IAC-17-F1.2.3

Project Moonwalk: lessons learnt from testing human robot collaboration scenarios in a lunar and Martian simulation

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Abstract

There is a global interest to send humans to the moon and to Mars and diverse early preparations are underway. One important aspect in preparing for future challenges is to develop technologies and tools that can help in simulation activities to train for future missions. Humans will be supported by robots on their missions in exploring and conducting science on extra-terrestrial surfaces.

The paper summarizes all the efforts undertaken by six European partners as part of a research and technology project in the European Union's Space Framework Programme. Under the lead of the DFKI (German Centre for Artificial Intelligence), industry partners Comex - France, Airbus Group UK, Space Applications Services - Belgium, LIQUIFER Systems Group - Austria and the research institutions NTNU – Norway (Samfunnsforsking, Centre for Interdisciplinary Research in Space) and INTA (Centro de Astrobiologia) – Spain collaborated to develop simulation hardware (space simulation suit, assistant rover) and tools (communications system, sampling) for human robot interaction.

The general objective of MOONWALK was to enhance European capabilities for future human space exploration, especially surface Extra-Vehicular Activity (EVA) for the moon and Mars. This was targeted through research, development and evaluation of operations concepts and technologies for exploration and exobiology-related EVA tasks, focusing on human-robot collaboration and the development of earth-analogue simulation equipment.

During a two-week simulation campaign conducting Martian scenarios, in Rio Tinto, Spain, a simulation astronaut and assistant rover collaborated as partners in mapping, surveying and sampling activities. Rio Tinto is an internationally recognized Martian analogue, having extremophile life similar to that on Mars, due to the pronounced mineral content of the region and the bacterial that feeds upon it. SHEE, the first European self-deployable simulation habitat, served as local mission control, and as ingress/egress for the suited astronaut. Lunar simulations were conducted in a depth of 10-metres, off the coast of Marseilles in open sea, and added to both which additional to the logistic challenge added a psychological challenge. Mission control for both analogues, was located near Brussels.

The paper will describe the set-up, components, the analysis and validation of the performed analogue missions with respect to technical and human factors. A dataset comprising of 120 variables, 75 responses and 14 respondents was analysed. Additionally, an open question survey was collected, 52 lessons learned, including many comments about components. Data was gathered from 28 different EVAs, comparing an astronaut-astronaut team versus the astronaut-robot team in terms of performance and psychological impact.

Keywords: simulations, moon, Mars, human, robotic, collaboration

Acronyms/Abbreviations

ART	Astronaut Rescue Tool
ATC	Astronaut Tether Control
DFKI	German Centre for Artificial Intelligence
EU	European Union
EVA	Extra-Vehicular-Activity
EVAIS	EVA Information System
FPC	Foldable Pick-up Claw
FP	Framework Programme
HI-SEAS	Hawai'i Space Exploration Analog and Simulation
HMI	Human-Machine Interface
INTA	Centro de Astrobiologia
LSG	LIQUIFER Systems Group
ODF	Operations Data File
MCC	Mission Control Centre
NTNU	Centre for Interdisciplinary Research in Space (Norway)
PST	Pantograph Sampling Tool
SCA	Suit Computer Assembly
SHEE	Self-Deployable Habitat for Extreme Environments
SOLID	Sign of Life Detector
SYSOPS/GC	System Operations/Ground Controller

1. INTRODUCTION

In the future, there is a good chance that teams of astronauts and robots will work together in-orbit or on planetary surfaces. On Earth, hybrid worker-robot teams are already a core component of the current digital revolution in industry. Human-robot cooperation is thus a topic with a very high relevance both for space research and terrestrial applications.

Moonwalk is an EU-funded (FP7 Space research programme) project that developed new approaches for astronaut-robot cooperation. The technologies were demonstrated and tested in two Earth-analogue simulations, in Rio Tinto, Spain simulating the Martian landscape and in subsea Marseilles, France simulating the low-gravity factor on the Moon. Extra-Vehicular Activities (EVAs) were tested and included exploration and scouting of a landing site, soil sampling and exobiology in-situ analysis, mastering emergency situations and egress and ingress from a planetary habitat (using SHEE, another FP7 R&D project). A small helper rover was developed to support an astronaut, or a team of astronauts.

All elements were combined in an integrated mission architecture which served as the basis for the Martian and lunar trials of the project. The results of these trials can be used to help train and test for future human missions. In the simulations, technologies are tested that address problems that could be encountered in real missions. Mission scenarios were developed in Moonwalk, foreseeing solutions to these problems. The technologies that were developed to counter these challenges were tested in simulations. The complexity of a simulation can be modelled and advanced using either a single event simulation or a multiple event simulation. [1] Project Moonwalk tested different technologies within an integrated simulation set-up, demonstrating a multiple event simulation.

