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

Rhizome

Contribution to D11 (Documentation of all systems optimization)

Development of Swarm Robotics (WP6)

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1.0	15-05-2022	A.Cervone M. Verma	TU Delft	Initial version

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Acronyms and Abbreviations

ABC Artificial Bee Colony

DE Differential Evolution

ESA European Space Agency

TU Delft Delft University of Technology

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Summary

This deliverable summarizes the activities conducted in the framework of the Rhizome project for defining and simulating the operations of a swarm of working robots (rovers) serving the construction of the habitat.

As a starting point to perform this work, a preliminary Concept of Operations for the habitat construction activities has been defined, as described in ***Chapter 1*** of this document. The Concept of Operations for the swarm robotics, in particular, is based on three different types of rovers: Scouting Rovers, Precision Rovers and Cargo Rovers. Scouting Rovers will allow for thorough exploration of the environment, preparation for the construction phase, and will search for in-situ construction materials and life support resources. The scope of the Precision Rovers will be to provide support to the construction of all necessary infrastructures. They 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.

The requirements and constraints currently known for the habitat, robotic arm and all other related systems are described in ***Chapter 2*** of this document. These requirements and constraints have represented the starting point for the simulation work described in ***Chapter 3*** of this document. Swarm algorithms based on an Artificial Bee Colony (ABC) approach have been used for the Scouting Rovers and Cargo Rovers, while a Differential Evolution (DE) approach has been used for the Precision Rovers. In these simulations, the exploration area and maximum range for transportation is set to 2250 km (radius) from the landing location. ABC 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. DE simulations have shown that, when given the task to serve a given number of assembly sites, a Precision Rover is capable to optimize the best possible path, both in terms of minimum energy and shortest time.

1. Concept of Operations

Robotic systems are expected to play a critical role in all aspects of the mission to Mars, from validating the best location for the habitat to mining materials and building the habitat.

Robots will be the first major systems to land on the Martian with the 2028 flight, according to the current planning of flights (see Figure 1.1), which will bring to Mars multiple miniaturized Scouting Rovers. The swarm of Scouting Rovers will have two primary objectives:

a) scouting multiple potential habitat sites
b) map the surface and sub-surface for in situ materials and water in a wide area around the landing site.

A few years later (with the 2033 and 2038 flights), Precision Rovers and Cargo Rovers will be brought to Mars. Precision Rovers will provide support to the construction of all necessary habitat infrastructures. This will start with the power generation system, 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. The rovers functionality can be expanded to inspection of habitat and other crucial locations where telepresence is needed.

Replacements for these initial rovers will then be continuously sent to Mars with each following crewed flight. These new rovers likely will be improved versions from the previous ones, and will allow to increase the size of the swarm to not only continue mapping the nearby areas but also map in detail the chosen skylight and caves in preparation to eventual new construction activities.

