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

Rhizome

Contributions to D12 (Documentation of WP outcomes)

System Level Design and Integration (WP8)

Development of Swarm Robotics (WP6)

Partner(s): TU Delft – Aerospace Engineering Faculty

Author(s): Angelo Cervone – Maneesh Verma

Version 1.0

ESA Contract Number:	**133536**
Programme acronym:	OSIP Off-Earth Manufacturing and Construction Campaign-Study Scheme
Contract type:	OSIP
Start date of project:	01-04-2021
Duration:	12 months
Date of submission:	**15-05-2022**
Contact of responsible author:	A.Cervone@tudelft.nl

Disclaimer: This document reflects only the authors view. ESA is not responsible for any use that may be made of the information it contains.

Change Control

Version #	Date	Author	Organisation	Main change(s) made
1.0	15-05-2022	A.Cervone	TU Delft	Initial version

Change History

N/A

System Level Design and Integration (WP8)

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

To deal with these inherent uncertainties, the systems engineering approach chosen for this project has started with the definition and the preliminary design of an Interplanetary Transportation System serving the requirements and needs of the Rhizome habitat. The proposed design for the transportation system has been adapted from the results of a work conducted by a group of TU Delft students during the final project of their BSc study program, under the Academic supervision of Dr. A. Cervone. 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 summarized as follows:

- 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.
- It is possible to meet the requirements and needs of the Rhizome habitat by scheduling the first three flights as cargo missions (departure dates from Earth in 2028, 2033 and 2037), and a departure of the first crewed flight in October 2041. The habitat will be ready and fully operational by the arrival on Mars of this first crewed flight.
- Each cargo flight can bring to Mars surface a payload with mass of 45 tons and volume of 200 m^3, while each crewed flight can bring to Mars surface a payload with mass of 16 tons and volume of 50 m^3, plus 5 crew members.
- 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.
- The crewed flights will bring to Mars surface the food and other raw materials necessary to sustain the life of all crew members, plus spare/replacement items for the swarm of rovers, the robotic arms and the construction tools.

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

Development of Swarm Robotics (WP6)

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

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

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

The first cargo flight will bring to Mars a large number of Scouting Rovers (50 in total), to allow for a thorough exploration of the environment and preparation for the construction phase. Scouting Rovers will 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.