Human Assisted Robotic Vehicle Studies - A conceptual end-to-end mission architecture

Human Assisted Robotic Vehicle Studies - a conceptual end-to-end mission architecture

B. A. E. Lehner[a]*, D. G. Mazzotta[b], L. Teeney[c], F. Spina[d], A. Filosa[e], A. Canals Pou[f], J. Schlechten[g], S, Campbell[h], P. López Soriano[i]

[a] *Department of Bionanoscience, TU Delft, Van der Maasweg 9,2629 HZ Delft, Netherlands,* b.lehner@tudelft.nl
[b] *Department of Mechanical and Aerospace Engineering (DIMEAS), Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy,* daniele.mazzotta@polito.it
[c] *European Astronaut Centre (EAC),European Space Agency (ESA), Linder Hoehe, 51147 Cologne, Germany,* leo.teeney@gmail.com
[d] *European Astronaut Centre (EAC),European Space Agency (ESA), Linder Hoehe, 51147 Cologne, Germany,* aerospina@gmail.com
[e] *Argotec S.r.l., Via Cervino 52, 10155 Italy,* andrea.filosa@argotec.it
[f] *European Astronaut Centre (EAC),European Space Agency (ESA), Linder Hoehe, 51147 Cologne, Germany,* amcanalsp@gmail.com
[g] *Department of Computer Science, University of Geneva,7,route de Drize, CH-1227 Carouge ,Switzerland,* jonathan.schlechten@gmail.com
[h] *Tait Stage Technologies, London, United Kingdom,* shona.campbell7@gmail.com
[i] *Cologne Game Lab, Schanzenstraße 28, 51063 Cologne, Germany,* pablo@kednar.com
* Corresponding Author

Abstract

With current space exploration roadmaps indicating the Moon as a proving ground on the way to human exploration of Mars, it is clear that human-robotic partnerships will play a key role for successful future human space missions. This paper details a conceptual end-to-end architecture for an exploration mission in cis-lunar space with a focus on human-robot interactions, called Human Assisted Robotic Vehicle Studies (HARVeSt). HARVeSt will build on knowledge of plant growth in space gained from experiments on-board the ISS and test the first growth of plants on the Moon. A planned deep space habitat will be utilised as the base of operations for human-robotic elements of the mission. The mission will serve as a technology demonstrator not only for autonomous tele-operations in cis-lunar space but also for key enabling technologies for future human surface missions. The successful approach of the ISS will be built on in this mission with international cooperation. Mission assets such as a modular rover will allow for an extendable mission and to scout and prepare the area for the start of an international Moon Village.

Keywords: Telerobotics, Plant Growth Experiments, Lunar Mission, Moon Village

Acronyms/Abbreviations

Degree of Freedom (DoF)
Deep Space Habitat (DSH)
Deep Space Network (DSN)
Environmental Control and Life Support System (ECLSS)
Earth-Moon Lagrangian Point 2 (EM-L2)
European Space Agency (ESA)
Gas Chromatography (GC)
Ground Control Station (GCS)
Human Assisted Robotic Vehicle Studies (HARVeSt)
High-Performance Liquid Chromatography (HPLC)
Inertial Measurement Unit (IMU)
International Space Exploration Coordination Group (ISECG)
In-Situ Resource Utilisation (ISRU)
International Space Station (ISS)
Line Of Sight (LOS)
Low Earth Orbit (LEO)
Near-Rectilinear Orbit (NRO)
Net Carbon Exchange Rate (NCER)
Micro Electro-Mechanical (MEM)
Multi-Layer Insulation (MLI)
Pacific International Space Center for Exploration Systems (PISCES)
Radioisotope Thermoelectric Generator (RTG)
Thermal Control System (TCS)

1. Introduction

Since the end of the Apollo program, human space exploration has been confined to Low Earth Orbit (LEO). An ambitious vision has now been put forward by space agencies around the world to build on the knowledge and experience gained from the International Space Station programme and to venture to the Moon and Mars [1]. The International Space Exploration Coordination Group (ISECG) Global Exploration Roadmap lists human missions in the lunar vicinity with an evolvable Deep Space Habitat (DSH) to follow the International Space Station (ISS), with the ultimate destination of Mars [2].

One step on the way to realising an outpost on the Moon's surface is to first gain operational experience in cis-lunar space. With an emphasis on novel human-robot operations, HARVeSt:Moon (Human Assisted Robotic Vehicle Studies on the Moon) will test new technologies and make new scientific discoveries that will pave the way for the future human settlement of the Moon, and eventually Mars.

HARVeSt's main mission will consist of a rover and a plant growth chamber system that will be deployed to the south pole on the lunar far-side with the goal to investigate plant growth in partial gravity and under high radiation [3]. Developing our knowledge of plant growth is critical for future long-term missions to the lunar and Martian surface. Astronauts on-board a DSH in cis lunar space will control assets deployed to the lunar surface when required as a demonstration of deep-space tele-operation [4]. While it is assumed that this DSH will be located in a halo orbit around Earth-Moon Lagrangian Point 2 (EM-L2), as put forward in several existing mission architecture proposals [5] [6], the mission would also be possible with a DSH located in other orbits. One such option under consideration by NASA and its international partners is the Near-Rectilinear Orbit (NRO) [7]. A DSH located in NRO would offer suitable communications access to both the lunar south pole and Earth.

The mission is split into three stages, with different ascent and descent modules deployed to the lunar surface for each one of them.

HARVeSt will demonstrate a vital capability for future long duration space missions: the ability to grow crops for food. It is imperative to realise HARVeSt's goals if humans are to spend long periods away from Earth. Human civilization has grown around the ability to harvest crops, and in space it will be no different.