Fig. 1. Moonwalk mission elements: helper rover, astronaut, habitat (Martian base), credit: Bruno Stubenrauch

1.1 Moonwalk Objectives

The general objective of MOONWALK was to enhance European capabilities for future human space exploration, especially surface Extra-Vehicular Activity (EVA) on the moon and Mars. This was targeted through research, development and evaluation of operations concepts and technologies for exploration and exobiology related EVA tasks focusing on human-robot collaboration and the development of earth-analogue simulation equipment. The following goals were established:

- To enable human-robot and human-human cooperation in extreme environments with shared robot control between Control Centre and on-site astronaut(s).
- To adapt an earlier, existing autonomous operating rover-type robot platform for the purpose of human-controlled interaction.
- To design the setup of communications, mission planning & operations infrastructure which can be adapted to various mission scenarios (such as moon or Mars with variable communication delays).
- To develop an EVA simulation suit that can be utilized under water, simulating various levels of gravity (reflecting conditions on moon and Mars).

- To evaluate human performance in extreme environments (in function of gravity-level variations and temperature)
- To establish the physiological correlations between crew activity, suit performance, crew health and the subjective well-being of astronauts in extreme environments, using a protection garment (EVA simulation suit) fit with a portable life support system, including a biomonitoring system.
- To define search methodologies and strategies for the detection of extremophile life forms and bio-signatures in terrestrial analogues by integrating existing hardware in the mission scenarios.
- To develop sampling tools and field exploration procedures that can be utilized in extreme environments and in different application fields.

The paper presents an overview of the project Moonwalk and its components and focusses on the results from the two mission simulations in Rio Tinto, Spain and subsea in Marseilles.

2. International context

Integrated mission simulations are still quite rare because of their complexity and the financial resources involved. Recently, quite a few of highly engineered mission simulators with scientifically sound mission simulations have been built around the globe.

The most recent is LUNARES (see Figure 2), a mission simulator including a habitat for a six-person crew, a laboratory space, greenhouse, and a space to simulate EVAs on the moon or Mars. It is located on a former military base in Pila, Poland. Since it has only opened in summer this year, no human-robot collaboration mission has been conducted yet. [2]

Fig. 2. LUNARES, Poland, credit: LUNARES 2017

The HI-SEAS (Hawai'i Space Exploration Analog and Simulation) mission simulator (see Figure 3), "is a Habitat on an isolated Mars-like site on the Mauna Loa side of the saddle area on the Big Island of Hawaii at approximately 8200 feet above sea level. The HI-SEAS site has Mars-like geology which allows crews to perform high-fidelity geological field work and add to the realism of the mission simulation" [5]. The simulations focus mainly on habitat activities so no extensive human–robot collaboration EVA has been conducted yet. A private sponsor invested into building the infrastructure, while it is currently operated through NASA funds.

Fig. 3. HI-SEAS, Hawaii, USA, credit: NASA

The LUNAR Palace was built and is operated by the Chinese Space Agency. To the authors current knowledge, no Mars or moon EVA simulations have been executed in the Chinese facility, or in any outdoor equivalent.

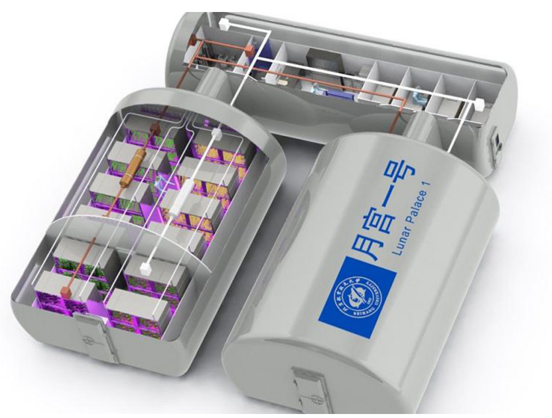


Fig. 4. Lunar Palace, credit: CSA

NASA's Desert Research and Technology Studies (D-RATS) have been stopped due to lack of funding. They had located their infrastructure for habitat, rovers and EVA simulation equipment in the high-desert terrain and isolation of northern Arizona.

"The arid climate, harsh winds, and rocky desert terrain of the region allowed NASA to evaluate different conditions that enabled multiple destinations for future human exploration including high Earth orbit, Lagrange points, the Moon, near-Earth asteroids (NEAs), Mars moons, and ultimately the surface of Mars. Experiments and training conducted at the Desert RATS site focussed on equipment and spacesuit tests, vehicular excursions and exploration, remote communication protocols, and astrogeology." [3]

Fig. 5. Desert-RATS, credit: NASA

Closest to the Moonwalk Mars mission simulation in Rio Tinto, are the missions organized and operated through the Austrian Space Forum. One example, where human-rover collaboration was tested, was MARS2013 Morocco Mars Simulation. [6] The interaction of astronaut–rover was not through gesture control however, and the rover technology was on a lower TRL than that that was demonstrated in Moonwalk.

Fig. 6. Austrian Space Forum, MARS2013 Morocco Mars Simulation, credit: Katja Zanella-Kux, 2015

3. Moonwalk problem statement

Looking at international references, many simulations have been performed and are being conducted, each with specific mission requirements and their related experiments. Moonwalk is seen as complementary with a focus on human-robot collaboration and some novel achievements. Human-robot interaction will be one of the most common operational set-ups when exploring unknown terrain. Little has been studied in this direction yet, so Moonwalk addresses this area specifically with a gestured-controlled rover.

