Van der Vlugt, 2019).

3.2 Space systems

Given the complexity and intrinsic multidisciplinary nature of the proposed off-Earth infrastructure, its design is strictly associated to a number of space systems engineering challenges, ranging from the accurate definition of all resource budgets (mass, volume, power, data) to the design of the interfaces between all subsystems making use of these resources. Consideration has to be given to the characteristics of the launcher/interplanetary spacecraft used to transport the required material from Earth to the final site, and the associated mass and volume constraints.

These challenges will be tackled by a dedicated Systems Engineer, who will be a core member of the project team and keep continuous contact with all other team members working at the relevant parts of the project. Standard systems engineering tools will be used in this respect, such as budget estimation tables, qualitative/graphical trade-off methods, and N2 interface charts. The approach will be similar to, and will take advantage of the expertise acquired from, what has been done by the SSE chair of the Aerospace Engineering faculty for previous ESA projects, such as the Phase 0 of the LUMIO Lunar CubeSat mission, for which TU Delft had the specific responsibility of the systems engineering of the spacecraft (Speretta et al., 2019).

Preliminary, energy/mass/volume considerations and total amount of required power have been estimated by Aerospace Engineering students in the recently completed Design Synthesis Exercise with 10 BSc students.

Figure 5: Zebro robot

3.3 Autonomous multi-functional robots swarm

For this project, a swarm of mobile robots i.e. rovers developed at TUD are considered for implementing tasks such as excavating, transporting, and processing materials. Since 2013, TUD has been actively working on small scale rovers Zebro Rover (see 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 is a decentralized architecture meaning that any number of rovers can be added to the swarm. To demonstrate the technology, TUD plans to 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.

In this proposal, the technical design of a swarm of rovers implementing excavation and reinforcement of the habitat is explored. In this context, there are three main challenges that need to be solved as far as swarm technology is concerned: (i) Deployment strategy of SI(s) resulting in developing a unifying SI, (ii) Identifying number of rovers per type, (iii) Defining technical specifications of rovers based on the given system constraints, e.g. power required, power source, payloads, robot mass and size, and ensuring their compatibility to the available budgets.

The main tasks for the robot can be broadly divided into: (i) exploration/mapping implies that the surface and subsurface will need to be mapped for topology and composition before any type of mining takes place; (ii) mining implies 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; (iii) maintenance: as the material is being progressively taken out of the ground, robots reinforce the structure to stabilize them; and (iv) construction implies that robots with specialized payloads build the structure. Hence, the swarm will carry out various tasks in a specific order and will use different 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, four SI swarm behaviour algorithms will be used to manage the swarm: General Algorithm (GA), Differential Evolution (DE), Ant Colony Optimization (ACO), and Glowworm Swarm Optimization (GSO). The different types of robots proposed for each task (as listed above) are implementing specific tasks relying on various types of SI:

1. Exploration/mapping is implemented with drones, hexapods and/or wheeled robots using ABC (which spread out and randomly or orderly map for AoI).
2. Maintenance involves drones and wheeled robots using GA.
3. Excavating/Mining is implemented with tracks and/or power bank robots using GSO (specific locations are needed to be populated after exploration and mapping/prospecting).
4. Construction requires tracks and/or wheeled robots using DE (train the robots to make construction fast and efficient).

In this proposal, the focus is on the technical design of the points 3 and 4. Furthermore, the interactions between robots and humans is also an important aspect of swarming, as most SI do not take human interaction into account as they are developed to operate in full autonomous mode. But, 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 will therefore be identified during the project, and recommendations will be formulated on how to organize and design these interactions in the following project phases.

4. Human-Robot 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 it 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 and therefore robotic agents assist humans instead.

