MOONWALK

TECHNOLOGIES AND HUMAN-ROBOT COLLABORATION FOR SURFACE EVA EXPLORATION ACTIVITIES AND TRAINING IN EUROPEAN ANALOGUE ENVIRONMENTS

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Final Project Report

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1. Objectives, project management, work progress and achievements

1.1 MOONWALK Objectives

The overall objectives of the MOONWALK project, expressed in general terms, can be summarized as follows:

- Develop innovative technologies to support co-operative human-robot exploration of planetary surfaces (robot-assisted EVA);
- Use and further develop infrastructures, technical systems, and know-how needed for analogue simulations in Europe;
- Test and demonstrate the technologies developed in MOONWALK in two analogue simulations (in Rio Tinto and Sub-Sea Marseille) under simulated Mars and lunar conditions;
- Reach out to the (European and international) Space community and to the public to boost the interest in human space flight and in European analogue simulations.

Specific technical objectives about how MOONWALK will research and validate key technologies for robot-assisted EVA in space exploration are listed on page 2 of PartB of the MOONWALK Description of Work (DoW). The table below (Table 2) lists the main MOONWALK objectives and the way these objectives were addressed and met in the MOONWALK project.

Table 1: Moonwalk Objectives

Technical Objectives	**How objectives were addressed in MOONWALK**
O1: Human-robot and human-human cooperation in extreme environments with shared robot control between the Control Centre and the astronaut on-site. This includes wearable Human-Machine Interfaces (HMI) that work in extreme environments and under difficult operation conditions.	Various HMI (Wrist display, tablet, gesture control) and CC successfully implemented and tested in relevant environments (EVA simulations). Proof-of-concept that the interfaces work under difficult conditions was provided. Shortcoming: Direct robot control through CC was not fully integrated; TRL of interfaces was low.
O2: Adaptation of an (existing) autonomous operating rover-type robot platform for human-controlled interaction inclusive required instrumentation (cameras, sensors, communication and navigation package).	YEMO robot is a new construction based on the DFKI ASGUARD system, fulfilling the requirements of MOONWALK (amphibious operation). Sensors include cameras and communication package. Shortcoming: Because focus of project was on astronaut-robot interaction/control, decisional autonomy of robot was low and limited to follow-me function; low TRL of follow-me functionality
O3: Design and setup of communication, and mission planning & operations infrastructure and tools (control centre) which can be adapted to various mission scenarios (such as Moon or Mars with variable communication delays).	Mission control infrastructure was set up (CapCom on-site, MCC in Brussels) and successfully tested in both simulations. Variable communication delays were implemented. Shortcoming: Communications on-site partially unreliable;
O4: Evaluation of human performance in extreme environments (in function of gravity level variations, pressure and temperature) and the effect of robot-human cooperation. To establish lessons learned for the design of future exploration missions and associated technology. To establish	Human performance was measured in both simulations, both with technical means (bio-monitoring) and with empirical means (questionnaires). Lessons learned were formulated (see D8.1 and D8.2).

the factors and stressors which affect human performance and to develop mitigation strategies.	Shortcomings: Simulations were too short to really identify stressors and develop mitigation strategies; empirical assessment not possible.
O5: Sustainability of life in extreme environments through protection garment and portable life support systems for astronauts. This device will include a bio-monitoring system included in the EVA suit to monitor basic life signs of the astronaut during the EVA. To establish the physiological correlations between crew activity, life support suit performance, crew health and well being (subjective).	A new simulation space suit was implemented. It is useable for terrestrial and under-water simulations. A bio-monitoring system was integrated.
O6: Definition of search methodologies and strategies to detect extremophile life forms and bio-signatures in terrestrial analogues by integrating existing hardware in the mission scenarios.	Devices for in-situ analysis of soil probes (A RAMAN spectroscope and the SOLID tool) were customized to be carried by the exploration rover. Shortcomings: technical problems reduced possibilities to test science tools in scenarios
O7: Manual and robotic sampling tools and field exploration procedures that will be tested in extreme environments (low temperature, microgravity) and in different application fields (geology and exobiology). To assess the effectiveness of the tools for use by crew in extreme environments.	Manual sampling tools and field exploration procedures were developed and tested in the analogue simulations. Support tools for sampling (e.g. payload box, on-board RAMAN) were implemented. Use of tools by crew was evaluated empirically. Shortcoming: An active robotic sampling tool could not be implemented due to budget constraints. Quantifications of the effectiveness of the manual tools could not be provided due to the small number of EVA simulations.

2. Work Progress and Outcomes

2.1 WP1 – Project Coordination

Lead: DFKI

Objectives: The objective of WP1 was to perform the administrative and financial management of the project. This includes reporting and coordinating of contacts with REA, quality management, timing of the project and the resolution of conflicts between the consortium partners. On a technical level, WP1 will set up appropriate communication and collaboration tools.

In addition to the co-operation of the full project partners, WP 1 is also responsible for the co-operation with the associated partner NASA and with other potential parties of interest (e.g. ESA).

Table 2: WP 1 - List of deliverables

Deliverable Number	Deliverable Description	Lead beneficiary
D1.1	Project Procedures Manual (PMM)	DFKI
D1.2	Periodic Review Report 1 (RP 1)	DFKI

D1.3	Technical Interim Progress Report (RP 2)	DFKI
D1.4	Periodic Review Report 2 (RP 3)	DFKI
D1.5	Ethics Approvals	DFKI

2.1.1 T1.1 Administration and Project Coordination

Task lead: DFKI

The project coordinator (DFKI) organized the administrative co-ordination of the project. This included intensive communication with the project partners (via telephone and e-mail) and with the REA project officer (via telephone and e-mail). In addition, the project coordinator organized meetings and/or helped partners with the organization of meetings, conducted monthly telephone conferences, and supervised the quality control and submission of project deliverables.

The Project Coordinator was supported by the Technical Manager (COMEX) in the guidance of the technical work-packages in RP1 and in the quality check of the deliverables.

To further improve co-operation between project partners in MOONWALK, regular monthly telephone conferences were held.

During the last review period, several integration meetings and the two simulations took place. Therefore no additional physical administrative meeting was organized.

MOONWALK Gantt Chart		YEAR1												YEAR 2												YEAR 3											
	0	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	M16	M17	M18	M19	M20	M21	M22	M23	M24	M25	M26	M27	M28	M29	M30	M31	M32	M33	M34	M35	M36
		2013				2014												2015												2016							
		9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8
WP1	Project Coordination	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
T1.1	Administration and project coordination	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
T1.2	Reporting and financial coordination											▨	▨											▨	▨											▨	▨
T1.3	Quality assessment & risk management										▨	▨	▨										▨	▨	▨										▨	▨	▨
WP2	Scenario development	■	■	■	■																																
T2.1	Review of operational constraints and procedures in EVA	▨	▨																																		
T2.2	Field exploration - exobiology and geology		▨	▨	▨																																
T2.3	Infrastructure		▨	▨	▨																																
WP3	Concept Definition and Architecture					■	■	■	■	■																											
T3.1	Human factors for safety and dependabitlity					▨	▨																														
T3.2	Robotic Platform					▨	▨	▨	▨	▨																											
T3.3	EVA Suit					▨	▨	▨	▨	▨																											
T3.4	Man-manchine platform							▨	▨	▨																											
WP4	R&D of Man-Machine Platform										■	■	■	■	■	■	■	■	■	■	■	■	■	■	■												
T4.1	Control Center and Platform Development										▨	▨	▨	▨	▨	▨	▨	▨																			
T4.2	Wearable Procedural Display												▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨												
T4.3	EVA suit integrated robot control										▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨												
WP5	R&D Robotic Platform										■	■	■	■	■	■	■	■	■	■	■	■	■	■	■												
T5.1	Robot Adaptqation to Earth-Analogue Environments										▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨																
T5.2	Robot Locomotion Control										▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨												
T5.3	Robot Intelligence and Interaction												▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨												
T5.4	Robot Payload Mock-Up												▨	▨	▨	▨	▨	▨	▨	▨	▨																
WP6	R&D of EVA Training Suit										■	■	■	■	■	■	■	■	■	■	■	■	■	■	■												
T6.1	Suit Modification										▨	▨	▨	▨	▨	▨	▨																				
T6.2	MMI Integration													▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨												
T6.3	Biomonitoring Integration																	▨	▨	▨	▨	▨	▨	▨	▨												
T6.4	Manual Toosl for EVA																			▨	▨	▨	▨	▨	▨												
WP7	Tests & Simulations																						■	■	■	■	■	■									
T7.1	Pool Tests EVA Suit, MMI, biomonitoring																						▨	▨	▨	▨	▨	▨									
T7.2	Lab-Tests Robot + EVA Suit																						▨	▨	▨	▨	▨	▨									
T7.3	Lab-Tests Control Center																						▨	▨	▨	▨	▨	▨									
WP8	Earth-Analogue Tests																									■	■	■	■	■	■	■	■	■	■	■	■
T8.1	Experimentation plan and procedure preparation																								▨	▨	▨										
T8.2	Moon simulation (Subsea Marseilles)																											▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
T8.3	Mars simulation (Rio Tinto)																											▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
WP9	Dissemination & Outreach	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
T9.1	Dissemination of the results	▨	▨	▨	▨	▨	▨																														
T9.2	Training for testbed deployment and utilization	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
T9.3	Exploitation, management of knowledge and IPR issues													▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
T9.4	visualizations, images, animations, videos							▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	Milestones	MS-1			MS-2					MS-3									MS-4									MS-5								MS-6	MS-7

