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Chapter 2
Advancing Design-To-Robotic-Production and -Assembly of Underground Habitats on Mars

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Abstract In order for off-Earth top surface structures built from regolith to protect astronauts from radiation, they need to be several metres thick. In a feasibility study, funded by the European Space Agency, Technical University Delft (TUD aka TU Delft) explored the possibility of building in empty lava tubes to create rhizomatic subsurface habitats. With this approach natural protection from radiation is achieved as well as thermal insulation because the temperature is more stable underground. It involves a swarm of autonomous mobile robots that survey the areas and mine for materials such as regolith in order to create cement-based concrete reproducible on Mars through in-situ resource utilisation (ISRU). The concrete is 3D printed by means of additive Design-to-Robotic-Production (D2RP) methods developed at TUD for on-Earth applications with the 3D printing system of industrial partner, Vertico. The printed components are assembled using a Human–Robot Interaction (HRI) supported approach. The 3D printed and HRI-supported assembled structures are structurally optimised porous material systems with increased insulation properties. In order to regulate the indoor pressurised environment a Life Support System (LSS) is integrated, which in this study is only conceptually developed. The habitat and the D2RP production system are powered by an automated kite power system and solar panels developed at TUD. The long-term goal is to develop an autarkic, automated and HRI-supported D2RP system for building autarkic habitats from locally obtained materials.

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2.1 Introduction

Building habitats on Mars requires the acknowledgement of three interconnected aspects: First, an adapted-to-Mars conditions design methodology is needed; second, the understanding of the geology, the climate, the available materials and possible hazards, which play a major role in the construction process; and third, the understanding of the limits in terms of mass and volume for interplanetary space travel (Bier et al. 2021).

Based on the current and expected level of technology readiness level, Mars is a target for future long-term exploration and eventually for the establishment of settlements.[1] According to previous research, regolith, crushed rock and dust can be used as construction materials (inter al. Spiero and Dunand 1997; Happel 1993), and regolith-based constructions can protect astronauts from radiation (inter al. Akisheva et al. 2021). However, galactic cosmic rays would require a regolith layer of several metres thick in order to protect the astronauts sufficiently. Furthermore, thermal stresses that occur from large temperature changes during the day-night cycle on Mars and pressure stresses on the envelope from the pressurised indoor environment need to be taken into consideration.

As presented in the Spool issue on off-Earth construction (Bier et al. 2021) precedent case studies aim to counteract these challenges in various ways, as, for instance, (i) the Mars Ice House and the National Aeronautics and Space Administration (NASA) feasibility study, The ICE Home, uses ice as a main construction material as it is more effective against radiation than regolith-based constructions. Extra measures are taken to keep the ice from sublimating into the air, for which the use of inflatable plastics is proposed[2]; (ii) Foster and Partners autonomous habitation sintering study uses regolith as the main construction material and 3D printing by fusing the layers[3]; (iii) Apis Cor's X-House is a 3D printed habitat that uses Martian concrete reinforced with basalt fibbers and expandable polyethylene foam[4]; and (iv) 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 since the material has a high hydrogen concentration.[5]

All these examples are NASA 3D printed habitat challenge contestants and all of them are top surface design proposals. NASA stated that excavation and drilling into any off-Earth location would require large and heavy equipment making it infeasible. The Technical University Delft (TUD aka TU Delft) team sees an opportunity to investigate possibilities in particular by assessing how autonomous rovers

[1] Link to ISECG's Global Exploration Roadmap: https://www.globalspaceexploration.org/?p=1184.

[2] Link to NASA-Langley: https://www.nasa.gov/feature/langley/a-new-home-on-mars-nasa-langley-s-icy-concept-for-living-on-the-red-planet.

[3] Link to Foster: https://www.fosterandpartners.com/projects/lunar-habitation/.

[4] Link to Apis Cor: https://apis-cor.com/.

[5] Link to AISpaceFactory: https://www.aispacefactory.com/marsha.