The aim was to develop scenarios where a small helper robot is used to support an astronaut on mission exploration such as; walking down a steep slope where it is too dangerous for the astronaut to walk, going into a cave which is too small and too dangerous for a human to explore, and for carrying tools, and following the astronaut. The astronaut used gesture-control to control the support rover.

Fig. 7. Moonwalk mission scenarios, credit left: LIQUIFER Systems Group, middle and right: Bruno Stubenrauch, 2016

To test these and other mission scenarios Moonwalk developed a couple of first-evers to address the objectives:

- First-time demonstration of collaboration between an astronaut and a gesture controlled rover (YEMO)
- First European demonstration of a new underwater EVA space suit simulator from COMEX ("Gandolfi-2"), for lunar EVA simulations
- Testing of the COMEX suit simulator in two environments, on ground and immersed in water
- First use of an advanced Extra-Vehicular Activity Information System (EVAIS) in a water immersion, partial gravity simulation
- First integration of a self-deployable simulation habitat into an analogue test (SHEE – Self-deployable Habitat for Extreme Environments)

4. Moonwalk components

A brief overview of the single components is displayed.

4.1 Small assistant-rover (helper rover)

A small helper rover was developed on the basis of DFKI's Asguard design [7]. This design features four individually actuated leg-wheels and a rover chassis subdivided in two sections connected with a passive joint. This design showed very good all-terrain capabilities, including the fast traversal of difficult terrain. The small rover with a total weight of less than 20 kg is thus well suited to follow an astronaut during a planetary exploration EVA.

For the purpose of the Moonwalk earth analogue simulations, the robot (dubbed "Yemo") was constructed as an amphibious vehicle, with all electronics and batteries encapsulated in pressure-proof housings. A water-proof omnicam provided a continuous 360-degree view both to the operator and the robot control system.

The robot was remote-controlled by the astronaut. As part of the Moonwalk project, several human-machine interfaces for remote control were evaluated, including a wrist display and control-by-gesture. The latter proved to be a comfortable method of robot-control for an astronaut seriously impeded by a heavy space suit. The robot control-by-gesture worked well not only under standard conditions, but also in the underwater simulations. It may therefore be used not only in space applications, but also for the control of underwater vehicles by divers.

Fig. 8. DFKI Yemo rover in Rio Tinto, photo credit: Bruno Stubenrauch, 2016

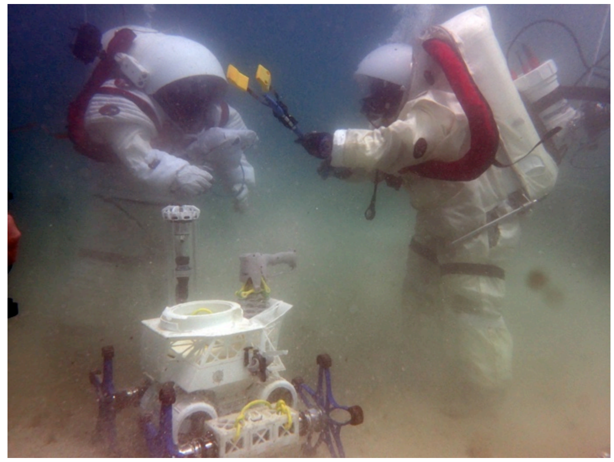


Fig. 9. DFKI Yemo rover during an astronaut-astronaut simulation underwater in Marseilles, photo credit: Comex, 2016

4.2 EVA simulations space suit – Gandolfi-2

The COMEX space suit simulator served as basis for the implementation of communications and robot control equipment. Its main functionalities are

i) simulating the movement constraints of a pressurized suit. Two different models of the COMEX suit were used in Moonwalk, one simulating a Russian Orlan space suit, and a second one simulating the NASA Z-1 suit.

ii) simulating the weight of a spacesuit in Martian environment (Rio Tinto simulations) and in lunar environment (Marseilles simulations). For the latter, the suit was equipped with buoyancy elements to simulate underwater, the reduced gravity on the moon.

Fig. 10. The COMEX space suit simulator is shown during pool trials in Marseilles and dry tests in the French Calanques. Photo credit: COMEX, 2016

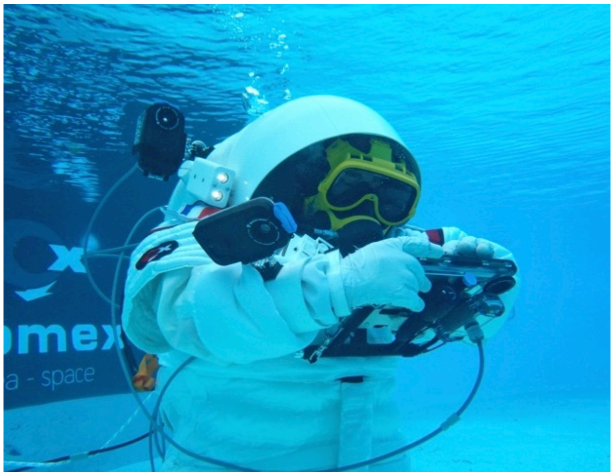


Fig. 11. The space suit simulator is operated underwater by a diver. It can be used to test various tools and control elements with the constraints of a pressurized suit. Photo credit: COMEX, 2016

4.3 EVA Information system (EVAIS)

The main components of the EVA Information System were a chest display and a wrist display running the EVAIS software developed by Space Applications Services.