Figure 1: MOONWALK Schedule

Table 3: List of deliverables

#	*WP No*	*Del No*	*Title*	*Lead*	*Nature*	*Diss.L.*
1	WP1	D1.1	Project Procedure Manual	DFKI	Report	RE
2	WP1	D1.2	Periodic Review Report 1	DFKI	Report	CO
3	WP1	D1.3	Technical Intermim Progress Report	DFKI	Report	CO
4	WP1	D1.4	Periodic Review Report 2	DFKI	Report	CO
5	WP1	D1.5	Ethics Approvals	DFKI	Report	CO
6	WP2	D2.1	Operational Constraints and Procedures Report	NTNU	Report	RE
7	WP2	D2.2	Field Exploration Scenarios Report	LSG	Report	RE
8	WP2	D2.3	Draft Roadmap on Earth-Analogue Simulations for Humar	DFKI	Report	CO
9	WP3	D3.1	Human Factors Report and Operations Concepts	NTNU	Report	RE
10	WP3	D3.2	Robotic Platform Design	DFKI	Report	CO
11	WP3	D3.3	EVA Suit Design	COMEX	Report	CO
12	WP3	D3.4	Man-Machine Platform Design	SPACE	Report	CO
13	WP3	D3.5	Test Procedures Design	COMEX	Report	CO
14	WP3	D3.6	Interface Control Document	SPACE	Report	CO
15	WP3	D3.7	Detailed Hardware Development Plan	DFKI	Report	CO
16	WP4	D4.1	Control Center Simulation System Concept	SPACE	Report	CO
17	WP4	D4.2	Wearable Procedual Display System Concept	SPACE	Report	CO
18	WP4	D4.3	Control-by-Gesture System Concept	DFKI	Report	CO
19	WP5	D5.1	Earth-Analogue Test Rover	DFKI	Prototy	CO
20	WP5	D5.2	Algorithms for enhanced robot locomotion control	DFKI	Report	CO
21	WP5	D5.3	Robot Intelligence Concept	DFKI	Report	CO
22	WP5	D5.4	Robot payload mock-up	LSG	Prototy	CO
23	WP6	D6.1	EVA Suit Concept	COMEX	Report	CO
24	WP6	D6.2	EVA Suit Prototype	COMEX	Prototy	CO
25	WP6	D6.3	Biomonitoring Manual	EADS	Report	CO
26	WP6	D6.4	Manual EVA Tools Prototypes	LSG	Prototy	CO
27	WP7	D7.1	Report on EVA pool tests	COMEX	Report	RE
28	WP7	D7.2	Report on Robot pool tests	DFKI	Report	RE
29	WP7	D7.3	Control Centre test report	SPACE	Report	RE
30	WP8	D8.1	Report Marseilles analogue simulation	COMEX	Report	RE
31	WP8	D8.2	Report Rio Tinto analogue simulation	INTA	Report	RE
32	WP9	D9.1	Webpage including secured intranet site	LSG	Other	RE
33	WP9	D9.2	Childrens competitions report	LSG	Report	RE
34	WP9	D9.3	Project Flyer + Dissemination material	LSG	Other	RE
35	WP9	D9.4	Dissemination Plan	LSG	Report	RE
36	WP9	D9.5	Exploitation and IPR Plan	DFKI	Report	RE
37	WP9	D9.6	Final Dissemination Report	LSG	Report	RE
38	WP9	D9.7	Draft Exploitation Plan	DFKI	Report	CO
39	WP9	D9.8	Newsletter 1	LSG	Other	PU
40	WP9	D9.9	Newsletter 2	LSG	Other	PU
41	WP9	D9.10	Newsletter 3	LSG	Other	PU
42	WP9	D9.11	Final Roadmap on Earth-Analogue Simulations for Humar	DFKI	Report	PU

Table 4 Milestones

MILESTONES							
MS no.	Milestone name	WP no	Lead benef.	Delivery date	Achieved Yes/No	Actual / Forecast date	Comments
MS-1	Completed Kick-Off Meeting	WP1	1 DFKI	09/2013	Yes	09/2013	
MS-2	Exploration scenario for the two analogue site campains	WP2	6 INTA	01/2014	Yes	02/2014	Achieved with submission of WP2 deliverables
MS-3	Adapted Operations Concept	WP3	5 NTNU	05/2014	Yes	07/2014	Achieved with submission of WP3 deliverables
MS-4	Sub-system Concepts ready	WP3, WP4, WP5, WP6	1 DFKI	02/2015	Yes	05/2015	Achieved with submission of concepts (D3.2, D4.x, D6.1)
MS-5	Technical subsystems ready for earth analogue tests	WP4, WP5, WP6, WP7	2 COMEX	11/2015	Yes	04/2016	Integration week and pool tests in Marseille
MS-6	Earth-Analogue Simulations Completed	WP8	7 – INTA	07/2016	Yes	06/2016	Successful completion of Rio Tinto and Marseille
M-7	Project finalization and final report submission	WP9	4	08/2016	Yes	10/2016	Submission of all missing deliverables

Synergies with other EU-FP 7 projects: The MOONWALK team tried to leverage synergies with other EU-funded projects where possible. One such example was the SHEE (Self-deployable Habitat for Extreme Environments) project (http://www.shee.eu/main). The planetary habitat test-bed for terrestrial analogue simulations was used at the MOONWALK simulations in Rio Tinto for an astrobiology laboratory and the Local Mission Control. Specifically for the MOONWALK project a suit-port was built to the SHEE habitat to simulate ingress and egress procedures for the first time in Europe.

Co-operation with the SHEE project: The habitat developed in the EU-funded SHEE project was identified as being a potentially very valuable asset in the planned Rio Tinto analogue simulations. Because a number of MOONWALK partners are also partners in SHEE, the discussion about if and how to use the SHEE habitat in Rio Tinto were initiated early on. MOONWALK could convince SHEE to deploy the habitat in Rio Tinto. Prior to the Rio Tinto simulations, the habitat was thus transported from Straßburg to Rio Tinto. The cost for the transport (and the transport back after the simulations) was covered by MOONWALK. On the other hand, staff from the SHEE consortium stayed on-board in

Rio Tinto and provided valuable support to the MOONWALK team. Overall, the co-operation proved to be beneficial for both projects.

Cooperation with ESA: Throughout the project, there have been strong ties to ESA, in particular with regard to MOONWALK components (the suit, the tools, the communication architecture). Consortium members presented the concepts and approach of MOONWALK to the ESA-EAC in Cologne. As a result, ESA-EAC representatives supported MOONWALK in the scouting of the site at Rio Tinto and were present during the simulations, both in Rio Tinto and Marseille. A former ESA astronaut, Jean-Francois Clervoy, participated as an observer in the Rio Tinto simulations.

Synergies with two ESA studies ("LUNA Analogues for Preparing Robotic and Human Exploration on the Moon – Needs and Concepts", MOONDIVE) could be used. Both are dedicated to artificial analogues in preparation of future lunar exploration as a described by the ESA DG Jan Wörner in his Moon Village concept. In both concepts, MOONWALK hardware is integrated and thus becomes key components of the ESA concepts. MOONDIVE is a study about scenarios for the Neutral Buoyancy Facility at ESA-EAC with the Gandolfi 2 suit to train astronauts for future lunar exploration. LUNA is about a whole artificial analogue to be established at ESA-EAC to support astronauts in training for future lunar or Martian surface missions. Furthermore, MOONWALK was introduced at the ESA Isolation Steering Committee meetings as a facility ready to be used for future ESA isolation studies.

Cooperation with NASA: Early on in the project, the MOONWALK consortium established a contact to NASAs Habitability and Human Factors Branch at Johnson Space Center, Houston. The consortium visited analogue sites and labs in the US and established contact to staff in charge of NASA analogue efforts. These contacts (mainly to Jonathan Dory, head of the Human Factors Branch) was kept alive throughout the project. However, efforts to come to a formal commitment for co-operation between MOONWALK and NASA failed due to buerocratic obstacles on the side of NASA. Also, invitations to attend MOONWALK workshops and meetings could not be accepted by NASA staff for legal reasons. Nevertheless, NASA staff could be involved in MOONWALK workshops via teleconference.

During the Kaunertal Mars Simulation, which was observed by a MOONWALK delegation, contact with Andrew Abercromby, Head of the EVA Physiology Lab of NASA JSC, could be established. He showed interest in the MOONWALK Announcement of Opportunity and suggested to propose an experiment for the Rio Tinto simulation. In Rio Tinto, Matt Deans from JSC attended the simulations as an observer. However, again prohibited by NASA buerocracy, he was not able to bring the proposed experiment to Spain.

In summary, the cooperation with NASA had a good start, but was seriously constrained by NASA buerocracy. While NASA staff appeared to be genuinely interested in the project and willing to participate, legal and administrative obstacles made a fruitful cooperation almost impossible. Nevertheless, the project managed to develop a joint draft roadmap for analogue simulations (D9.X). However, a second document (D9.11 Final Roadmap for Analogue Simulations) had to be completed without contribution from NASA.

Cooperation with NASA through Georgia Tech: As an alternative to direct NASA participation in the analogue simulations, the project partner SPACE was able to establish a contact with Georgia Tech University where Prof. Leslie DeChurch was willing to co-operate with MOONWALK within the framework of the NASA-funded project "SCALE: Shared Cognitive Architectures for Long-term Exploration".

During the Rio Tinto simulations, the MOONWALK mission control software was installed in the HERA habitat at NASA JSC. For a limited time, the US site was added to the MOONWALK communication infrastructure as an external science center. Interaction involved logging of data exchanges and direct communication between the US site and the astronauts in Spain.

Consideration of ethics issues: During the evaluation of the proposals, the reviewers raised a number of ethical issues in the Ethics Screening Document. The consortium took this document as a start and went through the *EU Guidance document on Ethics Self-Assessment* to identify potential issues that needed to be resolved. After thorough consideration (documented in D1.5 Ethics Approval Document), the consortium identified the following issues:

- MOONWALK research does involve human participants (mock-up astronauts). However, these are volunteers and healthy adults. Prior to the simulations, they were informed about potential risks. They then signed a liability waiver issued by the organizers of the simulations (INTA in Rio Tinto and COMEX in Marseille). In the selection process, the astronauts had to fulfill certain health criteria. During the simulation, prior to each EVA, the health status of the subjects was checked by a certified doctor.
- MOONWALK did also involve the collection of personal data, mainly bio-monitoring data during the simulations. A number of measures were taken, including obtaining a formal ethical evaluation of the experiment plan from the REK in Norway (as the data were evaluated by the Norwegian beneficiary NTNU), a registration of the planned data collection with the Norwegian Data Protection Office (NSD), and the creation of a “Data Collection and Management Plan” by NTNU. In addition, all subjects were asked to sign an “informed consensus document” prior to the EVA simulations.

In summary, as the objective of the MOONWALK project is to evaluate the feasibility of human-robot interaction in future space exploration missions and to test the technical equipment used in such missions, and does NOT include any empirical studies on humans (or animals) in the sense of medical research, the other issues mentioned in the Self-Assessment document were deemed to be not applicable to the MOONWALK project.

2.1.2 T1.2 - Reporting and Financial Coordination

Task lead: DFKI

The preliminary estimated use of resources indicates that all partners worked more, some of them signifcantly more, than initially anticipated. In particular the efforts for WP8 (Analogue Simulations) exceeded the efforts budgeted in the proposal / DoW.

The deviation in the use of personnel ressources is reflected, to a certain extent, in the estimated deviations of budget used. However, only some partners exceeded their budget while others underspent.

For details please consult the D1.4 Periodic Progress Report 2.

2.1.3 T1.3 - Continuous Quality Assessment and Risk Management

Task lead: DFKI

The main issues relevant in this task were the quality control of deliverables and the response to the comments raised by the reviewer(s) after the first (2014), second (2015), and interim (2016) project reviews.

For details please consult the D1.4 Periodic Progress Report 2.

2.2 WP2 - Scenario Development

Lead: NTNU

Objectives: This WP reviewed and selected procedures of robot-assisted EVA and evaluates, which aspects can be simulated in the two MOONWALK Earth Analogues Simulations (Marseille, Rio Tinto). The deliverables produced in this WP describe intervention scenarios for robot-assisted EVA related to Exobiology, Logistics and Field Exploration that are able to simulate typical applications of robot-assisted EVA under space conditions.

In addition, options for the co-operation with the associated partner NASA are evaluated and a joint research roadmap was drafted.