Fig. 2.1 Underground Martian habitat constructed using rovers, HRI and, KP-supported D2RP&A

equipped with a Human–Robot-Interaction (HRI) supported additive Design-to-Robotic-Production and Assembly (D2RP&A) system can construct subsurface habitats while also considering the restraints of interplanetary space travel. The main idea was to develop a D2RP method, which takes natural resources such as regolith for building underground habitats that are less affected by thermal stresses because the temperature is more stable underground. Materials for D2RP are mined through in-situ resource utilisation (ISRU), and the design approach is restricted by the methods of production and the materials available. The use of locally obtained materials and the naturally obtained shelter represent the advantage over other design proposals.

The idea developed by the TUD team for the call for ideas on ‘Off-Earth Manufacturing and Construction’ issued in the frame of the European Space Agency’s Discovery programme involves autonomous mobile robots, i.e. rovers equipped with various end-effectors that will harvest materials and construct habitats using 3D printing with cement-based concrete (Fig. 2.1). This choice is based on the extensive experience in using this material for building on-Earth habitats as well as the available expertise and 3D printing technology of the industry partner, Vertico.

2.2 Autarchic Kite-Powered and HRI-Supported D2RP&A

The study involved the adaptation of several technologies developed at TUD and industrial partner Vertico for on-Earth application to off-Earth conditions such as (1) Design-to-Robotic-Production and Assembly (D2RP&A), (2) Human–Robot Interaction (HRI), (3) Swarm Rovers (SR) and (4) Kite Power (KP). The habitat location, preliminarily selected for this feasibility study, has been identified in the Tharsis bulge among various possible candidates (Fig. 2.2).

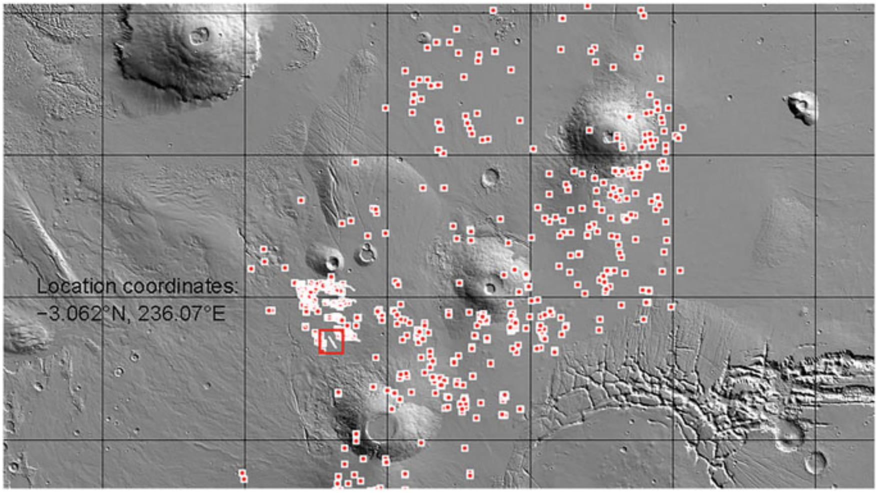

Fig. 2.2 Location of the habitat has been identified in Arsia North in the Tharsis bulge

2.3 D2RP&A

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) focuses on embedding robotic approaches into construction 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 (LSS) that requires D2RO methods, facilitating the integration of sensor-actuator networks into the built environment. These were, however, only marginally addressed in this project as the focus was on (a) HRI-supported D2RP&A, (b) energy generation, which is harvested from sun and wind and (c) system integration.

2.3.1 Subtractive D2RP

Excavation for ISRU is implemented with rovers adapted from Zebro rovers[6] developed at TUD for the Lunar environment. Expertise in subtractive D2RP developed by the Robotic Building (RB) lab, as well as expertise in underground structures

[6] Link to Zebro: https://tudelftroboticsinstitute.nl/robots/zebro.

developed at Civil Engineering and Geosciences (CEG), TUD have been employed mainly to identify suitable locations for building the habitat underground as, for instance, the Tharsis bulge (inter al. Sauro et al. 2020). Since the entrance to the lava tube has on average a 30 m drop down to the bottom of the tube, the use of a crane[7] as developed conceptually by the University of Oviedo in Spain (2019) has been proposed in order to bring material and equipment necessary to build access ramps and habitat.