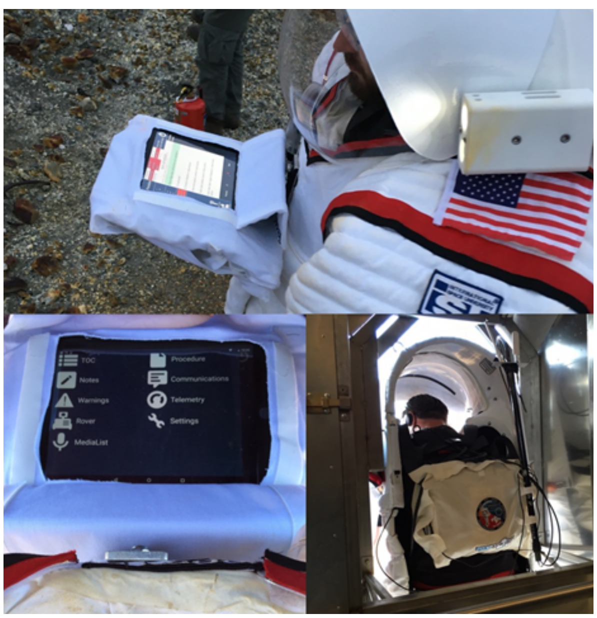


Fig. 12. EVA Information System (top, bottom left) and Suit Computer Assembly (bottom right), credit: Space Applications Services, 2016

The chest display consisted of a tablet computer which was located on the torso of the space suit. The touch-screen of this device was modified to work underwater. The interface displayed on the chest display was set up to enable the use with heavy space gloves. The chest display was mainly used to provide information related to the mission procedures (recorded in standard ISS Operations Data File - ODF format) to the astronaut.

The wrist display was intended a.) to replace the US-standard EVA cuff checklist on the spacesuit and b.) to provide an alternative to the gesture control of the robot. This display used a small screen to display an interface consisting of an array of simplified push buttons.

A Suit Computer Assembly (SCA) was integrated in the space suit to enable communication between the astronaut and the rest of the communications infrastructure.

The SCA was a computer unit in waterproof housing, that does the necessary processing for the HMIs, but also for other potentially required sensors, including the Rover Gesture Control. In the underwater simulations, the SCA was connected to a communication buoy via an umbilical. In the Rio Tinto simulations, a Wi-Fi connection was used to connect to CapCom.

4.4 Biomonitoring

Two distinct aspects of biomonitoring research were investigated: one looking at methods for monitoring and determining stress levels in the astronaut trainees, and the other, looking to help prevent astronauts from getting caught in dangerous positions owing to low gravity conditions or the restricted mobility of the suit.

The literature has shown that Heart Rate Variability (HRV) can be an indicator of physical and mental stress [13, 14, 15] so a system was devised for measuring the heart rate of the astronaut trainee. This presented several technical challenges to effectively monitor the ECG trace in the difficult environmental conditions. Particularly underwater which does not allow the ability for data transmission through wireless sensors.

A heart rate monitoring chest strap was worn against the skin by the astronaut trainee before entering the suit. By utilising lower frequency radio transmissions than standard wireless protocols (e.g. the 2.4GHz band used by Bluetooth), it was possible to achieve reception whilst underwater within 80cm without too much signal attenuation. A receiver was mounted within the training suit and was connected using waterproof cabling to the Suit Computer Assembly.

A machine learning approach was taken to 'teach' a classifier to recognise different stress levels. The classifier was trained with data from several experiments recreating mental and physical loadings. A simple 'traffic light' system was then used as an output, indicating 'Green' for a standard stress condition, progressing through 'Amber' and 'Red' as the astronaut trainee's stress levels increased.

The secondary system, termed the 'Hazardous Attitude Monitoring System', utilised accelerometers to measure the activity of the astronaut. Without a common reference point (i.e. 1G Earth gravity) it can be difficult for a person to perceive their current orientation, leading to falls which can be very difficult to recover from given the restricted mobility of the training suit. The accelerometers were used to determine what could be defined as 'normal' movement in the suit, through data gathering during several EVA sessions. Again, a machine learning approach was taken to understand what is 'normal' behaviour and then issue an alarm when data from the accelerometer indicates that 'abnormal' (i.e. dangerous) behaviour is occurring (see Figure 13). An element of prediction was also built into the system to provide a warning a few seconds before a dangerous situation (such as leaning too far forward or backward) arose so the astronaut trainee could take corrective action.

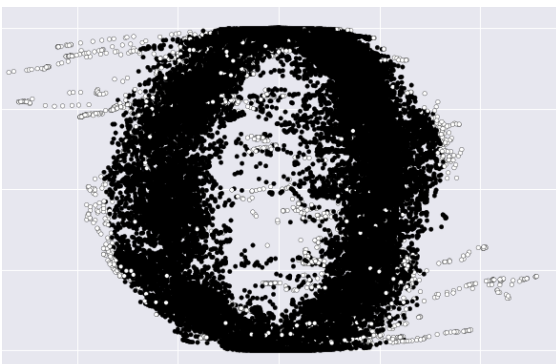


Fig. 13. Features extracted from accelerometer data. Filled black circles indicate 'normal' behaviour, unfilled circles indicate a hazardous condition.