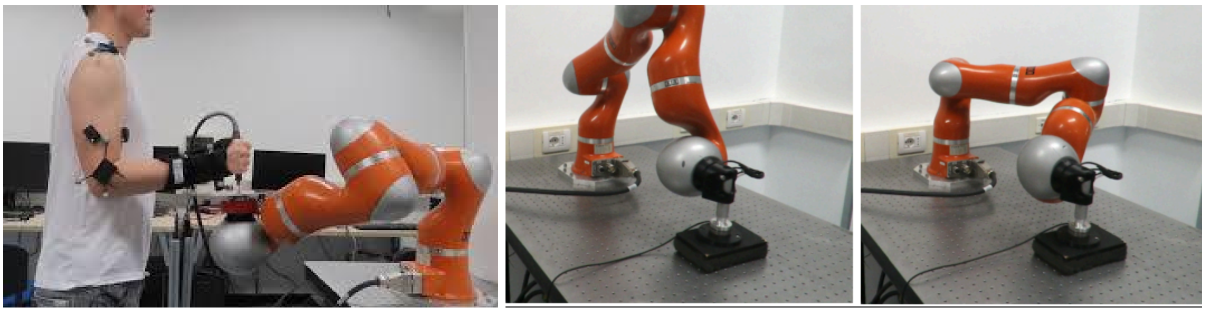

Figure 6: Muscle force estimation for fatigue management in human-robot co-manipulation (left) and wiping (middle and right)

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. These advantages can be exploited by establishing smart human-robot teams. In addition to direct physical human-robot collaboration based on expertise developed at TUD (inter al Peternel, et al. 2018), robotic agents in short-distance teleoperation. During the initial stages of underground habitat construction, the structure and environment might still be too hazardous for humans to work on it. For example, it might be unclear whether the structure is stable enough, or certain tasks might be risky due to the very preliminary work phase. In that case, the humans will teleoperate the robot from the nearby spaceship until the initial stage of construction is done though the robots, before moving underground themselves to finalise the construction. While robots can be teleoperated from Earth, the delays make such operation very difficult for complex tasks with physical interaction that require close-to-real-time feedback. To enhance the teleoperation system, the tele-impedance method will be employed, which enables the human operator to adjust the stiffness/softness of the robot (see Fig. 6). Such ability is crucial in tasks that involve interaction with unknown or unpredictable environments that are an integral part of space exploration.

Within the project's scope, the main physical human-robot collaboration scenario envisioned is due to the limited number of available robots. Since the same robots will be used to perform multiple tasks (i.e., excavation activities, printing the components for structures, and assembly of those parts), humans may need to help the robots to change the type of tools required for these tasks, as well as help the robots when they find themselves in unexpected situations that require complex decision making.

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WORK PACKAGE DESCRIPTIONS

WP1 [M1-12]: Project management is implemented by H. Bier from ABE, who will (i) organize bimonthly meetings incl. midterm and final reviews, (ii) set-up project website and data management plan, (iii) monitor project and implement risk management, (iv) document all WP outcomes in the form of contributions to the deliverables.

WP2 [M1-19]: Development of approach for excavation of subsurface structure is implemented by K. Gavin from CEG together with H. Bier from ABE, and L. Peternel from MMME. Building on the work on robotics, the main task will be to test the excavation approach that will be used in the construction of the underground structures while taking site conditions into account. This work will be undertaken in the geotechnical centrifuge wherein small-scale models that can be tested at appropriate scale and g-level. Tasks include (i) selection and characterization of test sand to represent regolith and/or other representative materials (ii) adaptation of centrifuge loading mechanism to accommodate robotic drill (iii) installation/drill tests, (iv) in-situ concrete formation and (v) retrieval and testing of specimens. A Master's student will work closely with the Subsurface research group under the supervision of K. Gavin and a PostDoc from the group.

WP3 [M1-9]: Development of swarm robotics and HRI approach is implemented by M. Verma from AE, L. Peternel MMME, and H. Bier from ABE in collaboration with DRI. The main task is the development of the deployment strategy, identifying number of rovers per type, defining technical specifications of rovers i.e power required, power source, payloads, robot size. Furthermore, improve existing HRI and robot teleoperation methods developed by experts at TUD (Peternel, et al., 2017, 2018) to be applicable to the given space exploration scenario. The human-robot collaboration approach will consider human intentions and control the complex physical interactions with the human and various objects. The teleoperation approach of remote robots will consider performing dynamical interactions tasks, where changing the robot's stiffness is critical. Additional task is to integrate the developed methods with individual robot control system and a higher-level swarm control system. The technical design of the developed HRI and teleoperation methods will be documented. The developed approach will be tested through experiment in the DRI facilities and the results will be documented in a report.