2.3.2 *Additive D2RP*

Additive approaches explored in RB lab using clay, silicon and thermoplastic elastomers as well as prototyping implemented with concrete by Vertico represent the basis for the 3D printing approach with concrete developed in the project. The printed structure has a Voronoi-based material, component and building design (Fig. 2.3). It is a structurally optimised porous structure, which has increased insulation properties and requires less material and printing time for efficient D2RP.

The assumption that porous materials have improved insulation properties is based on experiments implemented with ceramic clay at TUD. The expected increased insulation of porous concrete has been assessed and justified in this project by implementing numerical simulations and experimental testing. Knowledge of available simulants developed at TUD has been applied to identify and formulate processing and design constraints with respect to manufacturing of porous insulating materials proposed in this project.[8]

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. Printed components were assembled with the support of HRI technology and the use of rovers. Not only the assembly, which was the focus of the project, but the complete construction of the habitat is to be 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. However, some robots share a base design by having the same mobile platform on which different types of payloads are attached (for example, a robotic arm fitted with a milling or 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,

[7] Link to ESA: https://www.esa.int/Enabling_Support/Preparing_for_the_Future/Discovery_and_Preparation/ESA_plans_mission_to_explore_lunar_caves.

[8] Link to project deliverable D5: https://docs.google.com/document/d/11wwFsh6__r2Z_zzBL1I80MNLxNW2SjL7kuDADm8vAYg/edit.

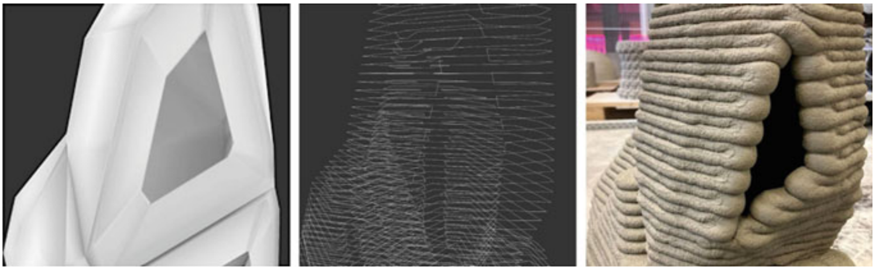

Fig. 2.3 Voronoi-based component design shown as the 3D model (left) from which robotic paths are generated (middle) to print a prototype (right)

executes tasks by using Swarm Intelligence (SI). The SI is a decentralised, self-organising algorithm that manages the division of labour between various types of robots at different times. The rovers' swarm design builds upon technology developed at Aerospace Engineering (AE) and is described in section number 3.

2.3.3 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 section number 2.

2.3.4 Design-To-Robotic-Operation (D2RO)

The 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, the envelope is coated with a sealing layer (Kim et al. 2000) to ensure pressurisation and thus counteract Mars's low atmospheric pressure, which

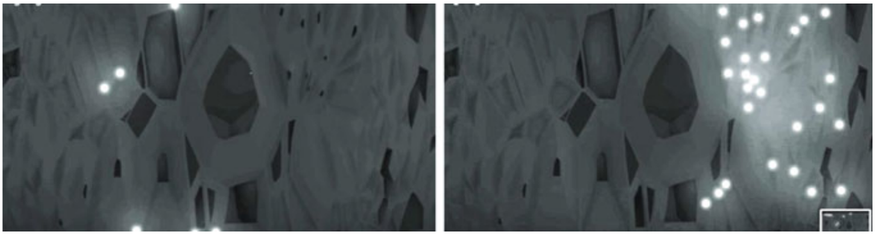

Fig. 2.4 D2RO involving AmI engaging with users in a functional and/or playful manner

is, however, outside of this project's scope. The scope has been narrowed down to Ambient Intelligence (AmI), which is extremely relevant for astronauts because of their confinement to a large degree to indoor environments. The use of AmI implies that these indoor environments are designed to be sensitive and responsive to people due to networked, context-aware and adaptive devices that are integrated into the environment. In this project, the focus was on interactive lighting (Fig. 2.4), which responds to peoples' movement by changing colour, intensity, and on–off rhythm.

