Acta Astronautica 140 (2017) 380–387

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

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

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ARTICLE INFO

Keywords:
Telerobotics
Plant growth experiments
Lunar mission
Moon village

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.

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 farside 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

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

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http://dx.doi.org/10.1016/j.actaastro.2017.08.032
Received 3 January 2017; Received in revised form 12 August 2017; Accepted 29 August 2017
Available online 1 September 2017

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*).

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.

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