1.1 Assumptions

1. The mission will take place between 2025 and 2030.
2. A DSH in a halo orbit around EM-L2 will be operational at the time of the HARVeSt mission. This is compatible with the ISECG Global Exploration Roadmap.
3. The Orion capsule will be available for crew transportation.
4. Astronauts of some ISECG member states will form crews on the DSH and be assigned at times to perform HARVeSt tele-operations. The habitat may or may not be permanently occupied, however astronauts will be present at least during required times of HARVeSt tele-operations.
5. The mission will be a joint-operation between several ISECG members with different contributions.
6. The mission design is consistent with the current projected operations plan (Proving Ground) of NASA in cis-lunar space.
7. The mission will put a special emphasis on biological experiments and thus the use of an RTG is excluded. This decision will also decrease the cost and complexity of the mission.

1.2 Mission benefits

Developing our knowledge of plant growth under different circumstances is critical for future long duration missions on the Lunar and Martian surface. [4] An independent source of food, grown in-situ in a space habitat, will enable longer journeys with less need for expensive resupply missions. Moreover, the same mission can be used to build and test in-situ construction, such as the first landing pad on the Moon using in-situ resources, vital for a future Moon Village. The landing pad is not critical to the mission success and therefore it is a low-risk test of a necessary future technology. Additional technology demonstration is also possible, for example extraction of lunar volatiles, which will be important for future In-Situ Resource Utilisation (ISRU) technologies. This and other proposed ISRU activities are also in line with NASAs "Resource Prospector" plans. [8]. The HARVeSt mission could not only pave the way for further space exploration on the Moon and Mars, but also continue the proven International Space Station (ISS) model allowing partners to propose and perform experiments on the lunar surface using the HARVeSt rover and growth chamber as research platforms.

1.3 Technology assumptions

The HARVeSt mission will be the occasion to test the use of super capacitors as a dense, non-nuclear power source for the rover during short expeditions in permanently shadowed regions. The supercapacitors will be recharged frequently during operations by visiting nearly-permanently lighted areas of the pole. [9]. It is assumed that advances in this field would be sufficient to allow their use as power storage during lunar nights. The interchangeable end effectors used by the rover's robotic arm are currently available for Earth applications and could be adapted for space environments [10].

1.4 Mission objectives

1. To develop tele-operated robotic capabilities

and gain operations experience in cis-lunar space.
2. To demonstrate critical technologies required for future exploration missions (with a focus on plant growth).
3. To build on the ISS model as a platform for international cooperation and collaboration in space.

1.5 Similar Mission Architectures

The Jet Propulsion Laboratory (Caltech) [6] conducted research regarding a sample return mission from the lunar south pole using an Orion module at EM-L2 and a robotic sample return system. The mission design shows numerous similarities and could easily be extended with the HARVeSt mission. The vehicles (SLS, Orion) suggested for this mission are in line with NASA and international plans.

Another study from 2013 focuses on human-robotic interaction to retrieve samples from the Pole-Aitken basin [5]. This mission architecture also proposes use of the Orion vehicle as a temporary base while performing sample return from the Schroedinger crater. The observation of the currently unexplored area would allow new scientific discoveries while also demonstrating novel technologies.

The scientific focus of these missions is also the main difference to the HARVeSt mission architecture, which is majorly concerned about the preliminary steps for a Moon village including a focus on science operations.

In future telerobotic operations, astronauts would operate rovers on the Moon, Mars, and in deep-space from deep space locations. It is crucial to design the telerobotic system and operational protocols to work well with variable quality data communications, in terms of data rates, latency, availability, etc. [11].

In addition, the extended distance from Earth imposes the understanding of how efficiently and effectively a small crew of astronauts can work when placed in a more independent role.

2. Operations

The HARVeSt mission timeline, from the landing of the first vehicle on the lunar surface, is shown in Fig. 1, which details rover tasks and the operation phases as well as the corresponding stage of the plant growth for one specific model organism (*Lycopersicon esculentum*).

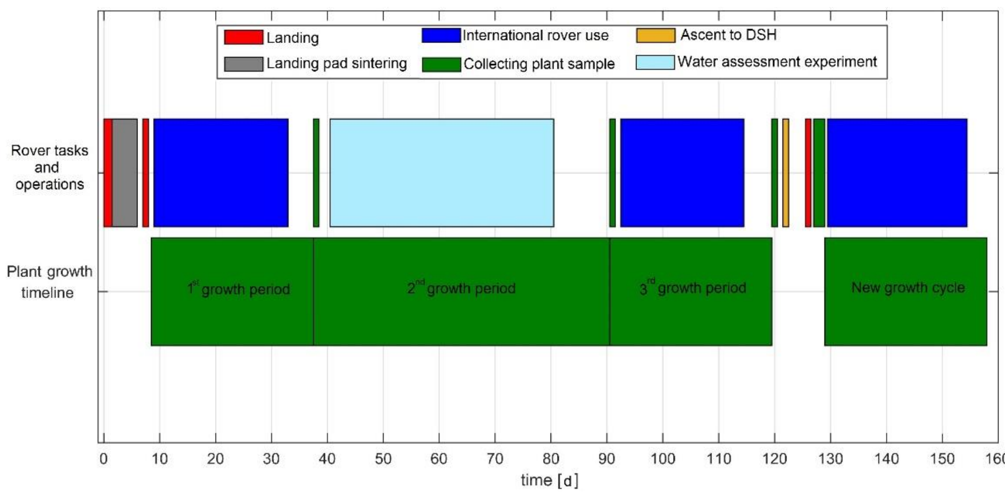

Fig. 1. HARVeSt mission timeline, with plant extraction (*Lycopersicon esculentum* as model organism) at different growth stage

2.1 Launch of mission assets

Two landers will be launched to the EM-L2 station using a Weak Stability Boundary (WSB) transfer. A WSB transfer is selected for the launches of non-crew vehicles in order to reduce the required delta-v, while manned expeditions will use faster direct transfers [12].