4.5 Manual tools for EVA

Gathering scientific data includes sampling and the investigation of these probes. Therefore, manual sampling tools and a sampling box were developed by Moonwalk partner LSG. The tools could be transported by the helper rover in the specifically developed Payload Box (PB). The manual tools included the, Astronaut Rescue Tool (ART), Astronaut Tether Control (ATC), Pantograph Sampling Tool (PST), and the Foldable Pick-up Claw (FPC).

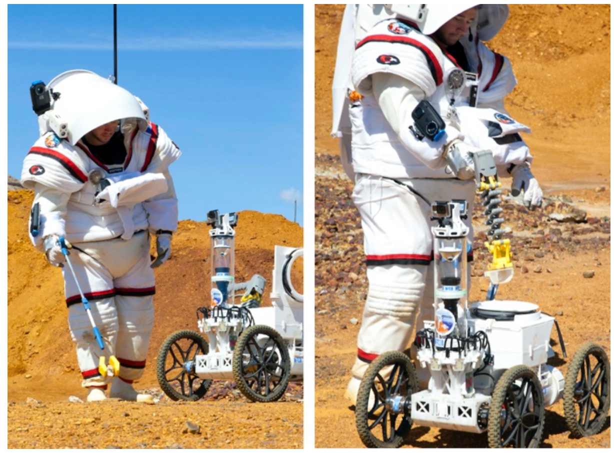


Fig. 14. Left: Sampling with the FPC, right: returning the sample in the rover Payload box with the PST, credit: Bruno Stubenrauch, 2016

Moonwalk tools were designed to be deployable, and for single-handed applications, by an astronaut, in cooperation with a small rover. The design focusses on functionality and usability. Astronauts can use the tools without needing to bend forward while using or retrieving the instruments. All manual tools can be stored in the small rover.

The PST is a tool that can be used for single-handed extension and contraction of a tool arm of which it's head is a container with closable lid. The container is box-like and tapered at one end so it can be used as a shovel. (See Figure 14, right) With a simple mechanism the container can be released and a new sample box can be affixed to the tool head. The collected samples are stored next to each other in individual boxes to avoid cross-contamination.

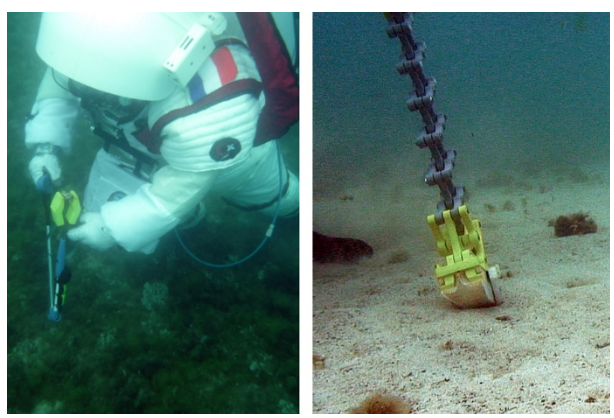


Fig. 15. Left: Sampling with the FPC, right: sampling with the PST, credit: Comex, 2016

The FPC is an enhancement of the lazy-tong concept, with which one can collect smaller rocks and debris. After having collected a sample, the astronaut can fold the FPC to inspect the samples directly in front of their visor to check the quality of the sample. (see Figure 14 left)

The Astronaut Tether Control allows astronauts to support a rover as it descends a steep slope or any other manoeuvres that would require additional security through a tether.

The Astronaut Rescue Tool (ART) is also foldable and can be used by an astronaut that has fallen over and cannot stand up on his/her own. ART can be deployed by single-handed flick and can aid the astronaut to stand up.

The rover is equipped with a mock-up Payload Box (PB), a container designed to carry the manual sampling tools, a sample storage unit, (all on the upper layer) and a portable RAMAN spectroscope in the lower layer. (See Figure 16 right)

Fig. 16. Left: Sampling with the PST, right: using the Raman Spectrometer, credit: Bruno Stubenrauch, 2016

4.6 Mission Control Centre

The Moonwalk Mission Control Centre (MCC) (see Fig. 17) was located near Brussels, Belgium, and operated by experienced flight controllers that guided the operations during simulation. Indications relevant to the experiments that need to be conveyed to, or obtained from the EVA test subjects went through the MCC. Nominally, three flight controllers, namely Flight Director (FLIGHT), Capsule Communicator (CAPCOM), and System Operations/Ground Controller (SYSOPS/GC), were present at the facility.

Flight controllers received on-site information via video feed, text and audio. The contents of this information included Cautions and Warnings, and Telemetry. The data was analysed in relation to mission procedures. Flight controllers were able to send operational data to the test subject, and to control the rover remotely.

During the Moonwalk simulations, this control centre simulated the MCC on earth. Consequently, a delay of a few seconds (moon) or 7 minutes (Mars) was implemented between MCC and the field to test the effects of delayed response and local vs. remote decision-making.