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 fertilise crops. For instance, research of the Micro-Ecological Life Support System Alternative (MELiSSA), an ESA-led initiative,[9] which aims to understand the behaviour of artificial ecosystems to develop technology for a future regenerative life-support system, has been conceptually integrated into 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.

Preliminary studies implemented with students in 2020 (Fig. 2.4), involved inter al. the integration of piping and identification of challenges concerning implementation and maintenance. 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. 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 (SM). Furthermore, the construction of the habitat relied on Human–Robot Collaboration technology developed by Cognitive Robotics (CoR).

2.3.5 Material Testing

Relevant experience on processing of regolith simulant has been acquired by characterisation of initial regolith powders, optimization of the 3D printing process,

[9] Link to ESA: https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Melissa.

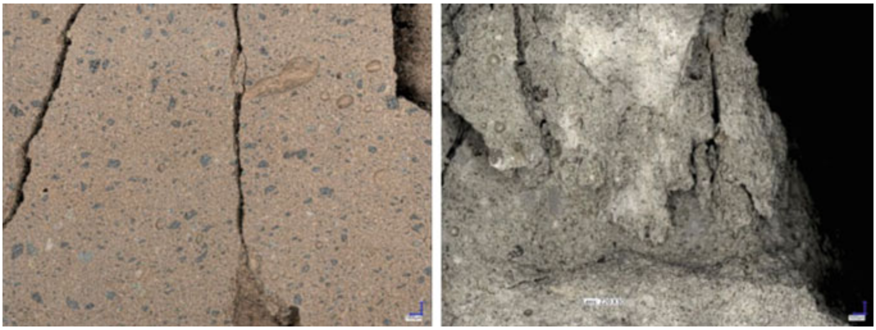

Fig. 2.5 Material testing showcasing 100% regolith sample (left) and 100% sand sample (right) after compression testing

relating processing parameters to materials microstructure and functional properties (mechanical and thermal isolation), and 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 in particular due to the porous material design.[10] Since critical properties are comparable to known terrestrial concrete, it can be concluded that 3D printed concrete based on Martian regolith provides a suitable and safe structural material (Fig. 2.5).

2.4 Human–Robot Interaction/Collaboration

One of the key challenges of space exploration is the limited availability of resources and agents to perform various tasks. While on-Earth specialised tools and robots efficiently perform specific tasks, in an off-Earth scenario 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 arms, 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 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

[10] Link to project deliverable D5: Ibid.

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 (Fig. 2.6a 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 (Fig. 2.6c and d). Third, the component's orientation must be aligned to fit the appropriate place in the structure (Fig. 2.6e). 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).

The physical interaction controller was based on previous work (Peternel et al. 2018) and several control modes were tailored for solving specific sub-tasks (Loopik and Peternel 2021). 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. 2.6c and d), the *lift and low mode* is used for lifting and lowering the 3D printed component (Fig. 2.6b and e), the *orientation mode* is used to orient the component before and after carrying (Fig. 2.6b and e), the *free mode* is used during the grasping where the human guides the robotic hand to the correct pose (Fig. 2.6a), 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 closing/opening the robotic hand.

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; Avaei et al. 2023).

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

(a) **(b)** **(c)** **(d)** **(e)**

Fig. 2.6 HRI-supported D2RA of components with (**a**–**e**) control modes the human, thus providing the robot with a significant degree of adaptability to new situations. 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)[11] with inconclusive results. Hence, further studies need to be implemented.

2.5 Renewable Energy, Space Systems and Rover Swarms Engineering

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

2.5.1 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 et al. 2016). Based on this resource assessment and the geoengineering studies, the site of the

[11] Link to deliverable D4: https://docs.google.com/presentation/d/1nEY7ndVd2UApp4HyE_Lh9pdGLXAwMJAO/view#slide=id.p12.