The launches of the non-crew vehicles are assumed to take place before scheduled periods, when astronauts will be present on the EM-L2 station. After the completion of the first plant growth cycle, the third lander will be launched from Earth, again on a WSB transfer. The mission is divided in three stages.

2.2 Stage 1

The HARVeSt mission operations begin when the first lander is approaching the surface. A landing area will have been precisely selected on the South Pole. The lander will autonomously choose the best landing site in the selected area. Astronauts in the DSH as well as the mission team at ground control will follow the mission, modifying the final landing area if necessary.

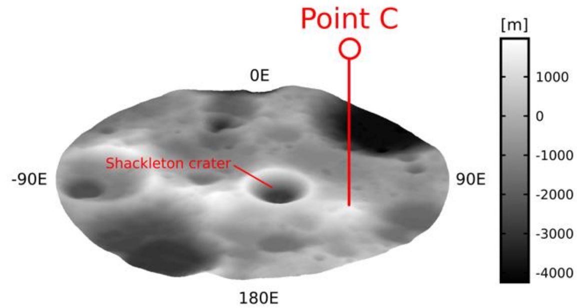

Fig. 2. Elevation map for the Lunar South Pole with the selected landing site

The selection of the best landing site is a key parameter for a successful mission. The site is selected according to the objectives of the mission, taking into account the conditions of operations at the location (the range of temperatures, the period of illumination, the topography, etc.). Since power production is based solely on solar panels, the local illumination is the most relevant factor for the selection of the landing site.

The selection was done using current maps of the lunar landscape. Errors on these maps may still be a potential problem of the mission design [13]. However over the last two decades, we have improved our knowledge and accuracy of the lunar topography thanks to a combination of laser altimetry and imagery collected from orbiting spacecrafts [14]:

- Clementine spacecraft (launched 1994)
- Japanese Selene Kaguya spacecraft (launched 2007)
- Chinese Chang'e-1 spacecraft (launched 2007)
- Indian Chandrayaan-1 spacecraft (launched 2008)
- LRO (Lunar Reconnaissance Orbiter)

These missions have allowed the creation of Digital Elevation Models for the lunar landscape with higher accuracy than ever before, which is critical for the analysis of potential landing sites and robotic traverses [14] [15]. For the HARVeSt mission the south pole region has been selected as the ideal region to carry out the operations.

Different sites have been considered on the south pole. After studying the pros and cons of the different locations, the most favourable area was shown to be the peak point illustrated in Fig. 2 (Point C) (88.79°S 124.5°E). Point C is located on a small ridge along the 120°E longitude line, in the proximity of the Shackleton Crater. From all the considered sites, this location provides not only the best annual mean illumination (86 %) but also the longest period of continuous illumination [16]. Concerning the communications, it is also a good vantage point for line of sight transmissions with an orbiting station in EM-L2 halo orbit [17].

Other regions near the south pole were also considered as potential landing sites. For instance, the Schroedinger basin presents some uncommon geological features since it is a relatively young crater with recent volcanic activity [18] [19]. Nevertheless, this site was not compatible with the main objectives of the mission. Despite the geologic interests, this area has significant drawbacks in term of operations when compared to the regions with nearly permanent illumination closer to the south pole.

Once landed, a modular rover is deployed on the lunar surface. Astronauts will tele-operate the rover to find the perfect location for a landing pad. Once the area has been selected, the astronaut will start an internal rover program, which would drive the rover over a set path. The rover would monitor progress using an inertial measurement unit to track the rover's movements. Any problems encountered during this task could be investigated by astronauts on-board the EM-L2 habitat.

The construction of landing pads will be mandatory in a future Moon Village to avoid ejecting dust that would otherwise damage equipment and surfaces [20].

A microwave sintering method has been chosen due to the favourable size and weight of the rover to carry the necessary equipment. A simple 2.45 GHz microwave provides enough energy to fully melt lunar regolith simulant in minutes [21].

2.3 Stage 2

Once the rover has finished the sintering process, the second lander containing the growth chamber then leaves the station and lands on the newly built landing pad. In the case of a non-sufficient landing pad construction another even spot close by will be used.

The plant growth chamber houses four containers containing 3 crops each. The astronauts monitor the chamber's internal environment via sensors and a camera. A tele-operated arm can be used for automatic and remote manipulation. The sensors measure the temperature, pH, light and humidity and automatically adjust the environment to maintain a suitable environment for the growing plants. At various points during the plant growth, astronauts will start and monitor a program to extract the samples into the airlock. The plant containers will then be sealed and frozen to maintain samples for transportation. Astronauts will use a partly tele-operated, partly autonomous approach for the HARVeSt rover to transfer the plant growth containers into an ascent unit. The rover would also cache lunar regolith samples in the ascent unit and it will then launch and dock with the DSH for analysis.