Table 5: WP 2 - List of Deliverables

Deliverable Number	Deliverable Description	Lead beneficiary
D2.1	**Operational Constraints and Procedures Report** Present operational concepts for past and current space missions and from other domains with similar operational constraints. Establish the project approach to mission design for collaborative robotic – human agents operations.	NTNU
D2.2	**Field Exploration Scenarios Report** Presents the scenarios selected for simulation in Rio Tinto and subsea Marseille	LSG
D2.3	**Draft Roadmap on Earth-Analogue Simulations for Human-Robot Co- Operation in Space Exploration** Presents the draft Roadmap and describe the facilities available in the US and in Europe and identify possibilities for a joint usage of these facilities	DFKI

2.2.1 T2.1 Review of the Operational Constraints and Procedures in Robot-assisted EVA

Task lead: NTNU

Relevant deliverables:

- D2.1 Operational Constraints and Procedures Report
- D2.3 Draft Roadmap on Earth-Analogue Simulations for Human-Robot Cooperation in Space Exploration

Task T2.1 had two main objectives:

1.) To identify operational constraints and establish procedures for the design of earth analogue simulations of robot-supported EVAs.

2.) To initiate a cooperation with the associated partner NASA on the subject of Earth-Analogue Simulation.

Operational constraints and procedures for simulations: To achieve the first objective, efforts were focused on identifying the exploration scenarios to be simulated in the desert like Rio Tinto and Moon-like Marseille underwater site.

The identification and discussion of operational constraints and approach to procedure standards was tailored to support the further work in Moonwalk in two ways:

1) Selecting scenarios and tasks relevant for:
- Challenges experienced during past and present analogue simulations.
- Challenges relevant for future moon/planetary EVA

2) Selecting scenarios and task in-line with:
- The relevant state of the art
- The nature of the two analogue sites
- The resource envelope of MOONWALK project

The constraints and proposed procedure standards were analyzed in the context of the project approach to operation concept design for the collaborative robotic – human agents operations.

Two aspects with key impact on the project philosophy were also addressed.

A.) Task level v.s. mission level simulation

One of the key questions addressed was: Are the MOONWALK analogue simulations **mission level simulations** or **task level simulations**?.

- Task level analog simulations are the execution of specific tasks or activities to be studied with respect to the performance of various EVA team configurations. For example, if the task under consideration is Geological Sampling, the MOONWALK operations concept would then only deal with methods relevant to this activity.
- Mission level analog simulations imply a holistic simulation of EVA related activities, including a sequence of level simulations. While the execution of mission level analog simulations would obviously provide more complete operations, this adds an additional amount of complexity to the execution of trials.

B.) Operational vs. simulation products and procedures

The project needs to address the analogue simulations with “on-stage”, i.e. operational and “back-stage”, i.e. simulation products and procedures. On-site analogue simulations products and procedures are needed for:

- Daily briefing and debriefs, including to remote participants
- Setting up security and safety policies, and ensuring they are carried out
- Tracking trial execution
- Facilitating communication between trial participants
- Act as a central communication point with local agencies as needed
- Organize local awareness campaigns (before and during the trials)
- Organize and facilitate dissemination activities during trials
    - On-site dissemination activities
    - Online dissemination activities

To achieve the second objective, the MOONWALK Coordinator (DFKI), supported by the Technical Coordinator (COMEX) and the MOONWALK partner SPACE approached the *Habitability and Environmental Factors Division* at NASA’s Johnson Space Center in Houston. The objective was to leverage NASA's long-lasting experience with earth-analogue simulations, both underwater and terrestrial.

Co-operation with NASA: In the first project month, an observatory and outreach mission to NASA that included visits to their NEEMO Earth Analogue UW simulation site in Florida and to the Johnson Space Center in Houston was initiated. Discussions were held with representatives from NASA to identify common research interests.

These discussions were continued in several telephone conferences throughout T2.1 within the first six months of the project. The result was D2.3 Draft Roadmap on Earth-Analogue Simulations for Human-Robot Co-Operation that outlines the objectives and measures for a co-operation between MOONWALK and NASA within the project. This document is the basis for a more general Roadmap to be delivered at the end of the project.

2.2.2 T2.2 - Field Exploration – Exobiology and Geology

Task lead: INTA

Relevant deliverable(s): D2.2 Field Exploration Scenarios Report

The objective of task T2.2 was to describe in detail future activities on the lunar or Martian surface related to logistics of human activities in space. Such activities include the selection of sites for habitations, maintenance activities, transport of equipment on the surface and rescue activities.

The *Field Exploration Scenario Report* (D2.2) reflects future surface operation activities which are based on the report “The Global Exploration Roadmap”, August 2013, compiled by space agencies participating in the International Space Exploration Coordination Group (ISECG). The MOONWALK objectives were described in the context of the ISECG analogue activity.

As an important consideration for developing the MOONWALK field exploration scenarios the likely future surface infrastructure elements for both lunar and Martian human exploration missions were discussed and have been complemented by a summary of the relevant Lunar and Martian surface characteristics.

Of mayor relevance to logistics of human activities on planetary surfaces, are both the characteristics of the terrain associated with the proposed exploration sites and the nature of the science and technological activities to be performed.

Possible lunar and Martian sites have been evaluated based on significant science return and/or potential technological advantages for future permanent lunar and Martian bases.

For relatively level mare and crater topology as well as more challenging exploration sites in graben, former fluid channels, crater and canyon walls etc. equivalent Subsea Marseilles and Rio Tinto analogue simulation sites have been identified.

Detailed descriptions of these analogue sites comprise several optional locations of each site which have been analysed and evaluated with respect to their individual surface operation simulation.capacities.

The planned equipment and methodology for the exploration and investigation simulation activities for both sites have been outlined and specific risks or constraints and proposed safety issues with regard to the individual sites were depicted.

The operational stages have been defined through scenarios with increasing level of complexity from Stage 1 with one or two astronauts handling manual or powered tools, over Stage 2 adding a robotic rover especially for scouting activities, Stage 3 including a habitat with suitports and Stage 4 adding an astronaut-driven surface rover. Only Stage 1 and Stage 2 apply to Marseille, Stage 4 was considered optional in the frame of the announcement of opportunities.

- To be able to distinguish and classify the scenarios three main types have been suggested: nominal, off-nominal and comparative scenarios (two preferably identical scenarios where human-human and human-robot collaboration is compared).

The main objective of the nominal Stage 1 scenario is the simulation of a manual sample collection and a comparison between the two analogues to better understand potential issues with low gravity on lunar and Mars surfaces.

Nominal Stage 2 scenarios focus on astronaut – robotic rover interactions using gesture commands for scouting function and sampling assistance.

Nominal Stage 3 scenarios focus on habitat related aspects, suit ingress and egress with respective suitport simulation activities.

Off-nominal Stage 1 scenarios aim at the support of an injured astronaut or dealing with mal-functioning equipment.

Finally the outcome has been displayed in table format as well as "story board"-format which provides a visualisation of simulation sequences at the two analogue sites. The chronological “story board”-format represents a valuable base for the further detailling of scenario design especially with regard to communication challenges within complete mission scenarios.

2.2.3 T2.3 – Infrastructure

Task lead: LSG

Relevant deliverable(s): D2.2 Field Exploration Scenarios Report

In T2.3, future activities on the lunar or Martian surface related to logistics of human activities in space (e.g. the selection of sites for habitations, the construction of habitations, maintenance activities, transport of equipment on the surface, rescue activities) were used to select and define scenarios for the two earth analogue simulation missions planned in MOONWALK (Marseille and Rio Tinto). The outcome of this task were detailed “story boards" for the simulations and became part of *D2.2 Field Exploration Scenarios Report*.

2.3 WP3 - Concept Definition and Architecture

WP lead: SPACE

Objectives: The objectives of WP 3 were to adapt the procedures described in WP 2 based on human factors and dependability analyses, and to develop a detailed operations concept for robot-assisted EVA missions and tasks.

This included the development of detailed technical concepts and designs for the robotic platform, the EVA suit, and new man-machine interface devices, taking into account the results of the human factor studies. Also, a human factors and dependability analyses based on the initial concepts from WP2 was performed.

Within the WP, technical concepts for the following system components were developed:

- Robotic Platform
- EVA Training Suit
- Man Machine Interfaces (integrated with the EVA suit)
- Mission Control Center (MCC)
- Communications
- Field tools

Table 6: WP3 - List of Deliverables

Deliverable Number	Deliverable Description	Lead beneficiary
D3.1	**Human Factors Report and Operations Concept** Presents human factors methodologies and assessments taken into account (and to be considered in the future for design of human-robot EVAs). Further, adapted scenarios and tasks to be evaluated in the field trials are presented.	NTNU
D3.2	**Robotic Platform Design** Presents the technical concept and design of the robotic platform, including design and integration concept of the sample payload box.	DFKI
D3.3	**EVA Suit Design** Presents the technical concept and design for the new EVA training suit that is usable underwater and on land. Further, provides preliminary concepts for integration of astronaut interfaces.	COMEX
D3.4	**Man-Machine Platform Design** Presents the technical concepts and design for the following systems/elements: • Communications (including time delay simulation) • Bio-monitoring • Gesture recognition • EVA displays and MMI • Control Center • Field tools	SPACE
D3.5	**Test Procedures Design** Identifies the different test campaigns and provides preliminary information on the organization and execution of the final field trials. As this document is expected to be continually refined based on updated inputs through the upcoming tasks, it is identified as a **living document**.	COMEX

D3.6	**Interface Control Document** Identifies different MOONWALk components as standalone systems, and defines interfaces between the systems. Details on each interface are provided (as far as possible at this stage of development). As this document is expected to be continually refined based on updated inputs through the upcoming tasks, it is identified as a **living document**.	SPACE
D3.7	**Detailed Hardware Development Plan** Identifies a complete list of hardware items to be developed/procured and integrated in the MOONWALK project. An estimated timeline (development or procurement) for each of these items is further identified as well as a dependency of the hardware components on other items/systems. Further, identified risks with respect to the components are also presented.	DFKI

Short description of work done in each task

The work package was started by a partner meeting in January, where preliminary concepts were discussed along with a division of responsibilities for items/systems which could be considered as shared items between partners. This face to face meeting was followed by a number of teleconferences (between all partners as well as bi-lateral or multi-lateral conferences between the partners affected) to review developments. The project progress meeting in May 2014 served as a milestone to discuss the technical concepts and finalize any open details wherever possible.

2.3.1 T3.1 Human Factors for Safety and Dependability

Task lead: NTNU

In this task, the work focused on adapting the procedures selected in WP2 based on human factors and dependability analyses and to develop a detailed operations concept for robot-assisted EVA missions and tasks. The operations concept and the approach to human factor studies aim to guide and support the detailed technical concepts and designs for the robotic platform, the EVA suit, and new man-machine interface devices to be developed.

The existing practices for addressing human factors for safety and dependability in space projects and new methods and approaches for human dependability that can bolster current approach to human factors and human dependability in projects concept and architecture definition are presented.

The use of prospective Human Reliability Analysis (HRA) to understand the potential for human errors in EVA's with astronaut-robot collaboration and how the HFACS and CRIOP® (Crisis Intervention and Operability Analysis) methods can be applied in a novel way in the Moonwalk project are discussed and proposed.

The approach selected for evaluation of the astronauts versus the astronaut-robot team in terms of performance and psychological impact of work in extreme environments is described. The development of a protocol for collection of the data required for the evaluations, e.g. comparison of the astronauts versus the astronaut-robot team is also outlined here.

Based on several teleconferences and face to face meetings with discussions on the constraints identified in WP 2 the mission scenarios (Story boards from D2.2) were updated.