WP4 [M1-9]: Development of subtractive and additive D2RP approach for constructing the habitat is implemented by H. Bier from ABE in collaboration with K. Gavin from CEG, L. Peternel from MMME, as well as SAM|XL and 3D Robot Printing. It consists of several subtasks: (i) develop D2RP approach for excavation, (ii) integrate D2RP approach with semi-autonomous robots, (iii) test approach at ABE on a fragment, SAM|XL, and 3D Robot Printing, (iv) document results.

WP5 [M1-9]: Development of D2RO approach for habitat incl. life-support system into the habitat is implemented by H. Bier from ABE and A. Cervone from AE involves several sub-tasks: (i) develop D2RO approach, (ii) integrate D2RO approach with life-support system, (iii) test approach at ABE on a fragment and (iv) document results.

WP6 [M3-9]: Development of the energy system by R. Schmehl and A. Cervone from AE. This includes the following sub-tasks: (i) assess the solar and wind resources and select the site of the habitat in consultation with geoengineering activities described in WP2; (2) redesign the kite power system for operation on Mars, increasing the wing surface area and develop automated launching and landing of the kite; (3) integrate the kite power system with PV modules and energy storage; (3) perform an optimization of this microgrid adjusting design and operational parameters, trading off safety, reliability and power quality.

WP7 [M3-11]: System level design and integration is performed by A. Cervone from AE and H. Bier from ABE and will include the following sub-tasks: (i) maintain continuous interfacing with all project units and collect (and continuously update) relevant technical data from them; (ii) Support all project units in their design choices through dedicated trade-off procedures; (iii) Define and continuously update, in collaboration with all project units, the main technical requirements for the project; (iv) Define and continuously update all resource budgets for the project (mass, volume, power, data, link budget); (v) Take into account the characteristics (required vs. available) of the launcher and/or interplanetary spacecraft used for transportation of the required material, proposing and analyzing several scenarios based on existing or currently planned launchers; (vi) Keep track of all interfaces between project systems and units, by means of N2 interface charts.

WP8 [M8-12]: Dissemination is implemented by the whole team by publishing results in conference proceedings, journals, and books.

DELIVERABLES

D1 (from WP1): Project website and data management plan [M1].

D2 (from WP2-5): Documentation of preliminary design of subsurface habitat using swarm robotics and HRI [M2].

D3 (from WP2-5): Documentation of developed design of subsurface habitat using swarm robotics and HRI [M4].

D4 (from WP6): Documentation of preliminary design of energy system [M4].

D5 (from WP2-5): Documentation of final design of subsurface habitat using swarm robotics and HRI [M7].

D6 (from WP6): Documentation of final design energy system [M9].

D7 (from WP8): Documentation of review with with invited experts from TUD, ESA, DRI, and/or SAM|XL [M9].

D8 (from WP2-5): Documentation of testing excavation and D2RP&O approach without integrated swarm robots and HRI [M9].

D9 (from WP8): Publication of relevant results on website and relevant media [M12].

D10 (from WP7): Documentation of integration of all systems [M10].

D11 (from WP2-7): Documentation of all systems' optimization [M11].

D12 (from WP1-8): Documentation of WP-outcomes [M12].

D13 (from WP1-8): Archiving documentation on 4TU database and publication of representative results on dedicated website and in various media [M8 and M12].

D14 (from WP8): Publication of results in Scopus-indexed journal Spool or other relevant venues on validation of novel investigation and construction drill for non-terrestrial applications and D2RP&O using swarm robotics and HRI [M12].

D15 (WP8): Publication of results in Springer book series Adaptive Environments [M12].

D4 (WP8): Final Report and Executive Summary including reports on the performance of the drill tool, on evaluation of HRI approach through experiments in the lab, on system engineering; Final Presentation slides; Illustration of the activity in one self-standing image; ±5 min video summarising the main results of the activity [M12].

PROBLEM AREAS

Several problem areas and the possible mitigations are identified 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). Nevertheless, it is not practically possible to reproduce such low-gravity conditions in the lab. To alleviate this problem, on a real mission, the robots will have to adjust their collaborative behaviour (pace, working style, etc.) based on the 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 will be 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. This will force the Systems Engineer to take a decision based on a number of assumptions and speculations and a certain amount of calculated risk. 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 will be collected on Earth-based similar research and demonstrations, that will be used as a starting point for the calibration of the initial systems engineering budgets and assumptions. The main systems engineering trade-offs envisaged at this stage of the project are: 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 & operations on Earth).