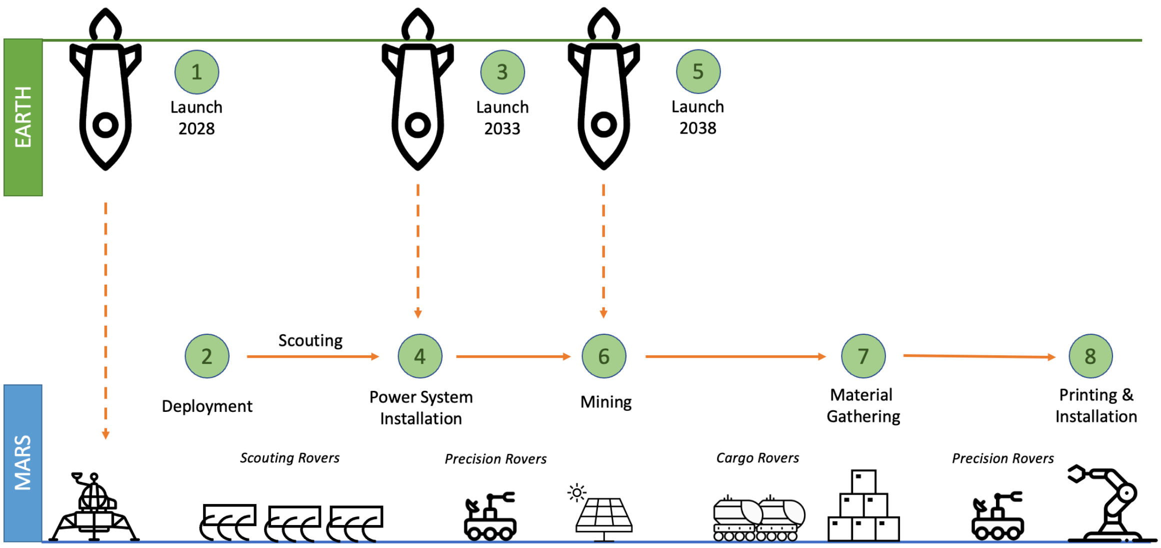

Figure 1.1 – Schematic Concept of Operations from the point of view of the swarm of rovers (first three cargo flights).

To have a deeper understanding of where and when different rovers be used once all the infrastructure is available on the Martian surface, the mission architecture shown in Figure 1.2 provides a clearer picture. The phases shown in the figure can be better explained as follows:

- 1a & 1b: The first step in building the habitat will be to transport raw materials from their mining site. These sites can be located on the surface or sub-surface. Sub-surface is the preferred location especially near to the printing and construction site. The entire operations of the rovers will be autonomous and deploy Differential Evolution Swarm Algorithm (see Section 3.2).
- 2: If the raw material arrives from the surface, it will be transported by the crane system located at the rip of the skylight. The crane is also used to lower other machineries and equipment like printer, precision rovers and power systems (if/when needed).
- 3: Once the raw material is made available and printer has been set up with the help of Precision Rovers and (when available) human crew, the printer will print habitat's outer and inner structural panels.
- 4: Printed panels are removed from the printing bed by Precision Rovers with help of an on-board robotic arm and placed on top of the rover for transportation between the printer and habitat location in the cave.
- 5: The panels are placed from base to top in a systematized way where the robots will bring the panel to the correct location and height, while (when available) human crew can make finer corrections before locking the panels into each other for the final time.
- 6: The power systems (kites, solar arrays, cargo lander vehicles) will provide power for all surface and sub-surface activities. The power systems may be present also in the cave which would make charging the sub-terrain rovers easier and practical. This would also reduce the cables needed to carry power to the habitat and printer.

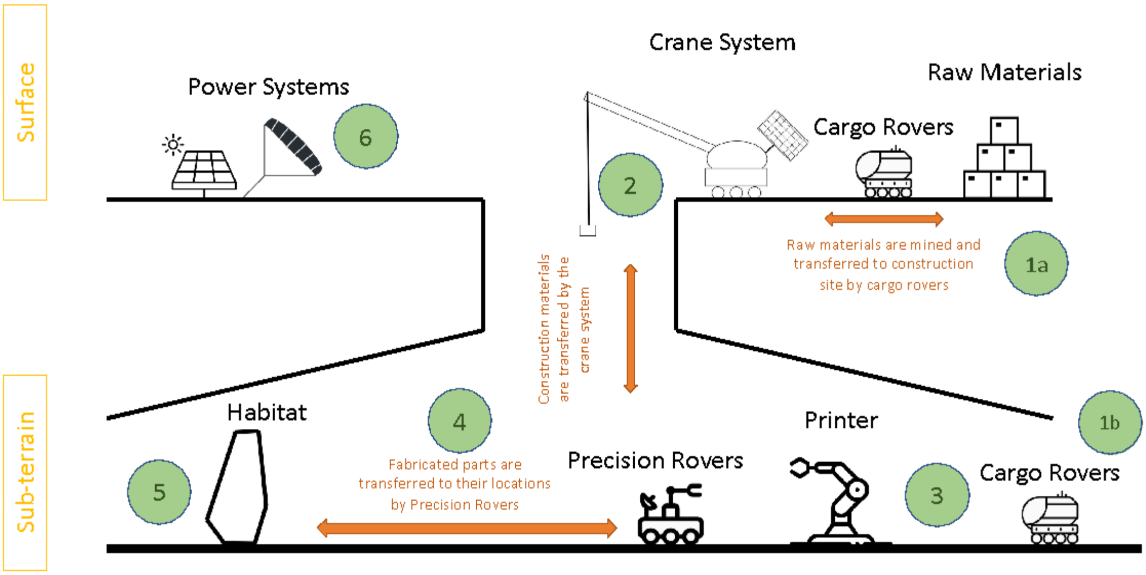

Figure 1.2 – Schematic surface architecture for the swarm of rovers during the habitat building phase.