The work related to test procedure design for the pool tests, control center tests and analogue sites tests are elaborated and presented in D3.5 - Test Procedures Design.

Based on the D 2.2 Field Exploration Scenarios Report, in collaboration with all partners an updated version of the scenarios was developed. The main stages of operational scenarios and the distinction of nominal/off-nominal situations were kept.

In the extended version as part of WP 3 prioritized scenarios with functions were established so that the storyboards became modular and now can be connected as appropriate and needed for the actual simulations either in Subsea Marseilles or in Rio Tinto. That leads to greater flexibility in using the scenarios as guide for the trials.

Especially the workshop in Bristol where the scenarios were thoroughly discussed contributed to an efficient way of collaboratively agreement on contents and focus.

The following tables are the conclusions from WP 3 discussions and the following prioritization of themes derived from the DoW (DFKI, et al. 2013) and the scenario storyboards in (LSG et al. 2014) has been determined:

Prioritized scenario	**Applicable Type**	
Exploration	Type I, Type III	Using gesture control, odometry, video feed-back, HMI buttons
Sampling)	Type I, Type III	Using gesture control, odometry, video feed-back,
Emergency	Type II, Type III	Using gesture control to see whether there are unacceptable positions of the IMU, visual tracking

Figure 2 : Scenario Prioritizion Table

Established function	**Applicable Type**	
Follow-me	Type I, Type II, Type III	Using gesture control, odometry, image processing, HMI buttons
Direct command	Type I, Type II, Type III	Using gesture control, HMI buttons
Documentation (take photos incl. 360° panorama, filming)	Type I, Type II, Type III	Using gesture control, odometry, video feed-back HMI buttons

Figure 3: Established Function Table

2.3.2 T3.2 Robotic Platform

Task lead: DFKI

In this task, a draft concept for the robotic assistant rover was developed. In the MOONWALK simulations, this rover will be a central element of the selected procedures for robot-assisted EVA. Requirements for the operation of the robot and for robot-human interaction in the planned simulations were identified. Based on these requirements, the results of the Human Factor Analysis in T3.1, and the availability of experience and suitable technology at DFKI a design and architecture for the robotic assistant were drafted.

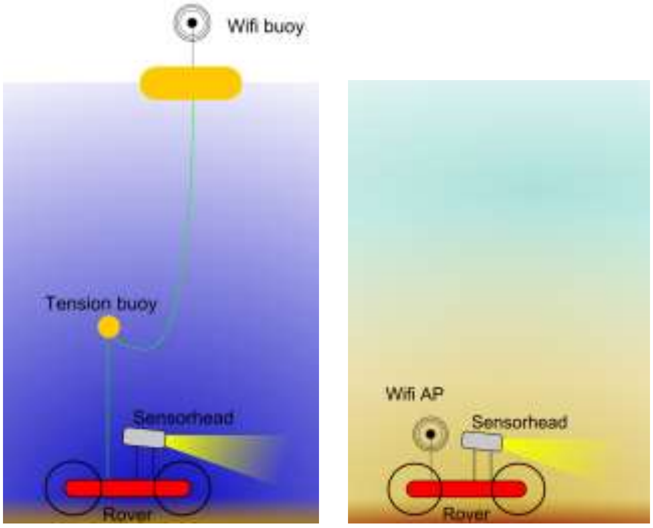


Figure 4: Functional robot concept for UW (left) and terrestrial (right) operation

Based on the analysis of the simulation scenarios developed in WP2, functional and technical requirements for the robotic platform were derived. In order to achieve a solution that can be realized within the time frame and budget of the MOONWALK project, the requirements were matched with the functional capabilities of legacy systems already available at DFKI. However, none of the available system was able to fulfill the functional requirements. It became obvious that in particular for the UW simulations, a new concept and new hardware was necessary.

Figure 5: First robot design concept (right), based on ASGUARD legacy system (left)

Thus the general concept of the well-tested and proven ASGUARD robot family at DFKI was used as the basis for the MOONWALK robot, but modified in a way to accommodate both operation under water and on land. A mechanical and an electronic design concept for the main rover body and the most important sub-systems was developed. A software architecture for the robot was sketched out.

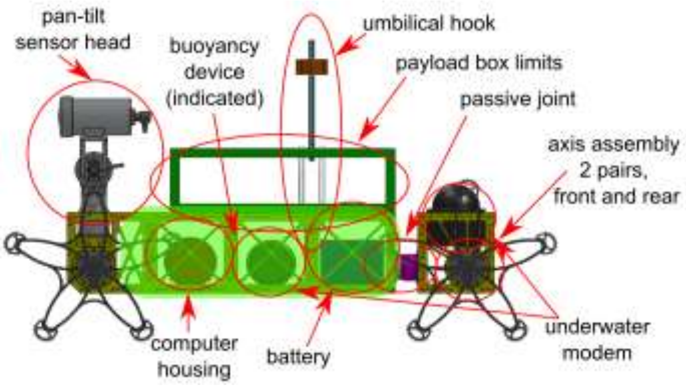


Figure 6: Main sub-components of robot

2.3.3 T3.3 EVA Suit

Task lead: COMEX

This task developed a concept and a design for a new EVA training suit. The design was influenced by previous work and experience of COMEX with the GANDOLFI EVA training suit. However, efforts were made to take also new designs of NASA suits into account. In addition, the concept takes into account the requirements for robot-assisted EVA identified in MOONWALK, the results of human factor analysis, and the operational requirements of the planned Earth Analogue Simulations.

Initial designs of a subsea EVA excursion module have been developed jointly by LSG and COMEX to interface with the EVA suit being developed for trials at Marseilles (subsea) and Rio Tinto. Named LEM (Lunar Excursion Module), this piece of equipment is being designed to meet subsea, land and sea transport, as well as Rio Tinto test requirements. The design is ongoing and currently represents a module similar in appearance to the Apollo lander but substantially reduced in size to meet MOONWALK requirements.

Figure 7: Legacy GANDOLFI suit (left), draft concept for new EVA suit (right)

2.3.4 T3.4 Man Machine Platform

Task lead: SPACE

In this task, technical concepts and designs for the various functionality and systems that fall under the umbrella of the Man Machine Platform were developed and described in Deliverable 3.4. In addition, and Interface Definition was made and a Hardware List and Development Plan compiled.

Technical concepts & designs:

- Communication: The communication system is meant to provide connectivity between all deployed systems, on the field and between field elements and the control center. The required architecture was defined and the appropriate components and technology identified. Further, a mechanism to allow for the simulation of communication delays was defined.
- EVA Human Machine Interfaces (displays and information systems): Building on the initial concept of a heads up display identified in the proposal, concepts for a wrist worn display and

a chest display were defined along with typical usage scenarios for each of the displays. Potential hardware solutions (preferring COTS products where possible) were identified.

- Bio-sensing: After a study of potential sensors and technology, a choice was made to use a COTS heart rate monitor and several criteria to determine stress levels and on-going activity from the sensor were identified.
- IMU Sensing / Gesture Recognition: A concept for human skeleton tracking based on a number of IMU sensors was detailed, and a concept for gesture recognition for rover control using a library of gestures and actions was identified. Interfaces with other systems to enable commanding of the rover and suitable user feedback were also identified.
- EVA Video System: This involved the study of different concepts to provide for a video camera system on the EVA suit to allow the astronaut to capture images and video for documentation purposes as well as the control center to receive visual imagery from the EVA.
- Suit Computer Assembly: It was decided to use a single computer assembly for the execution of the software of the different EVA MMIs to reduce the number of elements required to be worn by the astronaut. For this purpose, the design of a suitable computer system providing the required computing power and interfaces, and complying with environmental requirements of both analogue environments, was carried out.
- Control Centers (Mission Control Center, Habitat Control Center, Remote Science Center): Along with the Mission Control Center, the mission architecture identified the need for to additional control centers – the Habitat Control Center representing a planetary control center to provide real time EVA support in the presence of large time delays, and a Remote Science Center to allow scientists and investigators on earth to access relevant telemetry and science data. It is foreseen for all the control centers to run the same baseline software. Preliminary concepts, including functionality and user interface layouts, and control center architectures were defined.
- Field tools: Based on the EVA scenarios/tasks identified and available tools at partners, a list of field tools to use during the analogue trials was defined, and details of the tools were collected.
- Hand cart: Apart from the tools themselves, the design of a hand cart allowing the EVA astronaut to transport tools and collected samples from the simulated habitat to the field site and back was performed.

Tests to confirm the validity of preliminary concepts were also carried out. This included an on-site communications test at locations in Marseilles identified as potential test sites to verify the availability of telephone networks and confirm the validity of using 4G as the underlying technology communications between field elements and the control center for the field trials to be carried out in Marseilles.

Other tests were performed at the NEMO33 pool in Brussels (a 33m deep specialty pool where training for scuba diving is performed), following ISO standards and rigorous procedures. These tests covered the functionality of underwater data transmission, the functionality of the certain HMI components underwater, water tightness and resistance at water overpressure of certain waterproofing concepts.

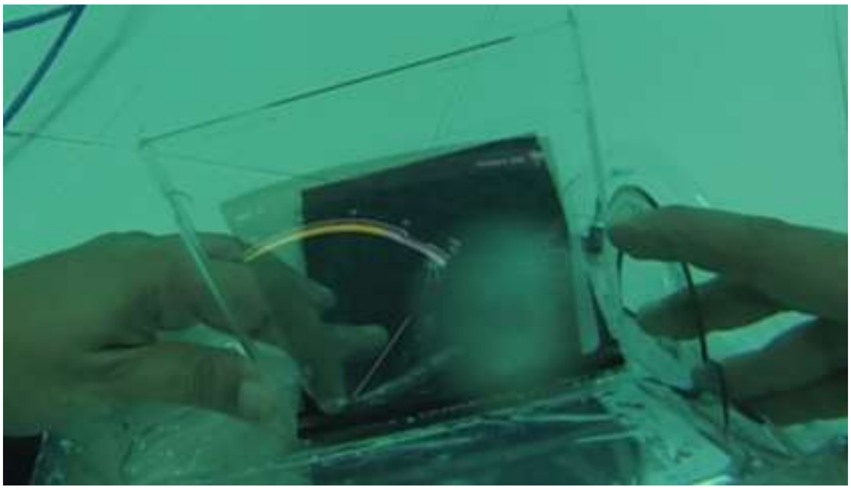


Figure 8: Image from preliminary tests of heads-up display

Interface Definition

This task started with the consolidation of identified functionalities into separate systems (based on the functionality of the systems as well as on the practicality of work division between consortium members).

Based on the identified division, an interface matrix was created and iteratively updated. This matrix, included in D3.6, identified the various interfaces between the systems.

After confirmation of the identified interfaces, details on each interface were collected and consolidated into the deliverable.

Hardware List and Development Plan

Once the development of technical concepts was suitably advanced, a list of all hardware elements was compiled (List of Elements) identifying the status of the item, interfaces to other hardware elements and design/procurement responsibilities.

On the basis of this list, and technical descriptions coming from other tasks, a dependency graph for the different elements was created, and development timelines identifying detailed design, procurement and integration were defined into an overall hardware development plan (D3.7).