BACKGROUND

Relevant existing own 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. Current research in tunnelling deals with the interaction between the Tunnel Boring Machine (TBM) and the surrounding soil, and indirectly with surface constructions. Furthemore, it deals with the development of a reliability-based approach combining analytical techniques, finite elements and probabilistic methods such as Monte Carlo simulation and the First Order Reliability Method (FORM). By analysing the excavation and construction of tunnels and galleries, as well as pre- and post-closure scenarios, within a probabilistic framework, the research highlights influential design parameters requiring further in-depth investigation.

ABE: D2RP&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 (Fig. 7). 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 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).

AE: Wind Energy: An experimental 20 kW kite power system has been in test operation since 2010, demonstrating automatic energy harvesting in 2012.

AE: Space Systems Engineering: Through the Space Systems Engineering chair of the Aerospace Engineering Faculty, TU Delft plays a leading role in the European research on space systems engineering, distributed space systems and nano-satellite design, as well as miniaturized satellite systems (radio hardware, analogue and digital circuit design, micro-propulsion). Research activities at the Space Systems Engineering chair focus on enabling technologies within space engineering. The chair research strategy is to realize complex space systems in an end-to-end engineering approach. In the last 10 years, the chair has successfully developed, launched and operated in space the Delfi-C3 and Delfi-Next satellites, and is consequently recognized worldwide as a flagship in nano-satellite development. An important part of the Space Systems Engineering research activities is dedicated to the Delfi program, within which end-to-end engineering of miniaturized satellite platforms is conducted in close synergy with the education activities of the group.

Recent projects in which the chair has been involved include: Stardust-R, an extensive consortium of 22 European and international partners on the exploration and exploitation of asteroids to make the use of space sustainable; LUMIO, a Cubesat mission for micrometeoroid impact detection on the Lunar far side; FleRaSS, a project related to the design of a flexible radio science system for new generation spacecraft; QB50, an international network of 50 CubeSats for lower thermosphere measurements and re-entry research.

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 landing on the lunar surface. Furthermore, it will cover as much distance as possible from the lander to test its power system and durability of the system.

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

TEAM

The team consists of experts in robotic building,civil engineering, aerospace engineering, swarm robotics, and HRI from academia and industry.

The core TUD team consists of: Dr. Henriette Bier (Architecture: Robotic Building), Prof. Dr. Ken Gavin, (Civil Engineering: Subsurface Structures), Dr. Roland Schmehl (Aerospace: Wind Energy), Dr. Angelo Cervone (Aerospace: Space Systems Engineering), BSc cand. M. Verma (Aerospace: Swarm Robotics) and Dr. Luka Peternel (Mechanical Engineering: Human-Robot Collaboration). Supporting TUD teams consist of researchers and students from Architecture and Aerospace Engineering.

Partners are: Delft Robotics Institute (DRI), SAM|XL, 3D Robot Printing, and DSM

TUD

University of Technology (Dutch: Technische Universiteit) Delft also known as TUD, is the largest and oldest Dutch public technological university, located in Delft, Netherlands. As of 2019, it is ranked in the top 20 best universities for engineering and technology worldwide and is the highest ranked university in the Netherlands. Four faculties from TUD participate in this proposal:

Architecture and the Built Environment: Robotic Building (RB)

The Architecture and the built Environment Faculty (ABE) at TUD is ranked third in the world after MIT and Bartlett. The Robotic Building (RB) group has been established in 2014 with the first robotic lab at ABE. Its research and education focus on developing (a) physically built robotically augmented environments and (b) robotically supported building processes. Reconfigurable, robotic environments incorporating sensor- actuator mechanisms that enable buildings to interact with their users and surroundings in real-time require design to production, assembly, and operation chains that are (partially or completely) implemented by robotic means. In several funded projects the group has developed expertise in 3D printing with ceramic clay, thermo-plastic elastomers, and silicon as well as wire cutting, milling expanded polystyrene, plastic, and wood.