During the plant growth, the rover is used to conduct ISRU demonstrations (these may be dependent on the findings and results of NASA Resource Prospect mission [8]) on the surface. One of them would be the extraction of volatiles such as ice from permanently shadowed regions [22] in the vicinity of the landing zone. The survey mission for water evidence would be tele-operated and would take approximately 40 days. During this period, the rover may be exploited to pursue the following tasks:

- Reach a cold trap close to the landing site. The time needed has been estimated to ~9 days.
- Use the drilling tool of the rover to extract 10-20 cm [23] of core sample. Time required ~2 days.
- Bring the collected samples back to the ascent module. Time required ~9 days.

A depiction of the path for the water extraction mission is represented in Fig. 3 and Fig. 4. Alternatively, depending on the configuration, the rover could be provided with instruments to test regolith samples in-situ; in this case the first two tasks should be reconsidered. The path of the rover should be carefully planned in order to assure quasi-continuous illumination for the solar panels; during sample extraction, rover operations will be driven in total darkness. The amount of time that the rover will be able to spend in darkness will depend on the supercapacitor and battery capacities and operating temperature range; the same considerations also apply for the trip to/from the survey site. When selecting the survey site, the maximum range of the rover should also be taken into consideration. With an average speed of 0.5 m/min, similar to the 0.6m/min average speed of the Mars Exploration Rovers [24], and a round-trip of 40 days, the radius of the exploration area should not exceed 14.4 km. The time span is only that small if *Lycopersicon esculentum* is used and multiple extractions, at different stages of the plant growth, are carried out. Advancements in artificial intelligence will lead to higher speeds during autonomous navigation, but conservative values have been used for the design of this mission.

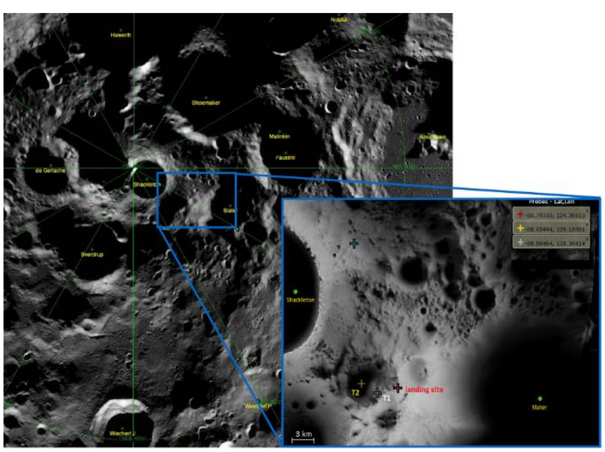

Fig. 3. Depiction of landing site and the testing area for the water assessment experiment

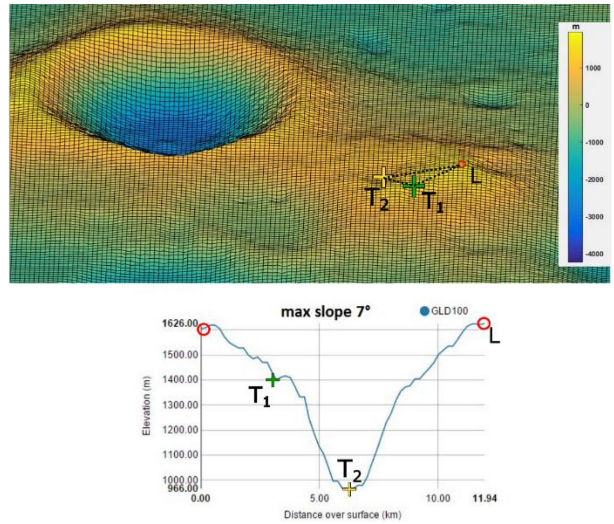

Fig. 4. Elevation profile of the rover path for the water assessment experiment

2.4 Stage 3

The third stage lander will be deployed carrying resupply materials including CO_2, H_2O, nutrients and new seeds in sealed sample containers. These resources will be used for new plant growth experiments with alternating conditions or different plant species. The crew will tele-operate the rover to transfer these supplies to the growth chamber system. Then the internal robotic arm will be used to place the plant growth container into position (via the airlock). The rest of the resources such as nutrient-water, CO_2 and liquid nitrogen can be replaced by the rover without opening the airlock. During the new plant growth cycle, different parameters are investigated while repeating the procedure of the second stage. Additionally, the third lander would have the capability of carrying a bank of additional tools for the rover, to extend its capabilities. When not used for the growth chamber operations, the rover will use these tools to achieve new mission goals. At the end of the new growth cycle the rover will take the frozen samples to the ascent module to return them to the EM-L2 station.

Further landers could be planned to extend the mission or to build up more assets in the area as the beginning of an international Moon Village.

3. Main Systems

3.1 The Rover

The HARVeSt mission rover is required to traverse the lunar terrain, carry out regolith sintering and retrieve samples. It shall have six wheels, each of which can be rotated on its own axis allowing on the spot turning with minimal friction. The speed of the rover will be 0.5 m/min. This speed will enable both tele-robotics and autonomous operations in a safe manner. It will also keep the amount of damaging dust lifted from the lunar surface to a minimum.. It can lock-up mechanical systems, damage seals and cause overheating. Therefore, precautions should be taken to limit dust exposure to increase the life of the rover. An illustration of the HARVeSt rover concept can be seen in Fig. 5.