2.4 WP4- R&D of Man-Machine Platform

WP lead: SPACE

Objectives:

In WP 4, detailed technical concepts for the system components conceptualized in T3.1 and T3.3 are developed and the systems are implemented. This includes system components for the

- Mission Control Center and communications infrastructure,
- Man Machine Interfaces (integrated with the EVA suit), and
- Rover control (integrated with the EVA suit).

Table 7: WP 4 – List of deliverables

Deliverable Number	Deliverable Description	Lead beneficiary	Deliverable due month	Actual delivery month
D4.1	**Control Center Simulation System Concept** Report on final concept and detailed design of the Control Center, including description of	SPACE	03/2015	04/2015

	communication interfaces implementing simulated time delay.			
D4.2	**Wearable Procedural Display System Concept** Report on final concept and detailed design of the Wearable Procedural Display, including communication with the Control Center.	SPACE	03/2015	04/2015
D4.3	**Control-by-Gesture System Concept** Concept and system specifications for robot control by gesture, based on non-optical movement tracking of the operator.	DFKI	03/2015	05/2015

The work package started in July 2014 and is ongoing until the end of 2015. The work was focused on the design of the Mission Control Centre (and the whole communication architecture between astronauts, rover, relay stations and the Mission Control Centre), the design of a wearable EVA Information System (chest and wrist displays and suit computer assembly), and the design of the rover control-by-gesture.

The EVA Information System has been for the most part integrated with the suit during the integration week mid-September in Marseille and the whole communication system for rover commanding and rover video streaming has been successfully tested from the suit EVA Information System (astronaut commanding the rover) and from the Mission Control Centre in Brussels (ground operator commanding the rover). Some integration tasks remain pertaining the wet setup for astronaut 2 (Suit Computer Assembly 2) and integration of the dry version of the SCAs.

2.4.1 T4.1 Control Centre and Platform Development

Task lead: SPACE

The task continues the development of a Mission Control Center (MCC) for the provision of mission support to the Simulations in Marseilles and Rio Tinto. A detailed definition of the technical architecture for communication between astronaut(s), the robot assistant, relay stations (e.g. buoys, surface vessel) and the MCC was developed. This architecture is able to simulate time delays of various lengths for the simulation of EVA under Lunar (delays in the order of seconds) and Martian conditions (delays in the order of minutes).

In the Mission Control Centre at the ground segment, YAMCS (the main mission control system (developed by SPACE) and the core of the communications architecture) is coupled with other components for archiving and playing video streams from the field segment (astronaut and rover) as well as for sending and displaying tele-commands, telemetries, caution & warning messages, chat messages, etc. In the field segment a Delay Gateway introduces the communication delay between the field segment and ground segment, and another YAMCS server provides the real-time communication (telemetry and tele-commands) between the astronaut and the rover. This “Field YAMCS” will also forward the data to the “Ground YAMCS” for archiving and displaying in the control room with delay implemented. The delay gateway supports the UDP and TCP protocols.

The YAMCS system allows connecting a potential Remote Science Centre (RSC) via a VPN to the MCC in order to allow the MOONWALK components installed at the RSC (which are a ‘out-of-the-box YAMCS’) to connect to our MOONWALK simulation. The MCC can delegate some tasks to the RSC, i.e. communication with the crew in the field, sending rover commands, monitoring all telemetry. Or all tasks can be delegated to the RSC which then effectively becomes a full-fledged control centre. A decision was taken to not be redundant in the development of the GUI functionality that is already present in the wearable procedure display, and reuse a wearable procedure display at the MCC.

Figure 9 Proposed layout of the MCC in the Space Applications Services lab

2.4.2 T4.2 Wearable Procedural Display

Task lead: SPACE

This task continues the development of a wearable EVA Information System to be integrated into the EVA suit. This Human Machine Interface (HMI) is developed with the objective to improve the exchange of information of an astronaut with Mission Control during EVAs. It allows the control of payloads and robots on the planetary surface and improves the situational awareness and autonomy of the extravehicular crew through the implementation of features such as:

- Procedure viewing
- Telemetry and Caution & Warning (C&W) display
- Video streaming delivery (including video from a helmet camera, and scouting robot with an omnidirectional camera)
- Voice loop communications system
- Robot control through push buttons and gestures
- Communications during emergency situations

The procedure viewer will accept procedures in the Operational Data File (ODF) standard used in the International Space Station (ISS). This procedure viewer draws upon experience obtained by SPACE during the MobiPV project, in which a system was launched to and tested on the ISS, for the Intravehicular crew to follow procedures with parallel real time follow-up by operators on the ground.

The telemetry and C&W capability will allow identifying trends in consumables or systems. In the mock-up, such trends will be predefined graphs, with the potential of adding anomalies real time for training or research purposes.

- The video streaming capability allows MCC to view either the rover or the helmet camera feed.

- The voice loop system allows communication between the astronauts and the operators in the MCC.
- The astronaut is able to switch between different sources of control of the robot (MCC, control by HMI displays, or gestures) on the HMI.
- The dedicated emergency communications screen provides very basic communications capabilities in case voice communications are not possible.

The EVA Information System consists of 4 main parts: the chest display, wrist display, heads-up display and the suit computer assembly (SCA).

The chest display is an interactive touchpad that makes use of modern display and interaction capabilities. The touch display hardware and user interface take into account the use of pressurized gloves to operate the display, both from a layout and a mechanical/electrical perspective. The tablet must be placed in front of the astronaut in a way that the display is within the work envelope of the spacesuit, as close as possible to the face of the subject, but allowing enough space for the arms and hands (in their mock pressurized containment) to enter the workspace and interact with the display. Furthermore, for the application in the underwater simulations, it needs to allow a line of sight that is at an angle smaller than the critical angle for the boundary water screen in order not to have full reflection and the consequent lack of visibility of screen contents (in water immersion simulations).

The wrist display is intended mainly to replace the standard US EVA cuff checklist on the spacesuit, using available technologies to add interactive capabilities and improve the available functionality. The display real estate, limited to fit on the wrist/arm of the EVA suit, means that touchscreen based interaction is not expected to be straightforward with the stiffness of the spacesuit glove. This display alternative is based on a screen that serves the sole purpose of displaying the interface, and for the purpose of interaction, an array of mechanical push buttons is in place (a joypad-like interface) that can be either hanging on a retractable tether (allowing two-hand joypad-like interaction), or on one of the wrists.

The heads-up display is to all purposes similar to the wrist display, however, the display is permanently in front of the suited crew, allowing continuous visualization of the most important telemetry and cautions and warnings. Interaction with this version of the HMI is achieved through a joypad-like array of mechanical push buttons.

The Suit Computer Assembly (SCA) is a computer (in a waterproof housing) that does the necessary processing for the Human Machine Interfaces, but also for other potentially required sensors, including the experimental Rover Gesture Control. The SCA connects to the topside via an umbilical, providing external connectivity towards Mission Control. It allows the connection to custom USB and Ethernet (cabled and WiFi) peripherals for specific tests.

There are 2 SCAs, each one with a dry and a wet version. Wet and dry versions share the electronics, but have a different casing. There is an SCA1 dry, SCA1 wet, SCA2 dry and SCA2 wet.

Audio streaming and recording capabilities need to be finished, as well as the video distribution system. A new SCA2 wet hardware case needs to be procured, modified and integrated, and SCA1 wet, SCA1 dry and SCA2 dry need to be wrapped up.

Figure 10 Spacesuit simulator with chest display in stowed configuration and Suit Computer Assembly (dismounted and opened) in the foreground.

Figure 11 Mock-up of one of the tabs of the chest display (Rover or Payload control).

2.4.3 T4.3 EVA suit integrated robot control

Task lead: DFKI

This task developed methods and mechanisms to integrate a robot control into the EVA suit. The main challenge was to develop control devices and/or methods that can handle the serious mobility constraints imposed to the astronaut by wearing a space suit; also regarding additional constraints introduced by the use of the suit and the device under water. The focus of investigation therefore was using motion tracking as a method for robot control (Control-by-gesture). As a backup, non-gesture based methods and devices were evaluated as well.

Figure 12 : Part of the sensor chain used to capture gestures. The depicted sensor string has been cast into epoxy for water-proofness. The smaller image shows the sensor's size.

To capture gestures executed by the user, a string of IMU sensors attached to appropriate positions at the user's upper arm, lower arm and back of the hand were used. Regarding the future underwater use of those sensors and to generally protect the circuitry against humidity, e.g. sweat, the sensors were cast into epoxy and water-tight cables were used for the data connections (Figure 12). The chosen sensors are small and therefore should integrate easily into the EVA.

For testing the usability and ergonomics of the sensor chain when attached to the astronaut, a series of simple tests were conducted. The sensors were attached to a user's arm at the respective places, the movements recorded by them were captured by an embedded system contained within a cardboard box worn at the user's back. The embedded system used was powered by batteries and used a Wi-Fi connection to issue the commands parsed to the robot.

Figure 13: Photograph of general tests conducted with the gesture command interface.

In this setup, the robot could be controlled by the movement of the user's arm: When lifting the arm to a certain height, the robot would get into an "attentive mode", i.e., it would perform a movement corresponding to the subsequent movement the user would then perform. E.g., if the user moves the arm forward, the robot would move forward as well. If the user lowered the arm beyond a certain height, the attention mode would end, the robot no longer reacting to subsequent movements (but continuously performing the last movement) until the user would again trigger the robot's attention by lifting the arm. By raising the arm beyond a certain height, the user was able to stop the robot's movement. An LED strip attached to the robot would light up to indicate its state of attention.

This simple demonstration of the gesture control already worked well, the user was able to control the robot surprisingly precise using this kind of input and didn't encounter any noticeable nuisance caused by wearing the system.

Final integration of the sensors in the EVA suit and testing of complex gesture control algorithms is still outstanding but will be finalized in the first half of the third Review Period.

2.5 WP5 – R&D Robotic Platform

WP lead: DFKI

Objective: The objective of this WP was to develop a robotic system able to support an astronaut in planetary exploration missions. The robotic system had to be light weight, small, and easy to handle with good all-terrain capabilities. For this reason, MOONWALK built on a rover concept developed at DFKI (the ASGUARD rover) which has already been used successfully in the EU FASTER projects and other R&D projects. The main objective of this WP was thus to adapt the ASGUARD concept to the requirements of the Earth Analogue Simulations planned in MOONWALK.

Deliverables: All deliverables were submitted.

Table 8: WP 5 - List of deliverables

Deliverable Number	Deliverable Description	Lead beneficiary	Deliverable due month	Actual Delivery Month

D5.1	Earth-Analogue Test Rover	DFKI	06/2015	09/2015
D5.2	Algorithms for enhanced robot locomotion control	DFKI	10/2015	10/2015
D5.3	Robot Intelligence Concept	DFKI	10/2015	10/2015
D5.4	Robot payload mock-up	LSG	06/2015	07/2015

Short description of work done in each task

The work package started in July 2014 and was finished by the end of RP2 (Sept 2015). Work was focused on the design of a rover (based on the proven ASGUARD concept) and on the implementation of the necessary (limited) robot intelligence and control.