Two remote science centres were set up: one, located at the Georgia Institute of Technology, who also operate for the NASA Human Research Program SCALE project, and another one which was operated through INTA.

The Mission Control, Remote Science Centres, and EVAIS rely on the YAMCS Control Centre Open Source software which is also used for operations in the International Space Station program. The YAMCS serves as a backbone for the exchange of data.

Fig. 17. Mission Control Centre, credit: Space Applications Services, 2016

4.7 SHEE habitat

SHEE, the Self-Deployable Habitat for Extreme Environments, was developed through another EU-FP 7 grant and it was of the team's and the European Commission's interest to integrate the EU project SHEE into the EU project Moonwalk. SHEE was utilized in the simulations at Rio Tinto serving a variety of functions. It served as the beginning and end point of all EVAs at Rio Tinto, provided shelter for a variety of functions and included a suitport, designed by LSG. The suitport served for the astronauts as ingress/egress to and from the astronaut suit.

In the habitat, the local mission control resembling the communications of a Mars base with the CAPCOM was located. The local mission control served as interface between astronauts and Mission Control (in Zaventem, Belgium) with a time delay of 7 minutes each way. Additionally, the habitat housed an astrobiology laboratory where collected samples were analysed for life detection with the SOLID instrument.

Fig. 18. Left: SHEE habitat, right: astrobiology laboratory in SHEE, credit: Bruno Stubenrauch, 2016

5. Testing and simulations

The developed components and technologies were tested in two mission simulations, one mimicking a Mars exploration mission in Rio Tinto, Spain and the other one for lunar simulations, subsea in Marseilles, France in spring of 2016. Data was collected during the Moonwalk simulations and measured the performance of both astronaut(s) and rover while conducting mission scenario tasks.

5.1 Scenarios, Procedures

These Mission 'scenarios' were developed by the Moonwalk team and outlined specific tasks that were to be performed at each site. The repetitive conduct of these tasks by both astronaut and rover, in the case of project Moonwalk, allowed its team members to analyse the developed concepts and technologies.

The Moonwalk team developed a variety of scenarios which had clear set-ups. Firstly, they would address the necessary scientific objective when exploring the moon or Mars. Therefore, the first scenarios addressed the mapping of the area, then scouting and finally sampling. The investigation of the samples was undertaken in the astrobiology laboratory which had been set up in the SHEE habitat.

The core components of project Moonwalk were then developed: the gesture-controlled helper rover and the EVA suit. To create a comparison, all scenarios were scripted for both an astronaut-rover team and for an astronaut–astronaut team. The scenarios were also compared between Mars (Rio Tinto) and moon simulations (subsea Marseilles).

The basic mission scenario 'scripts' were translated into Procedures, simplified versions of the Procedures astronauts use on the ISS, giving explicit directions to the astronaut(s) performing EVAs.

The main scenarios were:

- Mapping, surveying
- Scouting
- Sampling with the tools and using Raman spectrometer measurements
- Exploring a steep slope and a cave where the astronaut depends on the capabilities of the rover

5.2 Rio Tinto simulations, Spain

To test the technology and procedures developed during Moonwalk, a human Mars exploration simulation campaign in Rio Tinto was conducted. Three basic elements; the SHEE habitat, an astronaut, and a gesture-controlled small rover (YEMO), followed the procedures and executed the EVA scenarios to achieve the mission objectives:

(i) finding a safe site for human settlement,
(ii) finding resources, and
(iii) searching for signs of live around the landing site.

The arid landscape of an old mining region in Río Tinto is considered a Mars analogue for field tests for Mars simulation studies due to: i) the strong resemblance to Martian landscapes (plains, trenches, canyons, caves, even dune-like field, and aggressive dust) (Figs. 1, 6); ii) the Fe-S based mineralogy resembling the one identified in Meridiani Planum [8] and; (iii) the particular microbiology living under extremely low pH and high heavy metal concentration [9] in the water or bound to minerals with minimal resources in the deep subsurface [10].

The Gandolfi-2 space training suit, the YEMO robot loaded with sampling tools, and a communication system with 7-minute time-delay, were used in executing the EVA procedures and mission scenarios developed for Mars exploration. Additionally, YEMO was equipped with ESA's ExoMars mission Raman instrument prototype as well as the Life Detector Chip (LDChip) and the SOLID (Signs Of Life Detector) instrument [11] to perform astrobiological research.

More than 50 EVA, accounting for a length of 12.3 km and duration of 14.5 h, were executed during the simulation campaign. EVA simulations involved astronaut-robot or only astronauts, as well as all the tools indicated above for scouting, sampling, or exploring inaccessible sites by any of them separately (e.g. a cave; Fig. 6). We successfully operated with a 7-minute delay communication between the MCC in Brussels and the astronaut-robot team and Martian base at the SHEE. Seven-minutes delay video images either from the astronaut or the robot cameras were observed and analysed by the remote Science Team and they were crucial for taking new decisions. The obtained information and samples collected by the astronaut-robot team during the Mars exploration simulation allowed the Science Team to: i) map the landing site, ii) identify resources (e.g. different materials for construction), iii) find minerals with raman spectrometer (Fig. 9), and iv) find and identify microbial markers in the collected samples (Fig. 7) as true evidence of life with the SOLID-LDChip in the astrobiology laboratory (Fig. 8). Such evidence included biological polymers and microbial remains from iron and sulfur oxidizing microbes bound to crucks on the rocks and minerals. Although still many improvements have to be done, these results permitted us to conclude that the simulation was successful and that the Río Tinto landscape is an appropriate and inexpensive natural analogue for training astronauts, robots, and instruments for future human planetary exploration missions.