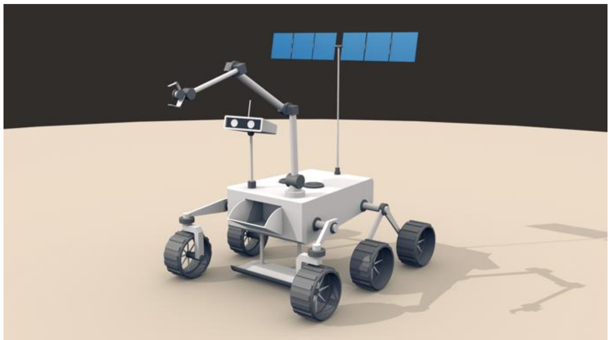

Fig. 5. HARVeSt:Moon rover visualisation

The rover should be equipped with a sintering panel measuring 8 cm x 8 cm. This device shall be deployed from underneath the body of the rover. The robotic arm of the rover will have 5 degrees of freedom and will be capable of lifting up to 25 kg. It will be equipped with interchangeable end effectors that can be quickly switched using a standard interface. Up to two additional end effectors will be carried on the rover when it will be deployed on the Moon surface. This includes a two-fingered gripper, a scoop for surface sample collecting, and possibly a drill for ice retrieval. The rover shall contain two optical cameras to allow 3D images to be sent to the EM-L2 station or ground station for remote driving. It will also contain micro-electro-mechanical gyroscopes and accelerometers for autonomous control.

To expand the use and life span of the rover on the surface, additional tools are planned to be provided to the rover. They will be sent through subsequent missions by any of the international partners in the mission as the need arises. Not only will this reduce initial cost, it allows the rover to take advantage of technological progress if standard interface connectors are maintained.

3.2 Thermal Analysis

Preliminary thermal simulations show that the temperature of the rover can be kept between 288 K and 318 K (Fig. 1). The analyses were performed considering, among others, the following assumptions:

- Lunar South Pole surface temperature ranges between 30 K and 280 K. [25]
- Equilibrium condition is used to calculate the rover temperature.
- Heat inputs: solar flux, albedo, heat conduction form solar panels, electronics, infrared radiation from the lunar surface.
- Average power consumption: 120-160W.
- Silver Teflon used as a thermal radiating surface to increase the emissivity of the rover.

From an electronics point of view, operational temperature for the scientific equipment is generally between 253 to 343 K; thus, the rover operations are feasible. On the other hand, current Li-ion batteries have much stricter operational temperature ranges, so the active time span may be limited when the lunar surface is not relatively hot (between 120 K to 270 K).
At the lower end of lunar temperature (30 K) no solar radiation is expected on the surface. Operations in these areas will be further restricted since they affect the survivability of the rover. Once the rover design is at a further stage, transient thermal analyses can show the maximum allowed time for scientific operations in the permanently shadowed craters.

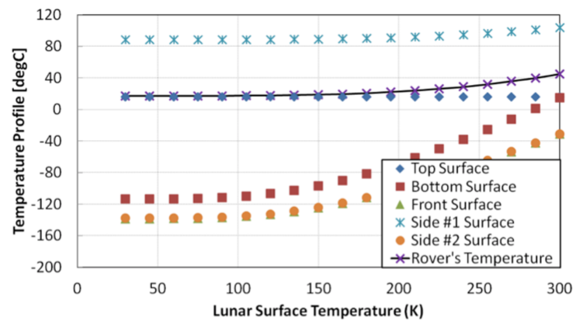

Fig. 6. Temperature profile of rover surfaces

3.3 The Plant Growth Chamber

The HARVeSt growth chamber will be a test-bed for artificial ecosystems. Valuable scientific data of plants growing under high radiation and partial gravity will be obtained. The growth chamber houses 12 crops in 4 special containers and cameras and sensors will monitor the growth cycle. One initial model organism could be *Lycopersicon esculentum* (tomato micro-species). Astronauts will be able to tele-operate the robotic arm to move samples when necessary. Tanks with CO_2, N_2 and H_2O with nutrients will supply the needs of the plants to grow under a controlled environment. One huge advantage of the design is that different microbiological or even zoological experiments could also be performed in the same containers with only minimal adaption necessary.

3.3.1 Growth Chamber Design

The crop internal arm will have seven degrees of freedom, three cylindrical joints and four revolute joints, as can be seen in Fig. 7.

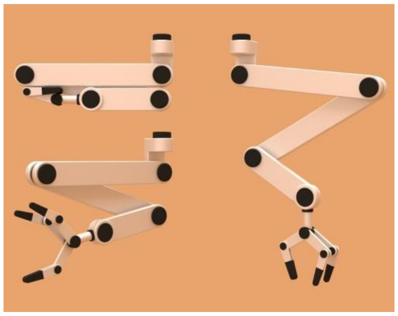

Fig. 7. Robotic arm for the growth chamber

The arm is located in the centre of the growing chamber (see Fig. 8), aligned with the airlock. With this configuration, the arm will be able to reach the plant containers and place them in the air lock without difficulty. It can also manoeuvre to the outside boxes on both sides with the correct approach angle to pick them up. In order to avoid unnecessarily complex manoeuvres, it is advised that the inside sample boxes are retrieved before the outer ones. There is enough space to lift one sample container over another if necessary.

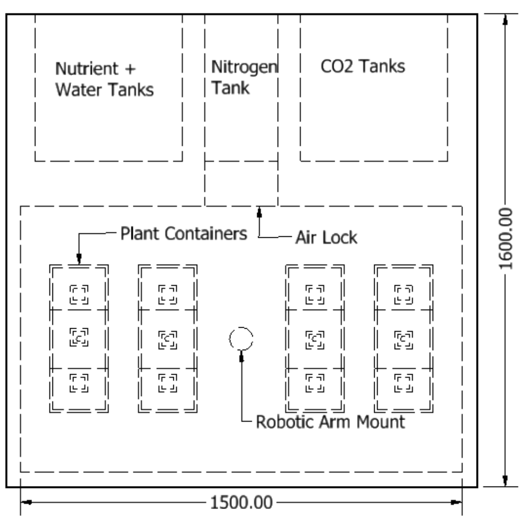

Fig. 8. Growth chamber: top view (units in mm)

The HARVeSt containers are sealed to the ground plate. This plate includes a water/nutrient delivery system, a connection to the liquid nitrogen tank and an electrical connection to seal the containers when they are removed. The first growing chamber already holds the ground-plate-connected HARVeSt containers and, due to lack of water, the seeds will not start growing before the water valve is opened.