2.5.1 T5.1 - Robot Adaptation to Earth-Analogue Simulation Environments

Task lead: DFKI

This task developed a detailed system design for the robotic helper accompanying the astronaut. The design was based on DFKI legacy systems and the first draft concept developed in WP 3. In the current review period, the detailed technical specification of the rover was initiated taking into account the design draft laid out in D3.2 Robotic Platform Design. The current design is descripted in detail in deliverable 5.1 – Earth analogue test rover. The integrated robot is shown in Figure 1.

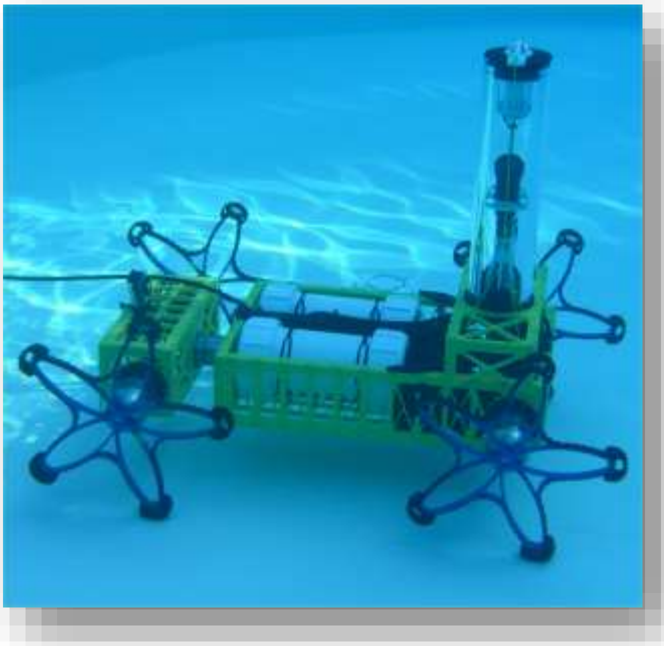


Figure 14: Integrated robot

The rover carries a 360 degree panoramic camera in the front. This allows the robot to track the astronaut independently from their orientation to each other. The electronics are housed in two pressure compartments on the main frame. One contains the main on board computer and the second one houses the battery plus supplementary electronics. We can achieve an uptime from approx. 90 minutes with the current battery capacity available. This time can be extended by shutting down unnecessary power consumers, thus forcing the robot into a standby state. Another option is to use the umbilical for power transmission too. Here the surface buoy may carry additional batteries or the umbilical can be directly plugged into an underwater node for long term observations.

Figure 15 Robot in underwater tests (sea)

The robot has already proven its function during two different trials. First we had the opportunity to travel to Vulcano Island, north of Sicily. There we could successfully test the robot in the open sea and in depth up to 12 meters. An example test drive is pictured in Figure 2. The robot was tele-operated and controlled through the visible umbilical. The operation himself only had the perspective of the panoramic camera available to orientate and navigate on the sea floor. An exemplary snap shot of this view is shown in Figure 3. The robots front faces here to the left. The image shows the sea floor with vegetation and two divers at the surface.

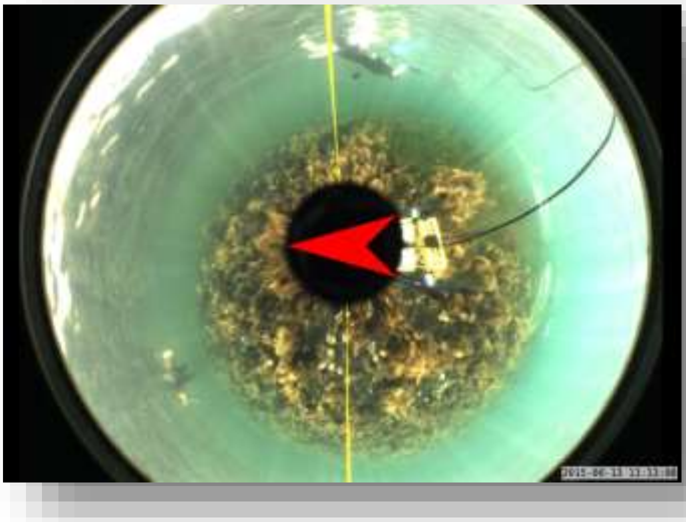


Figure 16 View from the omnicam installed on the robot

The second trial of the rover was the integration week of MOONWALK in September 2015 in Marseilles. Here the rover completed all tasks it was challenged with. Even the direct remote control of the submerged rover from the astronaut in the suit was possible. The trials showed that the astronaut can control the robot directly from underwater.
A detailed description of the rover can be found in “Deliverable 5.1 – Earth Analogue Test Rover”.

2.5.2 T5.2 - Robot Locomotion Control

Task lead: DFKI

This task developed algorithms for a smart locomotion control that dampens or eliminates the rover’s oscillations to allow a smooth and well-controlled movement of the rover and thus eliminate on of the major disadvantages of the leg-wheel design used in ASGUARD. The algorithms will be validated through the low-gravity simulations in Marseille.

The first underwater trials of the rover showed the expected behavior with oscillations and jumps away from the sea floor. Both limited the time a feed had ground contact and therefore the maximum available forward force. The situation of ground contact loss is shown in following figure.

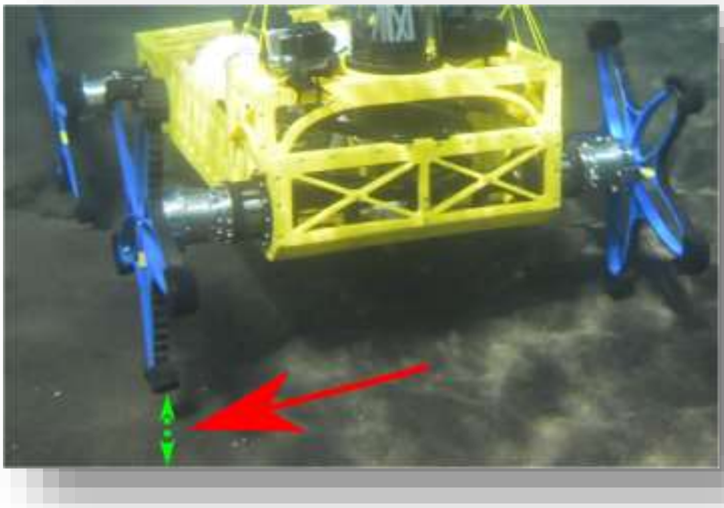


Figure 17 Oscillations of the rover leg-wheel

We could observe during explicit acceleration trials, that the rover behaves normal, when it is accelerated very slowly. In addition the increased weight of 13 kg for the trials in Marseilles 2016 will help to bring the rover back down. We plan further to try out different feedback controllers to reduce the jumps and oscillations during fast drives. The tests for this modifications will be conducted in the DFKI’s test pool after its maintenance has been finished.

This concept is described in detail in “Deliverable D5.2 - Algorithms for enhanced robot locomotion”.

2.5.3 T5.3 - Robot Intelligence and Interaction

Task lead: DFKI

This task developed the interfaces for human-robot interaction and sub-systems for robot autonomy. The robot will not be fully-autonomous, but will feature some semi-autonomous abilities, e.g., it will be able to follow an astronaut, to react to specific commands (e.g. gesture-control), and to assist in simple tasks (e.g. sampling, bio-monitoring). A first concept for gesture-based locomotion control was developed in WP3. As part of T5.2, a number of hands-on tests are planned to evaluate the general and technical feasibility of the concept as soon as possible. This includes investigation in hardware (e.g. IMUs, IMU suits) and an evaluation of the efforts needed to integrate this hardware in the EVA simulation suit.

The main achievement in the reporting period is the definition of a concept for the AI control. The AI control to be developed and integrated in the demonstrations has to enable a number of specific abilities to the system, e.g. make the robot follow the astronaut after he has been recognized in the camera images (if the corresponding mode of operation is set). Above those rather operation specific abilities, the AI also has to maintain the robot system to be responsive and operating in a safe manner at all times. This also includes coping with predictable errors and failures as well as coping with unpredictable situations. To enable the robot to do so, the concept of a hierarchically organized set of running states has been defined. In this concept, every running state or mode of operation that the robot can reach or is able to perform is considered and hierarchically aligned to former and future states (c.f. Figure 1).

I.e., a structure of every reachable state or activated mode of operation (item) is defined, along with the events that allow transition between those items (triggers), the conditions to be met (constraints) and the definition of possible issues or problems that are expected to possibly arise (exit conditions) when such an item is active within the system. This allows the system to possibly cope with problems that may arise during execution, if e.g. something goes wrong or a specific task can't be fulfilled, it can safely traverse along the item structure given for running states to a former or more abstract state, from which it may then try to start the failing task over or perform something else. This prevents the system from reaching undefined states of operation, displaying unwanted or even dangerous behavior or from "hanging" (e.g. in a loop trying to accomplish a task that can't be fulfilled).

For example, if the system is set to "exploration" mode, a sequence of hierarchically arranged items have to be activated: The robot has to build an exploration route corresponding to a given exploration pattern, then, while moving along that route, continuously scan for obstacles, looking for possible samples and eventually picking them up. If anything in this sequence fails for some reason, the system possibly may cope with the problem if it falls back to a former, more generic step (item) in the sequence: If, for example it had located a promising sample but fails to pick it up (thus matching exit conditions or leaving constraints to be met), it may fall back to the former state, which would be scanning for another sample. If it wasn't able to find any, it again moves up one item and continues to move further along the route. If it then detects a (formerly not recognized) obstacle in the way, it may revert to again the prior step, which was building a movement route and so forth.

This way, even if the robot's current task – or, to be more specific in terms of the concept – the conditions to be met for the item activated at the current level of execution can't be accomplished, it may still perform another, possibly more useful action.