Dr. **Henriette Bier**, who acts as PI of this project, is leader of the Robotic Building group. She will be responsible for coordinating the project (WP1) as well as developing the D2RP&O approach (WP4 and 5) together with 1 researcher and ±15 MSc students. There are in total 2.7 FTE allocated.

Civil Engineering: Subsurface Structures

Subsurface Engineering focuses on every aspect concerning the use of underground space. This includes infrastructure for traffic as well as utility systems, underground storage, multiple use of land and space, safety, legal aspects, trenchless technologies for the construction of utility systems and various building techniques (for example boring techniques, immersed tubes and trenchless techniques).

Prof. Dr. **Kevin Gavin** is an active researcher in geotechnical engineering with more than twenty five years' experience in the field. He is the Professor Foundations and Underground Space in the Geotechnical Engineering section at TU Delft. He has led or participated in a number of Joint Industry Projects developing foundation systems for the offshore sector and has extensive experience in large-scale field testing and the design of complex structures. He has been the coordinator of a number of EU projects focused on the effects of climate on transport infrastructure. He has published widely (over 250 papers) in the areas of deep foundations, slope stability and reliability analysis. He is a member of the International Society of Soil Mechanics and Geotechnical Engineering technical committee on offshore geotechnics and pile foundations and past chairman of Geotechnical Society of Ireland. Together with a PostDoc and a MSc student he will contribute with a total effort of 1.2 FTE to the project.

Aerospace: Space Systems Engineering

Dr. **Angelo Cervone** is an expert in aerospace and space systems engineering at AE TUD, with specific expertise in the design of small satellite deep space science and exploration missions. He has managed more than 15 projects, mostly funded by ESA, on various R&D activities related to space systems and components. He is author or co-author of more than 40 book chapter contributions/papers on peer-reviewed international journals, and more than 100 papers in international conference proceedings. Dr. Cervone will contribute to the project with a total effort of 0.5 FTE.

Aerospace: Swarm rovers

BSc cand. **Maneesh Verma** is project manager and systems engineer at the Zebro group and will be responsible in this project for developing the technical design of the Zebro rovers swarm. He will be supervised by a senior researcher and Dr. A. Cervone and will contribute to the project with a total effort of 0.5 FTE.

Aerospace: Airborne wind energy

The Airborne Wind Energy Research Group is part of the Section of Wind Energy and a pioneer in the exploration of innovative wind energy solutions using tethered flying devices. From 2010 until 2015, the group operated a unique 20 kW kite power system at their test center on the former Naval airbase Valkenburg, demonstrating automatic operation first in 2012. Since 2016 the technology has been scaled up to 100 kW and commercially developed by spin-off company Kitepower BV. The research group has coordinated the EU F7 project NUMIWING, the EU H2020 doctoral training network AWESCO and the EU H2020 “Fast Track to Innovation” project REACH.

Dr. **Roland Schmehl** is the leader of the Kitepower research group. He will be responsible for developing the energy-system together with AE students and will contribute to the project with a total effort of 0.5 FTE.

Mechanical Engineering: HRI

The Cognitive Robotics Department at TUD contributes to responsibly introducing robotic technologies in human-inhabited environments. Research is organized in four sections: computer vision for intelligent vehicles, machine learning for learning and autonomous control, robot dynamics and human-robot interaction. In the section Human-Robot Interaction focus is on Cognitive Human-Robot Interaction and on Physical Human-Robot Interaction.

Dr. **Luka Peternel** developed several human-robot interaction methods relevant to the project. The physical human-robot collaboration method includes human models and smart sensory feedback systems that can detect human intention and other states, such as economics, which enable the robot to adapt in real time to facilitate efficient collaboration (Peternel 2017, 2018). Physical interaction control is solved by hybrid force/impedance controller that can simultaneously control interaction forces of the robot and motion through impedance. In addition, he developed a method for tele-impedance, which enables the human to change the impedance of the teleoperated robot to improve the task performance in unstructured and unpredictable environment (Peternel 2018). He will contribute to the project with a total effort of 1.2 FTE.

Partners

DRI Delft Robotics Institute unites all Delft University of Technology's research in the field of robotics. Its main challenge is to get robots and humans to work together effectively in unstructured environments, and real settings. It will contribute to the project in a consultancy role as part of the advisory board.