The samples will be transferred to the ascent unit where a cooling plate will keep them frozen in order to preserve until analysis.

3.3.2 Resupply of the Chamber

The first resupply materials will come from Earth. These resupply materials include new H_2O/nutrients, CO_2, N_2 (liquid) and new seeds. In the current ISS Environmental Control and Life Support System (ECLSS), CO_2 is gathered by the system and released to outer space. The life support system of the EM-L2 station could instead store some CO_2 for later use in the growth chamber [26]. One possible way of doing this is using Lithium Hydroxide granulate, which has already been proven, to bind CO_2 from air [26]. Human waste that is not directly usable for the EM-L2 station can also be filtered by different kinds of bacteria (reuse: volatile fatty acids, minerals, nitrates, etc. see MELiSSA loop [28]). Additionally, there are small amounts of water on some permanently shadowed parts of the Moon [29] [30] [31], which, if collected, could be mixed up with filtered human waste to generate a new nutrition solution.

New seeds could be gathered from the first samples and replanted in the HARVeSt containers. Lunar regolith could be tested as a possible soil for the plants in a future experiment.

3.4 Plant Analysis

During plant growth, Net Carbon Exchange Rate (NCER) will be monitored in real time using an infrared CO_2 gas analyser. NCER is useful as general plant-production efficiency metric, and can also act as a plant stress indicator if NCER changes dramatically. Post-harvest plant quality will be evaluated based on fresh weight, dry matter production, root to shoot ratio, fruit to vegetative tissue ratio, number of fruits, and fruit quality. Fruit quality will be evaluated based on size, colour, texture, and flavour. Sugars and various secondary metabolites will be quantified using High-Performance Liquid Chromatography (HPLC) Gas Chromatography (GC) and Mass Spectrometry (MS), respectively. Data will be compared to that of control plants grown terrestrially, in otherwise identical growth conditions.

3.5 Communications Systems

Frequent communication windows between the lunar surface, the DSH and the ground station is essential. From the performed analysis it has been concluded that, as it can be seen in Fig. 9, the EM-L2 halo orbit would have near permanent communications with the Deep Space Network (DSN) in Madrid, Goldstone, and Canberra.

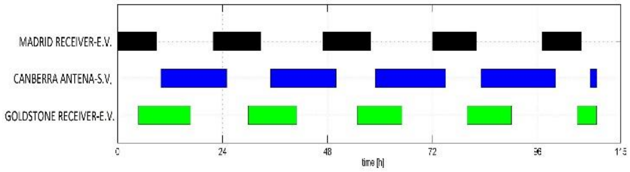

Fig. 9. Communications between EM-L2 halo and DSN, with Earth Visibility (E.V.) and Station Visibility (S.V.)

The main objective of the communication system is to support and maintain both the rover and the robotic arm of the growth chamber under control over the duration of all mission operations. Based on this, the main requirements of the rover communication hardware and EM-L2 station are presented in the following section.

3.6 Communication requirements

The HARVeSt rover should be able to receive commands from the DSH throughout the whole mission. A 99% of transmitted power must be contained within 10MHz Radio-Frequency bandwidth, while the bit error rate should be less than 10^{-6}.

The DSH should be able to receive and transmit data to and from the rover and Ground Control Stations (GCSs). The configuration of Earth stations (and/or satellites) should be such that the time delay is at its minimum. Moreover, the operation cost should be minimal and without any single point failures. Finally, the error correction codes should be decoded in real time.

3.6.1 Configuration

The communications architecture consists of several antennas to allow high-bandwidth communication between the rover and the EM-L2 station or Earth. Specifically, it consists of:

- A high gain antenna (X-band transmitter) on the rover to communicate with the DSH or, in case of failure, directly to a GCS [32].
- An omnidirectional antenna (X-band) on the rover to receive commands from the EM-L2 station. It can also transmit to Earth directly at low data rate if needed.
- The DSN using the X-band to ensure around the clock coverage.

Variability in bandwidth and data rates will occur during operations due to access windows from the DSH to the lunar south pole that will be considered in remote operations of the rover.

3.6.2 Failure Modes

To prevent the failure of communications, which could jeopardise the success of the mission, some redundancy has been designed in the communications system. The communication system has a robust fail-safe architecture. First, the phased array has inherent redundancy: failure of a few transmitters will not seriously degrade antenna performance. Second, if the phased array does completely fail, communication between EM-L2 station and Earth is still guaranteed via the inter-rover communications link. Third, the backup omnidirectional antennas provide a link to Earth, which is not subject to pointing problems, albeit at a greatly reduced data rate.

3.7 Tele-Robotic interface

HARVeSt will be an important test-bed for human-centric mechatronic haptic technology, thanks to the presence of the rover and the robotic arm of the growth chamber in the mission design.

The HARVeSt rover will be partially autonomous. It will be able to navigate autonomously alongside a pre-defined path or towards a target, and perform repetitive operations by itself, such as sintering the landing pad. Should a safety concern arise, it will be possible to override the navigation system and send specific real-time navigation commands from the EM-L2 station (Similar to Canadarm-2).