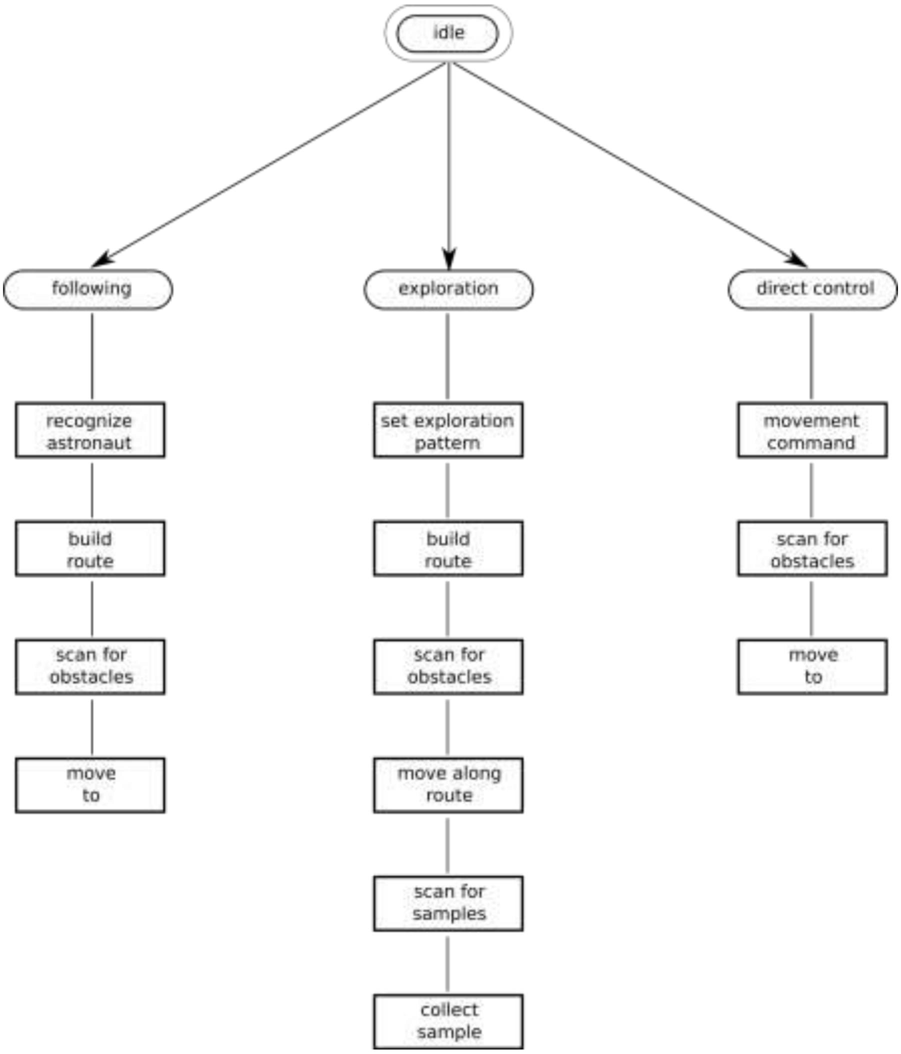


Figure 18 AI safe operation concept

Figure 18 depicts a simplified AI control hierarchy. Starting at an generic "idle" state, entering more specific run levels or executing specific tasks, the state of the control moves along the hierarchy. When something unexpected does happen or the execution of a current task is impeded, the control system can step back in the hierarchy, thus preventing the whole system to be in an undefined state or being "hanging". Note: Due to the simplification of the concept the figure lacks depiction of triggers that enable specific items, conditions to be met within those and conditions that indicate failures

2.5.4 T5.4 - Robot Payload Mock-Up

Task lead: LSG

This task derived a payload mock-up for the robotic rover. The payload mock-up was developed to accommodate all actions defined in the revised scenario selection. The payload mock-up is complemented by the manual tools for EVA developed in T6.4.

The revised robot operational scenarios comprise a range of astronaut-robot interactions of various degrees of complexity involving the use of the following items which will be attached to the rover: Payload Box (PB), Astronaut Rescue Tool (ART), Astronaut Construction Fixture (ACF), Rover Tether Attachment (RTA), RAMAN Spectrometer (RS).

- The Payload Box (PB) is designed as a container attached to the upper surface of the rover for temporary storage of geological samples during field exploration. Bagged samples will be placed in the PB either by hand or using a tong.
- The Astronaut Rescue Tool (ART) is designed as an aid to assist an astronaut to stand-up after falling over. The collapsible support is stored within a segment of the PB.
- The Astronaut Construction Fixture (ACF) is designed to aid an astronaut to construct a simple structure without aid from a second astronaut. It is positioned on the side of the rover.
- The Rover Tether Attachment (RTA) is an element fixed on the rear of the rover for attachment of a tether. The tether shall be used by an astronaut when the rover scouts a steep slope (crater, steep hill etc.) that is too difficult or dangerous for human exploration. The other end of the tether will be hand-held by the astronaut who may be secured by an attachment to a support structure.
- The Raman Spectrometer (RS) is a rover payload designed to use Raman spectroscopy to simultaneously distinguish signals of organic and inorganic materials in heterogeneous samples. It consists of a probe attached on the front end of the rover that is connected by a fibre optical cable to the electronics and battery box on the top of the rover.

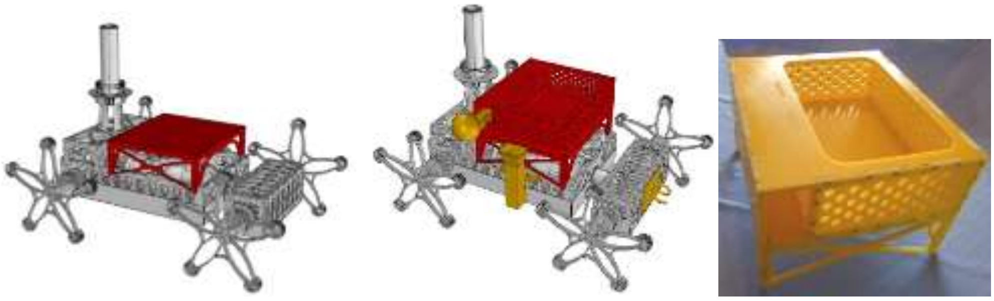


Figure 19: Raman spectrometer RS platform (left), Payload Box PB with Astronaut Rescue Tool ART, Astronaut Construction Fixture ACF, Rover Tether Attachment RTA (middle), Payload Box mock-up (right)

2.6 WP6 – R&D EVA Suit

WP lead: COMEX

Objectives: WP6 develops a novel design for an EVA training suit that can be used both for the (terrestrial) simulations at Rio Tinto and the (underwater) simulations in Marseille. A first EVA suit is available to the project ("GANDOLFI" development by COMEX) and the fabrication of a new second suit will allow to include novel devices, such as the HMI for robot control and means for communication/visualization. Together with the already existing suit, the new suit will also allow to perform simulations with two astronauts.

The development of the novel EVA suit is based on the concepts that were defined in D3.3 “EVA Suit Design”. The WP 6 started on month 10 and was finished month 24. The aims of this WP were to build the new EVA suit that includes innovative devices such as the robot control (gesture), man-machine interfaces and bio-monitoring.

Table 9: WP6 - List of deliverables

Deliverable Number	Deliverable Description	Lead beneficiary
D6.1	EVA Suit Concept	2- COMEX SA
D6.2	EVA Suit Prototype	2- COMEX SA
D6.3	Biomonitoring Manual	3- EADS

2.6.2 T6.1 – Suit Fabrication

Task lead: COMEX

The EVA training suit is now completed as shown on Figure 1 and incorporates:

- an exoskeleton made of hard and soft parts
- a diving gear for the astronaut diver for the underwater configuration

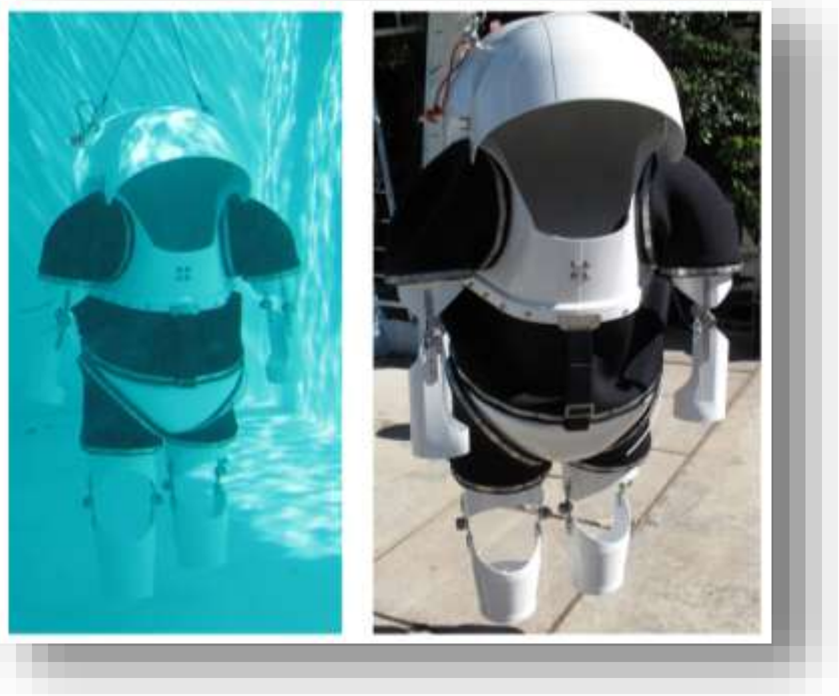


Figure 20: Prototype of the novel EVA training suit (Left) during first immersion at Comex (Right) Dry configuration before immersion

The exoskeleton design has three main drivers:

- Take into account ergonomics aspects of the Z-1 suit (NASA input to MOONWALK)
- Simulate constraints of movements as in a real pressurized space suit
- Put the astronaut/diver into neutral buoyancy (or reduced gravity), this function is only available in underwater configuration

This new training suit is based on the same architecture and anthropometric capabilities of the NASA Z-series spacesuits prototypes and includes a rear entry system as the Russian ORLAN suit.

As shown in Figure 20, the exoskeleton is composed of hard shells:

- Fiberglass composite parts : the pelvis, the 2X forearm, the 2X arm, the 2 X thighs, the 2 X legs, the backpack
- Carbon fiber composite: the helmet and the torso

The use of composite materials enables a significant weight gain compared to standard metal materials with a high mechanical resistance. Those parts are linked with neoprene parts.

The second major hard elements are the bearings (Figure 2) allowing rotations of the different limbs, whom rings are made of POM and ball made of 316L steel (AISI standard).The bearings location is directly inspired by the Z1 series American spacesuit to allow rotations of shoulders, arms, thighs and pelvis.

These hard parts are linked through soft neoprene parts, tailored-made manufactured by Beuchat company, fixed on bearings.

Figure 21: (Left) Shoulder ball bearing on the torso (Central) Torsion spring located on an elbow mounted on the arm assembly through adjustable tabs, the arm ball bearing is visible (Right) Neoprene soft part fixed on the arm ball bearing with clamp and screws

In order to simulate the movement-constraints caused by the use of a pressurized spacesuit, on one hand, the movement amplitudes of the novel training suit have been limited by the design itself and comply with the Z1 spacesuit movement constraint specifications.

In addition, a mechanical resistance was induced on the joint locations. The joint elements on the leg assemblies, located on the knees, and on the arm assemblies, located on the elbow, have the function of restraining movements by creating a resistant torque. This makes the flexion of the members harder. The joint elements are torsion springs, which are sized to be the closest of the Z1 spacesuit movement resistances.

Astronaut subjects using the novel EVA suit for MOONWALK are limited to the following heights: minimal 160cm to maximal 195cm. To adjust arm lengths and leg lengths, adjustment tabs are located on both elbow and knee joints as shown below. To adjust the torso-pelvis distance, the length strap located on the torso can be changed according to the subject’s height.

The retractable visor is made of PMMA (ALTUGLAS®) and fixed on the helmet authorizing a rotation for allowing it to be used in down or up position (Figure 22).The field of vision has been optimised through the helmet design and the full face mask performance and can theoretically reach 60°. This consideration is of importance for the head up display integration.

Figure 22: (Left) Helmet and visor mounting (Right) Used astronaut-diver’s full face mask

The gloves of the novel suit are almost completed at the edition of this report. The design of the gloves is based on current NASA EVA gloves (Figure 23).

Figure 23: (Left and central) NASA EVA gloves (Right) Ski gloves model used for the outer fabric of training suit gloves

The gloves are manufactured from a neoprene classic diver gloves recovered by the outer fabric of standard ski gloves (Figure 23). A home-made silicon parts are manufactured and stuck on the gloves outer skin in order to make them look like NASA gloves as shown on Figure 25. They will be upgraded to operate the touch screen tablet by integrating conducting wires on the fingers tips.