SAM|XL Smart Advanced Manufacturing XL is a collaborative research centre where technology is being developed, demonstrated, and de-risked for automated manufacture of large-size components. It will offer the setting for large scale subtractive prototyping of the habitat components.

3D Robot Printing is designing, developing and producing large-format plastic products and production systems. It will offer the setting for large scale additive prototyping of the habitat components.

DSM is a Dutch multinational active in the fields of health, nutrition and materials. Of particular interest for this project is the engineering plastics, which have better mechanical and/or thermal properties than the more widely used plastics.

TEAM RATIONAL

The team consists of experts in robotic building, aerospace engineering, swarm robotics, and HRI, who have developed technologies that are required for this project and have tested them on-Earth. The team is well connected with academic and industry partners, such as DRI, SAM|XL, 3D Robot Printing, and DSM, who will support the project in-kind.

PLANNING

The duration of the project is 12 months (excluding public holidays and two vacation periods). It includes at least three meetings/video conferences at the start, mid- and end-term, as well as 13 milestones. An overview is given by the Gantt chart shown in Fig 7.

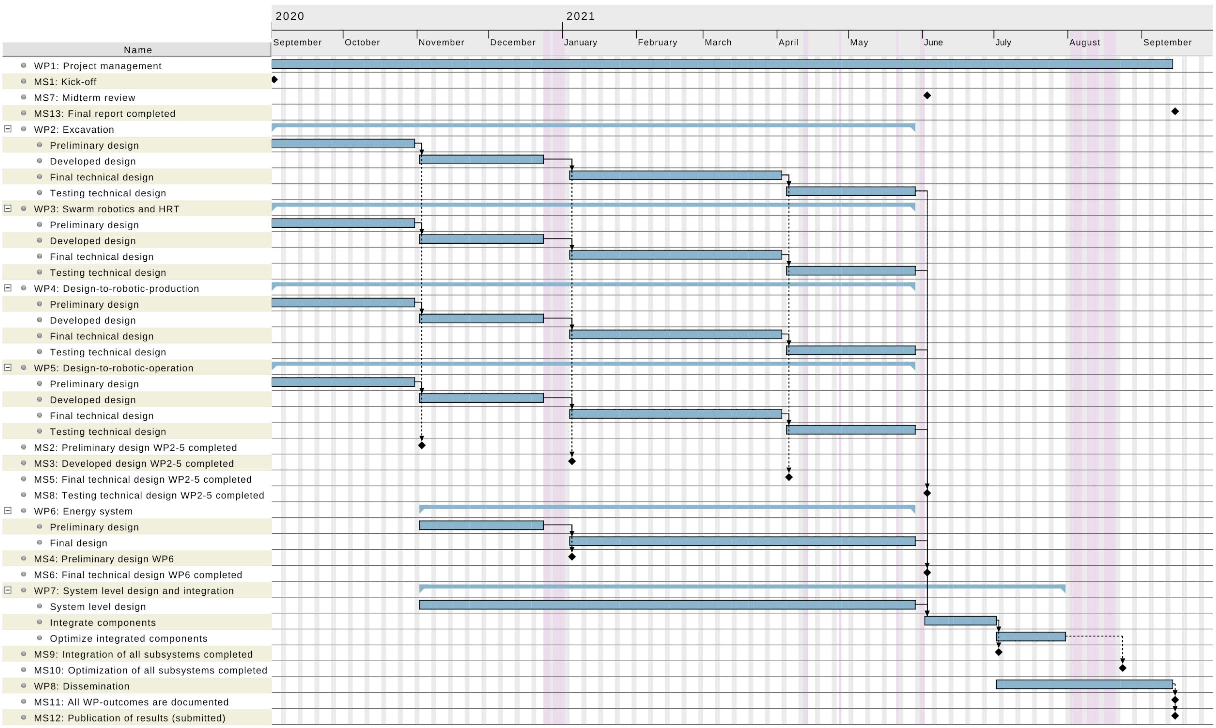

Figure 7: Gantt chart of the project.

TAGS

Underground habitat, excavation, robot swarm, D2RP&O, HRI, sustainable energy generation