There will be two ways in which the rover will navigate on the Moon's surface: the astronauts will transmit a series of specific commands that will be performed by the rover, or the astronauts will give the rover a target and it will autonomously find its own way. To decide which method should be used, the rover will send its current position to the station, alongside with surface topology, any obstacles and other useful data. The astronauts will then plot a move that will be executed by the rover or, if no major hazards are identified, they will just define an end point and trust the autonomous navigation of the rover. In order to safely navigate, the rover will be equipped with hazard avoidance cameras to build a stereoscopic map of the environment, identify which objects are too large to drive over, and then plot out a path to the end point. Simultaneous Location and Mapping techniques will be used to navigate and produce detailed maps of the lunar surface, paving the way for a later Moon Village. High performance joysticks with active joint impedance control will be used to drive the rover through the Moon surface when required. The rover's arm and the growth chamber internal arm could also be tele-operated by astronauts wearing a fully-actuated haptic exoskeleton for force reaction to the arm of the astronaut operating it. The haptic exoskeleton will feature joints equipped with joint position sensors, high resolution torque sensors, motor-gear units and input/output position sensors.

All joints of the exoskeleton will feature a high dynamic range and will allow for crisp force feedback.

3.8 Weight Estimations

Rover weight: 200 kg; with the assumption that the rover is capable of all tasks with a weight between SPIRIT [33] and SCARAB [34].

Growth chamber weight: 3,6 m^3 (inner volume) * 1400 kg/m^3 = 5.400 kg; with the assumption that the mass density of the growth chamber is ½ of the lunar lander of the Apollo 14 mission.

Ascent vehicle weight: 4800 kg * ½ = 2400 kg; with the assumptions that the ascent unit has a volume of 1.5 m^3 and a complexity which is lower than the LUNA 24 mission module [35] due to the reduced orbital maneuver to EM-L2 (reducing factor ½).

4. Conclusion and Future Perspectives

The HARVeSt mission scenario presents a great opportunity to develop and prove tele-operations concepts in cis-lunar space. Different types of human-robot interactions will be fundamental to future exploration missions.

Achieving the goal of growing plants on the Moon is a vital step and will prepare the space agencies for future long-term and Earth-independent space exploration. The scientific data gathered from this mission will develop our knowledge on the effects of high radiation and low gravity on plant growth. The mission has the ability to explore different species of plants and to use ISRU for resupply. The design of the growth chamber makes it reusable and the consumables within the system can be easily replaced.

In addition to operational experience and scientific output, the HARVeSt mission also demonstrates new technologies required to build a lunar outpost. This is achieved through the sintering of a landing platform and extraction of volatiles from in-situ resources.

The use of both tele-operated and autonomous robotic systems demonstrates the benefits of using human and robots in conjunction. Tele-operating the rover and the robotic arm from the EM-L2 station brings the benefits of quasi-real-time operation without the need of human intervention on the lunar surface. The time lag for tele-operations between Earth and the lunar surface is relatively small, but it is necessary to test its infrastructure close to home before moving on to Mars.

The autonomous abilities of the rover allow simple yet time consuming tasks to be completed, without requiring the valuable time of the astronauts. The creation of the landing pad is a small-scale achievable example of autonomous operations that can be extended to the building of bigger structures. This would allow the beginning of a future Moon Village that could be used as remote test-bed for operations and technologies farther from Earth.

The use of the rover as an international, modular research base with standardised equipment is another technology that is validated through the course of this mission. If successful, it paves the way for similar designs for use further away from Earth, for example on Martian or asteroid missions.

The HARVeSt mission can demonstrate the capabilities of modern technologies to build infrastructure and to grow plants for the first time on another celestial body. It will inspire a new generation of engineers and scientists by returning to the Moon with the ultimate goal to establish a permanent settlement.

References

[1] J. Woerner, "www.esa.int," ESA, 23 March 2016. [Online]. Available: http://blogs.esa.int/janwoerner/2016/04/26/presentation-on-moon-village/.

[2] "The International Space Exploration Coordination Group," [Online]. Available: The International Space Exploration Coordination Group. [Accessed 20 07 2016].

[3] K. Sax, "The Effect of Ionizing Radiation on Plant Growth," *American Journal of Botany,* vol. 42, pp. 360-364, 1955.

[4] J. Kiss, "Plant bioin reduced gravity on the Moon and Mars," *plant biology,* vol. 16, pp. 12-17, 2013.

[5] J. O. Burns, D. Kring, J. B. Hopkins, S. Norris, T. Lazio and J. Kasper, "A lunar L2-Farside exploration and space mission concept with the Orion Multi-Purpose Crew Vehicle and a teleoperated lander/rover," *Adv. Space Res.,* vol. 52, p. 306, 2013.

[6] L. Alkalai, B. Solish, J. Elliott, T. McElrath, J. Mueller and J. Parker, "Orion/MoonRise: A Proposed Human& Robotic Sample Return Mission from the Lunar South Pole-Aitken Basin," in *Aerospace Conference IEEE*, Big Sky, MT, USA, 2013.

[7] R. Whitley and R. Martinez, "Options for Staging Orbits in Cislunar Space," in *IEEE Aerospace Conference*, Big Sky, 2016.

[8] E. Mahoney, "nasa.gov," NASA, [Online]. Available: https://www.nasa.gov/resource-prospector. [Accessed July 2017].

[9] NASA, "TA3: Space Power and Energy Storage," NASA Technology Roadmaps, 2015.