2. Requirements and Constraints

This report is part of an early-stage study of habitat construction on Mars using in-situ materials with the help of robotic systems. The focus at this stage has been on studying the feasibility of developing and printing the panels for the habitat, which enabled the team to understand the needs and constraints for the operation of the swarm of robots. Hence, just a limited number of requirements and constraints are currently known for the habitat, robotic arm and all other related systems. These requirements are listed in the tables below, which have represented the starting point for the simulations on the swarms for robotics tasks, described in Chapter 3.

2.1 Habitat's Construction

Req. ID	Item	Value
HAB-01	Maximum surface area (floor) covered by the habitat	72.5 m^2
HAB-02	Minimum internal volume of habitat	310 m^3
HAB-03	Maximum external wall's thickness	40 cm
HAB-04	Maximum porosity of the external wall	0%
HAB-05	Maximum internal wall's thickness	40 cm
HAB-06	Maximum porosity of the internal wall	30%
HAB-07	Maximum surface area of structural surfaces	350 m^2
HAB-08	Maximum surface area of one building component	1 m^2
HAB-09	Minimum number of building components	~300
HAB-10	Maximum number of building components	~350
HAB-11	Maximum height to place the component	TBD
HAB-12	Maximum radius from point of lift inside the habitat	TBD
HAB-13	Max Depth	30 m

Table 2.1 – Requirements and constraints from habitat's construction.

2.2 Robotic Arm

Req. ID	**Item**	**Value**
ASB-01	Maximum reach of the arm	110 cm
ASB-02	Maximum mass of the arm	29.5 kg
ASB-03	Maximum mass of the gripper	3 kg
ASB-04	Maximum carrying capacity of the arm at full length	14 kg
ASB-05	Maximum radius of base	25 cm
ASB-06	Maximum mass of the power and processing system	23 kg
ASB-07	Minimum mass of harness	3 kg

Table 2.2 – Requirements and constraints from robotic arm.

3. Swarming

For an off-Earth mission, robots, are the obvious choice of labor as they are the only feasible solution available for the following two main challenges besides the harsh environment:

1) Large scale of multiple activities
2) Lack of real time teleoperations

This makes a strong case to use of swarm technology, as it brings self-organization and division of labor into the operations and maintenance of rovers. As already mentioned in Chapter 1, three main tasks will be performed by the rovers on Mars: exploration (Scouting Rovers), assembly (Precision Rovers), transportation (Cargo Rovers). Scouting and Cargo Rovers will make use of swarm algorithms based on an Artificial Bee Colony (ABC) approach, while a Differential Evolution (DE) genetic algorithm will be implemented by the Precision Rovers.

3.1 Design

As explained in Section 1, different types of rovers will be sent to Mars in the first three cargo flights: 50 Scouting Rovers (first flight), 6 Precision Rovers and 5 Cargo Rovers (second and third flight).

Another important design variable is the area of interest on Mars surface. While time to explore and travel this area would be of concern in many designs, for this preliminary study the time factor has been ignored due to the large amount of time available (in years) between two successive flights and necessary work rate required to accomplish tasks by rovers, as dependent factors are also not factored in (for example: charging time, loading and unloading time, rover's power systems, maintenance downtime, day-night cycles to avoid harsh temperatures and other weather related issues). The current area of exploration and maximum range for transportation is set to 2250 km (radius) from landing location, as it can be seen in Figure 3.1.