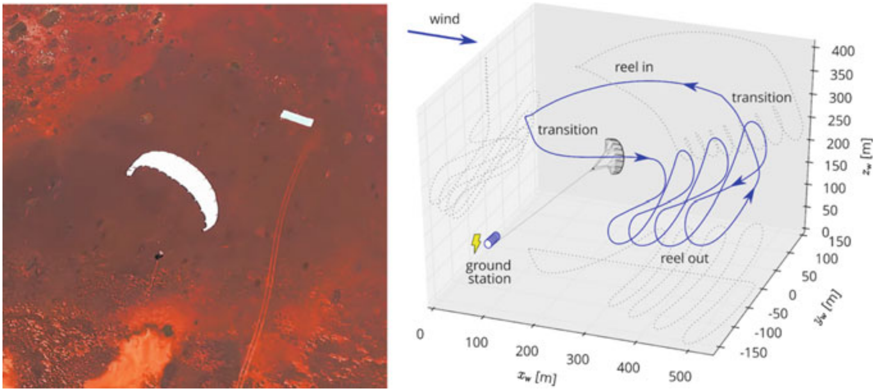

Fig. 2.7 Image of the KP system in operation on Aruba (left) and simulation (right)

habitat has been selected. As a next step, the automated kite power system developed at TUD (Fig. 2.7) 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 a 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 et al. 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 et al. 2019). The preliminary design of the energy system for the Mars habitat was developed within two consecutive Design Synthesis Exercise (DSE) projects at the Faculty of Aerospace Engineering. The final reports of both DSE projects have been published open access in the TUD public repository and the energy system analysis has been published as a peer-reviewed journal article (Ouroumova et al. 2021).

In the second step, the work of the DSE teams was combined in order to build a more accurate higher-fidelity energy system model. First, the implemented pumping kite model based on Luchsinger's theory (Luchsinger 2013) was revised to correct theoretical and modelling errors that were leading to an overestimation of the actual power output of the kite. Additionally, the theory was extended by accounting for an elevation angle of the tether. For this improved kite model, the wind resource information from the Mars Climate Database (Millour et al. 2018) was used. The wind resource was evaluated based on the habitat location at the Arsia North site and the operational height of 127 m. The Weibull probability function was evaluated for 16 equal periods of the year. The electrical power output for kite sizes ranging between 50 and 300 m given this resource availability was calculated as ranging between 2.5 and 17 kW.

2.5.2 Autonomous Multi-Functional Robots Swarm

For this project, a swarm of mobile robots, i.e. rovers, Zebros, developed for the Lunar environment and adapted for Mars have been chosen for implementing tasks such as excavating, transporting and processing materials. Since 2013, TUD has been actively working on small-scale rovers (Fig. 2.8). The rovers are specially 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 (2 to 5 kg) are an ideal sensor mobile platform and can be retrofitted with any instrument like radar, drills, or 3D printing systems to give them a specific use. The embedded swarm intelligence controls the overall behaviour of the swarm (>10 rovers) and it has a decentralised architecture meaning that any number of rovers can be added to the swarm.

The main tasks for the robot have 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 Swarm Intelligence (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 rhizomatic 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 SIs are developed to operate in fully autonomous mode. On Mars, there are certain tasks which are not advised to be in the 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

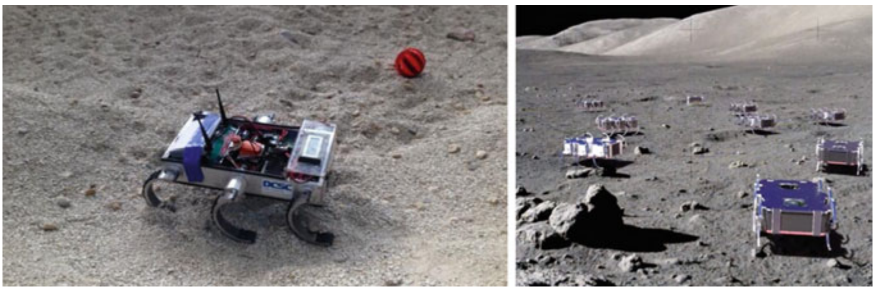

Fig. 2.8 Zebro robot (left) and swarm (right)

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:

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

Considering these three categories of operations, the Concept of Operations (CO) for swarm robotics has been based on scouting, cargo 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. These 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 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, 1 precision and 1 cargo rovers. This relatively small number of rovers will still be sufficient for all required operations on Mars, due 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 were set to 2250 km (radius) from the landing location.