5.3 Subsea simulations, Marseilles, France

In [12], nine potential lunar analogue sites have been identified offshore the city of Marseilles. At a reasonable depth, they have been selected for geomorphological similarity with some interesting spots on the moon.

Among them, Port de Pomegues has been selected because of its low exposure to the wind, its good communication data coverage, and the fact that the COMEX vessel MINIBEX can easily navigate in this zone. The site has been explored to identify several sampling and scouting locations, an appropriate position for the Lunar Exploration Module set-up, and a slope that could be used to test astronaut/robot collaboration while scouting an uneven terrain.

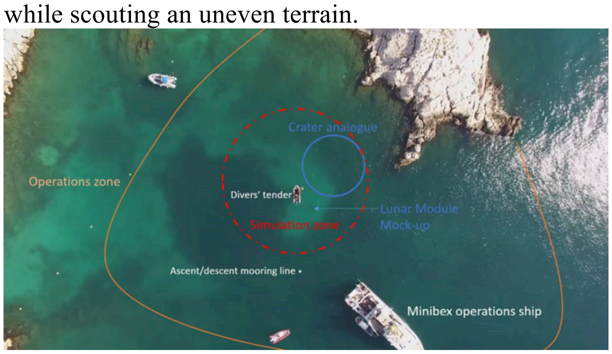


Fig. 19. Aerial view of the test site offshore Marseilles, credit: google earth

The EVA simulations in sea where conducted after repetition of the tasks in the COMEX pool in Marseilles.

Although there are not many differences in the technical or scientific outcome between pool tests and sea trials, the level of psychological stress, as experienced by humans, is significantly different.. The workflow was much more fluid and simple during the pool trials, with less operational constraints, but the few hours of simulation on the seabed harvested from three days on the sea were of great value to reproduce the extreme environments inherent in any planetary exploration mission. Three subjects performed the simulations underwater, and all of them performed a training session in the pool before going into the sea at Port de Pomègues.

6. Results

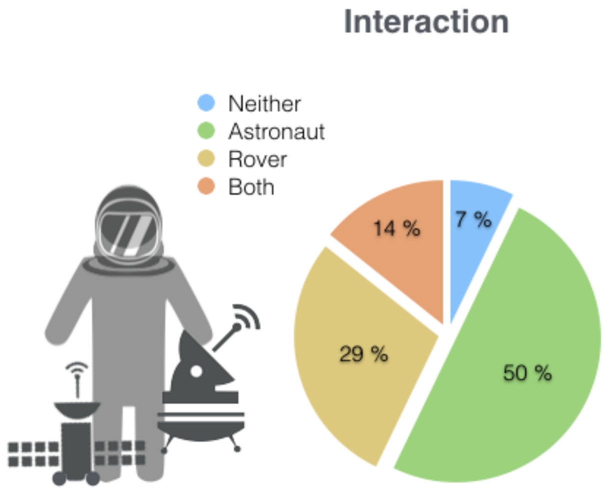
A core objective in the analysis of project Moonwalk was to evaluate the performed analogue missions with respect to human factors; and to evaluate and compare the astronaut-astronaut team versus the astronaut-robot team in of overall performance and psychological distress.

Dependent variables were measured by responses to a survey and through interviews conducted with the astronauts directly after each EVA. The 101-question survey presented to the astronauts included background-, descriptive-, and statements variables. Some questions were provided by consortium partners asking for feed-back of their specific component, other questions aimed to evaluate the simulations and the different effects that the components had on the subjects, and one section of the survey included the subjective mental workload assessment tool NASA RTLX (Task Load Index without weighing procedure.

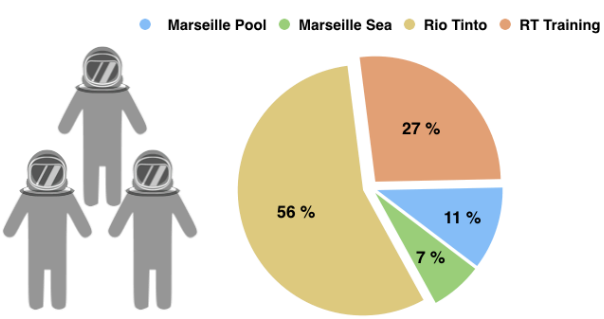
In total, the dataset consists of 120 variables, of which 101 were questions, 75 responses and 14 respondents. From the open questions, the survey collected 52 lessons learned, 33 comments about the different simulations, 55 comments about the tools, 63 comments about the HMI and 39 comments about the suit. Data was gathered from 28 different EVAs, 17 performed in Rio Tinto and 11 in Marseilles.