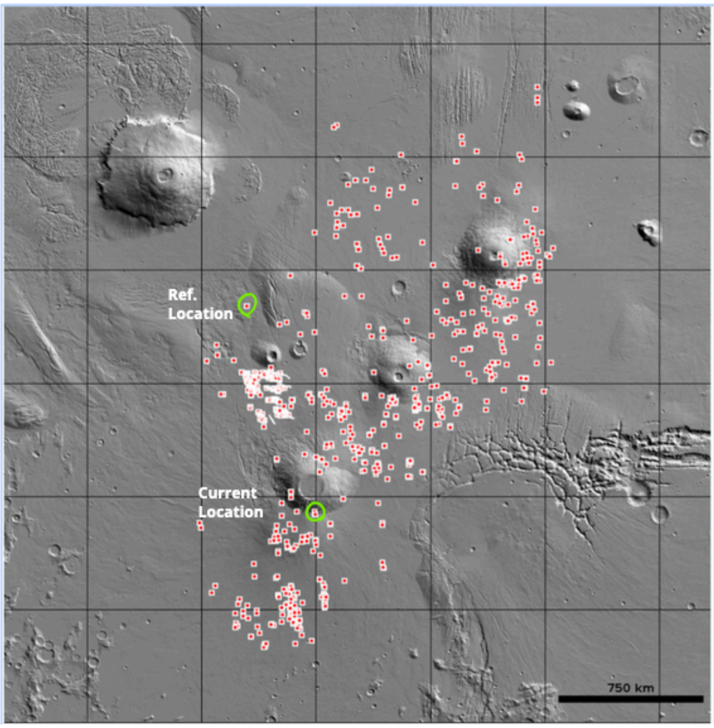

Figure 3.1 – Preliminary location of habitat's skylight (Reference location: Lon/Lat -126.07,6.76 N).

3.2 Simulation setting

The simulations have been written and run in MATLAB 2022a. The primary objective of conducting these simulations was to show the feasibility of deploying swarm algorithm when applied on a high-level system most likely based on swarm intelligence (centralized or de-centralized). As a large part of the requirements for rovers are still unknown, the simulations have been limited to the following aspects:

1. show the coverage pattern,
2. asses the feasibility of this coverage with respect to the number of rovers and origin points,
3. define the capabilities in terms of navigating distance over time.

To the contrary, a number of aspects are not assessed yet by these simulations and will need further work to fully understand the features of a swarming technology for the Rhizome Project:

1. optimum number of rovers,
2. best path for rovers to take for different tasks,
3. study the rover’s mission lifetime or related variables,
4. deployment and maintenance schedule.

The simulations are also based on the following additional assumptions:

1. The power systems provide all necessary infrastructure and locations to allow for charging the robots at any time when this is required
2. The lander vehicle lands sufficiently near to the chosen landing site
3. The rovers can operate with minimum or no human interface
4. Simulation have been conducted in 2D space
5. Rovers design and components allow them to survive the Martian environment

3.3 Analysis – Artificial Bee Colony (ABC)

ABC simulations are one of the best available algorithms which can be implemented for the exploration phase of a mission. In the algorithm, rovers are represented as bees and point of interests are the food sources. 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. Here the food source’s value can depend on the proximity, density, and ease of extraction of raw material, while “employed rover” is defined as the rover which is currently on route to the point of interest (PoI) or has positive feedback to share to neighbouring rovers. Unemployed rovers are then classified on the bases of that their PoI has resulted in negative feedback, and can be either recruited by other employed rovers to make their task more widespread, or tasked with new PoIs.

Thus, in summary, the primary application/tasks for these simulations have been to: spread out the swarm, randomly locate areas of interest, find the best path to these areas of interest.

In the simulation conducted by the team, the number of rovers is limited to one and number of PoIs is limited to the same number of rovers. To conclude if ABC is the right option for exploration, team opted to study the algorithm’s path planning capabilities for one rover for this preliminary study.

As it can be seen in Figure 3.2, the rover finds the best possible path over time around obstacles (pink dots) once the exploration phase is completed. At this point, the swarm will map its progress and then optimize the path between PoI (red star) and origin (blue dot, which can be landing site or printing site). This allows the rovers to share the best path between Scouting Rovers and Cargo Rovers.