[10] "Re2robotics," [Online]. Available: http://www.resquared.com/products/tool-changing/. [Accessed 20 10 2015].

[11] T. Fong, M. Bualat, J. Burns, J. Hopkins and W. Pratt, "Testing Astronaut-Controlled Telerobotic Operation of Rovers from the International Space Station as a Precursor to Lunar Missions," in *65th*

International Astronautical Congress, Toronto, 2014.

[12] Edward A. Belbruno, John P. Carrico, "Calculation of weak stability boundary ballistic lunar transfer trajectories," *American Institute of Aeronautics & Astronautics,* 2000.

[13] T. W. Murphy, E. G. Adelberger, J. B. R. Battat, C. D. Hoyle, N. H. Johnson, R. J. McMillan, E. L. Michelsen, C. W. Stubbs and H. E. Swanson, "Laser Ranging to the Lost Lunokhod~1 Reflector," *Icarus,* vol. 211, pp. 1103-1108, 2011.

[14] M. Barker, E. Mazarico, G. Neumann, M. Zuber, J. Haruyama and D. Smith, "A new lunar digital elevation model from the Lunar Orbiter Laser Altimeter and SELENE Terrain Camera," *Icarus,* vol. 273, pp. 346-355, 2016.

[15] A. W. Johnson, J. A. Hoffman, D. J. Newman, E. M. M. Zuber and M. T., "An Integrated Traverse Planner and Analysis Tool for," American Institute of Aeronautics and Astronautics, 2010.

[16] D. B. Bussey, J. A. McGovern, D. P. Spudis, C. D. Neish, H. Noda, Y. Ishihara and S. A. Sorensen, Illumination conditions of the south pole of the moon derived using kaguya topography, Icarus, 2010.

[17] "Space Station Selene," 2015.

[18] E. Zubritsky, "phys.org," 30 August 2010. [Online]. Available: https://phys.org/news/2010-08-moon-camo.html. [Accessed 8 August 2017].

[19] N. Potts, A. Gullikson, N. Curran, J. Dhaliwal, M. Leader, R. Rege, K. Klaus and D. Kring, "Robotic traverse and sample return strategies for a lunar farside mission to the Schrodinger basin," *Advances in Space Research,* vol. 55, pp. 1241-1254, 2015.

[20] R. P. Mueller, R. M. Kelso, R. Romo and C. Andersen, "Planetary Basalt Construction Field Project of a Lunar Launch/Landing Pad," in *47th Lunar and Planetary Science Conference*, 2016.

[21] L. A. Taylor and T. T. Meek, "Microwave sintering of lunar soil: properties, theory, and practice.," *Journal of Aerospace Engineering,* 2005.

[22] M. T. Zuber, J. W. Head, D. E. Smith, G. A. Neumann, E. Mazarico, M. H. Torrence, O. Aharonson, A. R. Tye, C. I. Fassett, M. A. Rosenburg and H. J. Melosh, "Constraints on the volatile distribution within Shackleton crater at the lunar south pole," *NATURE,* vol. 486, pp. 378-381, 2012.

[23] P. Rincon, "Ice deposits found at moon's pole.," 2010. [Online]. Available: http://news.bbc.co.uk/2/hi/science/nature/8544635.stm.

[24] "mars.nasa.gov," NASA, [Online]. Available: https://mars.nasa.gov/mer/mission/spacecraft_rover_wheels.html. [Accessed 2017].

[25] J. L. Linsky, "Models of the Lunar Surface Including Temperature-Dependent Thermal Properties," *ICARUS,* vol. 5, pp. 606-634, 1966.

[26] "International Space Station, Environmental Control and Life Support System," [Online]. Available: http://www.nasa-usa.de/sites/default/files/104840main_eclss.pdf. [Accessed 20 10 2015].

[27] M. Ewert and D.J.Barta, "Exploration Life Support Technology Development for Lunar Missions," [Online]. Available: http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20090019710.pdf. [Accessed 20 10 2015].

[28] "THe MELiSSA Foundation," [Online]. Available: http://melissafoundation.org/. [Accessed 20 10 2015].

[29] J. Dino, "LCROSS impact data indicates water on Moon," [Online]. Available: http://www.nasa.gov/mission_pages/LCROSS/main/prelim_water_results.. [Accessed 20 10 2015].

[30] E. Lakdawalla, "Water on the Moon: direct evidence from Chandrayaan-1' s Moon impact probe.," 2010. [Online]. Available: http://www.planetary.org/blogs/emily-lakdawalla/2010/2430.html. [Accessed 20 10 2015].

[31] S. M. Ahmed, T. P. Das, P. Sreelatha, P. Pradeepkumar, N. N. Sridharan, R. Supriya and G. Supriya, "Direct evidence of water (H2O) in the sunlit lunar ambience from chace on mip of Chandrayaan-1.," *Planetary and Space Science, vol. 58,* 2010.

[32] B. I. Edelson and J. N. Pelton, Satellite communications systems and technology., Maryland, 1993.

[33] NASA, "http://mars.nasa.gov/mer/newsroom/pressreleases/20070807a.html," 07 August 2007. [Online]. [Accessed 2016].

[34] P. W. Bartlett, D. Wettergreen and W. Whittaker, "Design of the Scarab rover for mobility and drilling in the lunar cold traps," in *International Symposium on Artificial Intelligence, Robotics and Automation in Space*, 2008.

[35] NASA, "http://nssdc.gsfc.nasa.gov/nmc/masterCatalog.do?sc=1976-081A," NASA, 1976. [Online]. [Accessed 2016].