The main hypotheses tested was: 1) EVAs will be experienced differently by an astronaut working with a robots compared to an astronaut working with another astronaut, and 2) Analogue sites are crucial to experience teamwork and to test technical systems in a comprehensive and realistic manner.

The first hypotheses is not supported by our results. There is little indication that the interaction with the rover/robot was experienced different than working with another astronaut. Interviews and observations supports this finding, and the astronauts underlined that the greater communications setup was important in order to include human interaction in a setup when working with a rover in scouting and sampling processes. When human communication systems failed, it was more difficult to operate alone with a rover instead of another astronaut.



The second hypothesis was strengthened by our results. The difference in sites proved to affect how astronauts experienced EVAs, as well as how they evaluated the tools and components to a high degree. This implies that different kinds of extreme conditions was included by the difference in the sites and successfully simulated different situations to be handled by the astronauts as well as the sociotechnical system as a whole. In Rio Tinto, there was a significantly higher physical discomfort due to both heat and gravity while wearing the suit, while the mental distress caused by performing the EVAs under water was significantly higher in Marseille.



As the same astronauts performed several EVAs we could also observe both learning and coping mechanisms as the astronaus found ways to handle the distress introduced to the simulations. In Rio Tinto the same astronaut could perform EVAs that lasted twice as long, and still experienced it as less discomforting, the last day compared to the first week of simulations.

The main suppositions drawn from this evaluation is that simulations in analogue sites provide a good tool for learning about the complex socio-technical systems that exists in a human exploration mission that utilises human-robot cooperation. Furthermore, analogue sites allows for different functions and purposes such as performing semi-controlled experiments, technology testing and development, and training of personnel. It is important to be clear about what purpose and function a simulation should have in order to not to disturb an experiment by changing the premises by a development process. If utilized correctly, this kind of analogue sites gives the ability to combine heterogeneous elements and thus create complex and highly relevant situations for technology development, training and, not least, experiment setups.

7. Conclusions

Project Moonwalk was a multiple analogue testing project through which six consortium members have developed a variety of technologies related to human-robot collaboration, more specifically a spacesuit simulator and a small helper rover with scenarios for exploration of unknown terrains. Additionally, a bio-monitoring system, the EVAIS communication system, and manual sampling tools were developed. Numerous EVAs were conducted in two analogue sites, in Rio Tinto and underwater offshore Marseilles which were evaluated and reflected the human-robot collaboration in relationship to human-human collaboration in a quantitative analysis. Project Moonwalk created valuable hardware, data and set-ups to advance preparations for future exploration of the moon and Mars through international collaboration.

Acknowledgements

The project Moonwalk has received funding from the European Union's Framework 7 Research and Innovation Programme under Grant Agreement no 607346.

References

1. Mohanty, Susmita, 2010, *Integrated high-fidelity planetary mission simulators: a toolkit for fidelity evaluation*; PhD dissertation, Department for Architecture, Chalmers University of Technology, Gothenburg, Sweden
2. LUNARES, mission simulator, http://lunares.space/ (accessed 25.8.2017)
3. Desert Research and Technology Studies (Desert RATS), Jeffrey Brief, June 10, 2015
4. https://www.nasa.gov/hrp/research/analogs/drats (accessed 25.8.2017)
5. HI-SEAS, Hawai'i Space Exploration Analog and Simulation, https://hi-seas.org/ (accessed 25.8.2017)
6. Austrian Space Forum, http://oewf.org/en/ (accessed 25.8.2017)
7. Schwendner, Jakob, Mathias Höckelmann, Martin Schröer, Thomas Vögele, Peter Weiss,

Bernard Gardette, Virginie Taillebot et al. "Surface Exploration Analogue Simulations With A Crew Support Robot."

8. Fernández-Remolar D.C. et al. (2005) *Earth Planet. Sci. Letter.* 240, 149-167
9. González-Toril et al. (2003) *Appl. Environ. Microbiol.* 69, 4853-65,
10. Fernández-Remolar D.C. et al. (2008) *Astrobiology*, 85, 1023–1047.
11. Parro et al., (2011) Astrobiology 11, 15-28.
12. Weiss, P., Gardette, B., Chirié, B., Collina-Girard, J., & Delauze, H. G. (2012). Simulation and preparation of surface EVA in reduced gravity at the Marseilles Bay subsea analogue sites. Planetary and Space Science, 74(1), 121-134
13. Wang, Jeen-Shing, Che-Wei Lin, and Ya-Ting C. Yang. "A k-nearest-neighbor classifier with heart rate variability feature-based transformation algorithm for driving stress recognition." *Neurocomputing* 116 (2013): 136-143.
14. Lakin, Robert, Catherine Notarius, Scott Thomas, and Jack Goodman. "Effects of moderate-intensity aerobic cycling and swim exercise on post-exertional blood pressure in healthy young untrained and triathlon-trained men and women." *Clinical Science* 125 (2013): 543-553
15. Brunoni, Andre Russowsky, et al. "Heart rate variability is a trait marker of major depressive disorder: evidence from the sertraline vs. electric current therapy to treat depression clinical study." *International Journal of Neuropsychopharmacology* 16 (2013): 1937-1949