In ABC simulations, rovers are represented as bees, and points of interest are the food sources (Fig. 2.9). 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, and 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.

The Neural Network (NN) training based on Differential Evolution (DE) 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

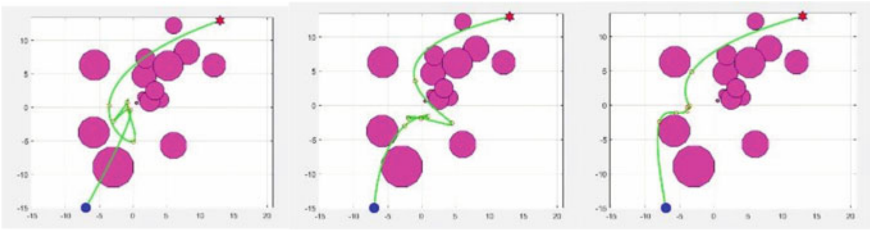

Fig. 2.9 Path of rover between point of origin and point of interest around obstacles using ABC algorithm

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 efficient. 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 the minimum energy and time required to reach all four assembly sites.

2.5.3 Space Systems

Systems engineering is not a trivial task for futuristic, highly visionary projects 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 envisaged 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 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 another DSE project running in parallel to the DSE project on Kite Power described in the previous section.

The main scope of this design effort was two-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:

(a) 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.
(b) It is possible to meet the requirements and needs of the 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 2041.
(c) Each cargo flight can bring to Mars surface a payload with mass of 45 tonnes and volume of 200 m^3, while each crewed flight can bring to Mars surface a payload with mass of 16 tonnes and volume of 50 m^3, plus 5 crew members.
(d) 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.
(e) 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 with building and maintaining the Rhizome habitat.

2.6 Conclusion

In this project analytical and experimental critical function and/ or characteristic proof of concept as well as component validation in laboratory environment have been successfully implemented. This technology can now be transferred to on-Earth applications involving (a) 3D printing of structures with various functionalities, (b) assembling with HRI support and (c) automating construction processes. The potential markets and customers are amongst others from the housing market and building industry which has been so far slow in adopting new technologies but is in *zugzwang* because of skilled labour shortage, more fatalities than in 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 construction are (i) development of alternative printing method using cement-less concrete to meet Sustainable Development Goals (SDG),[12] (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. In this context, the use of cement-less concrete is of particular relevance since production of 1 tonne of Portland cement is an energy intensive process that generates about 1 tonne of CO_2 which represents about 5–7% of the global green-house gas produced annually. With the use of cement-less concrete in the range of 20 to 50% replacement of Portland cement, the CO_2 emission from cement production is reduced by around the half (El-Dieb 2016). Furthermore, productivity growth to 1.4% annually[13] by using automated and HRI-supported construction, where a 1% increase in the robot density can lead to a 0.018% decrease in CO_2 emissions intensity (Lu et al. 2023).

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Abbreviations list

ABC	Artificial Bee Colony
D2RP&A	Design-to-Robotic-Production and -Assembly
D2RO	Design-to-Robotic-Operation
DE	Differential Evolution
DSE	Design Synthesis Exercise
ESA	European Space Agency
HRI	Human–Robot Interaction
IRL	Inverse Reinforcement Learning
ISRU	In Situ Resource Utilization
LSS	Life Support System
ML	Machine Learning
MELiSA	Micro-Ecological Life Support System Alternative
NASA	National Aeronautics and Space Administration
SI	Swarm Intelligence
TUD	Technical University Delft

[12] Link to SDG: https://sdgs.un.org/goals.

[13] Link to McKinsey report 2020: https://www.mckinsey.com/~/media/mckinsey/featured%20insights/digital%20disruption/harnessing%20automation%20for%20a%20future%20that%20works/a-future-that-works-executive-summary-mgi-january-2017.ashx.

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