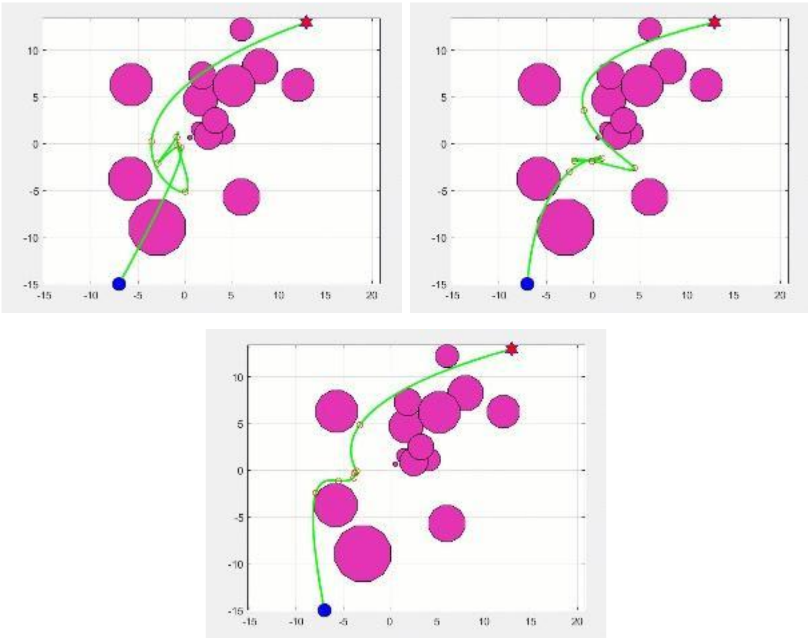

Figure 3.2 – Final path of rover between point of origin and point of interest around obstacles using ABC algorithm.

3.4 Analysis – Differential Evolution (DE)

Neural network training based on Differential Evolution has been focused on the movement of Precision Rovers between 3D panel printer and habitat, and their arm movement to place the panels in their correct location. This involves a large number of sensory inputs from cameras (placed on the arm) and localization sensors. Crew members can eventually provide positive reinforcement learning to ensure the swarm improves its performance over time and does not deviate or accumulate large errors, which would render the whole assembly operations very dangerous and might even result in mission failure given the scale of parallel running robots and their large size. If the algorithm is correctly implemented, little or no human contributions will actually be needed.

The idea behind this concept is that DE can be used to train the robots on Earth to cope with slightly different (updated) constructions, and then the robots on Mars will ‘’evolve’’ to make constructions faster and more efficiently. In its most basic form, the rovers will be able to correct their path to accommodate multiple destinations in one path. For this study, see Figure 3.3, the team assumes that the precision rover must travel to four different habitat sites (red dots) and circle back to the printer (origin). Initially, the path is quite rough (blue line), but over time and with positive reinforcement learning, the rover optimizes the best path possible (orange line) with minimum energy and time required to reach all four assembly sites.

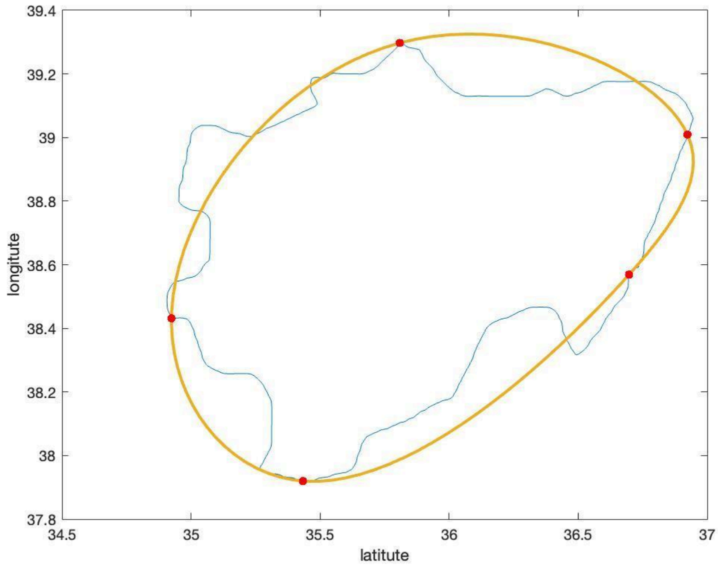

Figure 3.3 – Differential Evolution best fit path using cartographic simplification.

4. Conclusion

The Concept of Operations for the swarm robotics is based on three different types of rovers: Scouting Rovers, Precision Rovers and Cargo Rovers.

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

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

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