Figure 24: First iteration of novel training suit gloves

Figure 25: Tests of the gloves prototype in dry conditions on the HMI

2.6.3 T6.2 – HMI Integration

Task lead: COMEX

The task 6.2 is not completed at the edition of this report. The development of the HMI in the new suit was the subject of the D3.4.

As shown on Figure 7, the novel EVA training suit has complex environments and allows versatile uses. The HMI was being developed in order to improve the exchange of information of an astronaut with the mission control during EVAs and the situational awareness and autonomy of the Extravehicular Crew, through features such as procedure viewing, media transfer, telemetry display, video and audio streaming, voice-loop system, robot control through push buttons and gestures, and communications during emergencies.

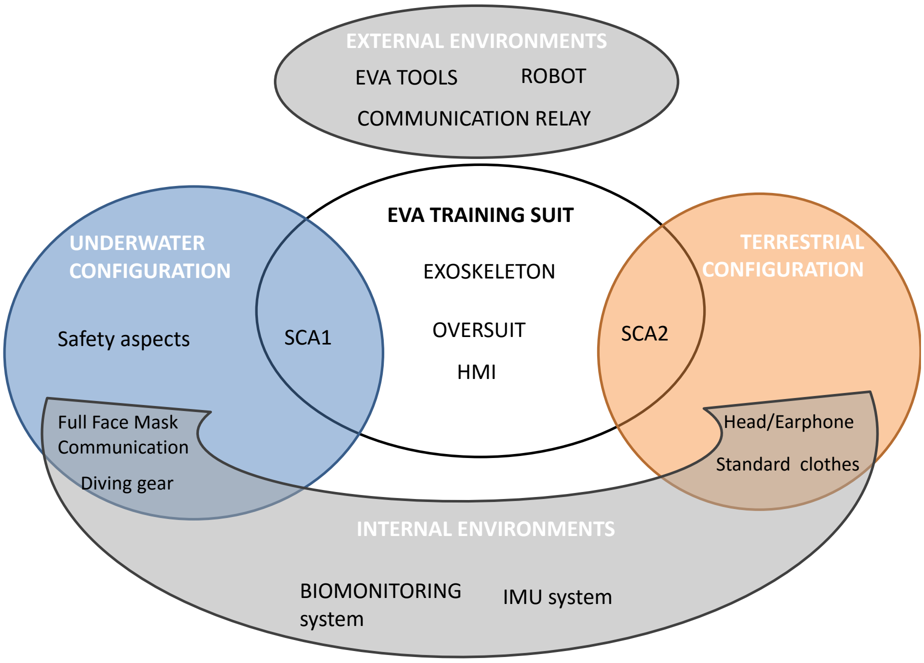


Figure 26: Overview of the novel EVA training suit interacting in the MOONWALK environmental framework

The HMI has 3 possible configurations: a wrist display, a chest display and a heads-up display, which are implemented for a comparability study. A Mission Control Centre is also being created in Brussels, Belgium, to test the HMI and to support EVA simulations.

The wearable HMI (Figure 27) includes a chest tablet which is located on the torso of the suit. The touch-screen of this device is designed to work underwater with specific modification to the simulations gloves that remaining to do at the edition of this report.

The wrist display is intended mainly to replace standard US EVA cuff checklist on the spacesuit. This display alternative is based on a screen that serves the sole purpose of displaying the interface, and an array of mechanical push buttons (a joypad-like interface that can be either hanging on a retractable tether, or on one of the wrist.

The head-up display is similar to all purposes to the wrist display and located in front of the suited crew.

The new Gandolfi suit: Gandolfi 2, has installed on its rear door the Suit Computer Assembly 1 (SCA1). The old Gandolfi suit has installed on its back the Suit Computer Assembly 2 (SCA2).

SCA1 wet has been integrated to the Gandolfi 2 suit. Gandolfi 2 is being modified to accommodate the SCA1 in the dry configuration. SCA2 wet, and the peripherals of the HMI, need to be mechanically integrated to Gandolfi 1, and SCA2 dry needs to be mechanically integrated to Gandolfi 1.

Figure 27: (Left) Overview of HMI system: chest display on the torso, suit computer assembly in the foreground (not installed) (Right) Overview of tested HMI location and fixing on the EVA training suit during integration trials at Comex, 2015

Table 10: Features of SCA1 and SCA2

	SCA1		**SCA2**	
Dry	Dustproof case to be installed on the new Gandolfi Suit	Integration status: 80% compete	Dustproof case as a backpack worn by shirtsleeve test subject	Integration status: 80% complete
Wet	Tubular underwater computer installed on the new Gandolfi suit	Integration status: Complete	Tubular underwater computer installed on the old Gandolfi suit	Integration status: SCA2 to be developed and integrated into the old gandolfi suit (previously foreseen case would leak)

2.6.4 T6.3 – Biomonitoring Integration

Task Lead: Airbus Group

Overall, the past year on Biomonitoring integration has been a challenging but interesting one. Some delays have occurred owing to significant staffing changes, with the primary data scientist leaving the team. Although a replacement has been in post shortly afterwards, there is the natural lower ‘efficiency’ whilst the new team member ‘gets up to speed’ with developments. Having said this, work has been ongoing in this field, and testing of a prototype system began in August 2015.

The underlying principle of the Biomonitoring system is that the astronaut's physiological signs can be monitored to improve the overall picture of their welfare. We intend to achieve this through a couple of systems: the monitoring of the user's heart rate (through traditional beats per minute (BPM) recording); and the assessment of the physiological and mental stresses being experienced by subjects.

The underlying approach used for the system is a machine learning approach, using classifiers to determine, from real life data, what state is being detected. As this is a statistical approach, there is not a requirement to understand the underlying physiological nature of the readings you are gathering, but instead to recognize patterns and behaviours in the underlying data stream and how they relate to previously acquired data.

In order to build this system, it has been required to firstly identify appropriate statistical features, and is a key focus for the research. A clear and well defined set of features will enable a more robust classification system. Prior research on the subject, and the experience of the research team, has focussed on Heart Rate Variability (HRV) as the primary source for these features. HRV is the change in time between each heartbeat, and is affected by physiological and mental stress.

Many of the candidate features are focussed on the frequency domain, understanding the various components that make up the overall 'signal' of the Heart Rate Variability. These features can be fused together, such as ratios between high frequency and low frequency components.

The focus of work this last year has been the identification of appropriate features and beginning to 'train' the classification framework. Test data has been acquired of various subjects in different conditions of physiological and mental stress, alongside a 'ground truth' to represent an indication of the stress levels experienced.

The current prototype system classifies the user's stress into three broad categorisations: Red, Amber, Green. This 'traffic light' system acts as a general indicator, 'Green' being a relaxed, non-stressed state, 'Amber' indicating medium physical and mental stresses, and 'Red' meaning a high level of physical and cognitive loading.

Over the last year, data has been gathered from a few different sources to gain an indication of user stress levels. Aligned with other projects, some data has been gathered and the stress monitoring algorithms tested with Firefighters.

An opportunity also presented itself with Airbus Helicopters to carry out some biomonitoring experiments at their Helicopter Simulator Facility in Aberdeen. This gave the chance to gather biomonitoring data for our algorithms using subjects carrying out simulated activities, which is the focus for the Moonwalk project.

Before the trials are scheduled to take place in the next year, it is the aim to further refine these algorithms, and undertake the formal implementation on the final hardware of the Moonwalk Suit Computer Assembly.

T6.4 – Manual Tools for EVA
Task lead: LSG

This task comprises improvement of existing manual tools and adaptation to accommodate all actions defined in the revised scenario selection. The manual tools for EVA are complemented by the payload mock-up developed in T5.4.

The revised robot operational scenarios comprise a range of astronaut-robot interactions of various degrees of complexity involving the use of the following items which are manually operated by the astronaut: Astronaut Rescue Tool (ART), Astronaut Tether Control (ATC), Pantograph Sampling Tool (PST), Foldable pick-up Claw (FPC), Manual Tool Rack (MTR). All the manual tools aim at safe operation through a single astronaut in cooperation with a robotic rover.

The Astronaut Rescue Tool (ART) for astronaut assistance should he/she fall over is a manual tool which is positioned in a separate compartment of the Payload Box (PB). The collapsible tool is single-handed accessible to the fallen astronaut and can be deployed single-handed by flicking the arm. It is developed from an off-the-shelf walking stick with adapted handle and anti-slip elements along the stick. The Astronaut Tether Control (ATC) is the manual control for the rover scouting a steep slope. ATC is developed from an off-the-shelf retractable dog leash with adapted control buttons and modified handle to fit the astronaut glove. The end of the tether is modified for easy attachment to the rear of the rover.

The Pantograph Sampling Tool (PST) is a retractable sampling tool which can be used single handed to collect samples and feed them into sampling bags. The design is being developed from a lazy tong concept which allows elongation and contraction of the tool arm. It is equipped with a scoop gripper. The Foldable pick-up Claw (FPC) for sample collection is based on an off-the-shelf foldable system. Both collapsible tools can be transported in the payload box of the robotic rover or can be attached to the astronaut suit when feasible. The Manual Tool Rack (MTR) replaces the manual tool cart which was foreseen for (sampling) tool transport in earlier scenario versions. The rack simulates a rack for bigger existing tools (supplied by COMEX), sampling bags and construction material similar to the Lunar Roving Vehicle (LRV) rack. It can also serve as support to secure the Astronaut-rover tether operations with a winch system.

Figure 28: Astronaut Rescue Tool ART (2 left), Astronaut Tether Control ATC (middle), Pantograph Sampling Tool PST (middle right), Manual Tool Rack MTR (right)

2.7 WP 7 – Tests and Simulations

WP lead: COMEX

Objective: The objective of WP7 was to integrate the technical sub-systems (robot, EVA training suit, communication infrastructure and Control Center, bio-monitoring) and perform a first round of intensive tests under lab conditions. For this purpose, the underwater test facilities available in the consortium (at COMEX in Marseille and DFKI in Bremen) were used.

Table 11: WP7 List of deliverables

Deliverable Number	Deliverable Description	Lead beneficiary
D7.1	**Report on EVA pool tests** Report on the trials in pool with the EVA suit based including measurements of quantifiable parameters for the evaluation (e.g. weight at different gravity levels, zone of reachability, ergonomic parameters).	COMEX
D7.2	**Report on Robot pool tests** PP restricted report on Robot pool tests	DFKI

D7.3	**Control Center Test Report** Test report on final lab and integration tests of the Control Centre, including results from an end to end dry run of the control centre system	SPACE

2.7.3 T 7.1 Pool Test EVA Suit including HMI and Biomonitoring

Task Lead: COMEX

Prior to the analogue simulations in Rio Tinto and in Marseille, the systems were integrated and tested in the pool on the premises of COMEX. A total of four integration weeks and pool tests were performed, each with a different objective and involvement of partners (see Figure 29).

Three tests were run in the current reporting period, in December 2015, January 2016 and February 2016. The test in January 2017 was a dry test in which an astronaut was wearing the EVA suit over an extended period of time.

For a detailed description of the pool tests, please refer to D7.1.

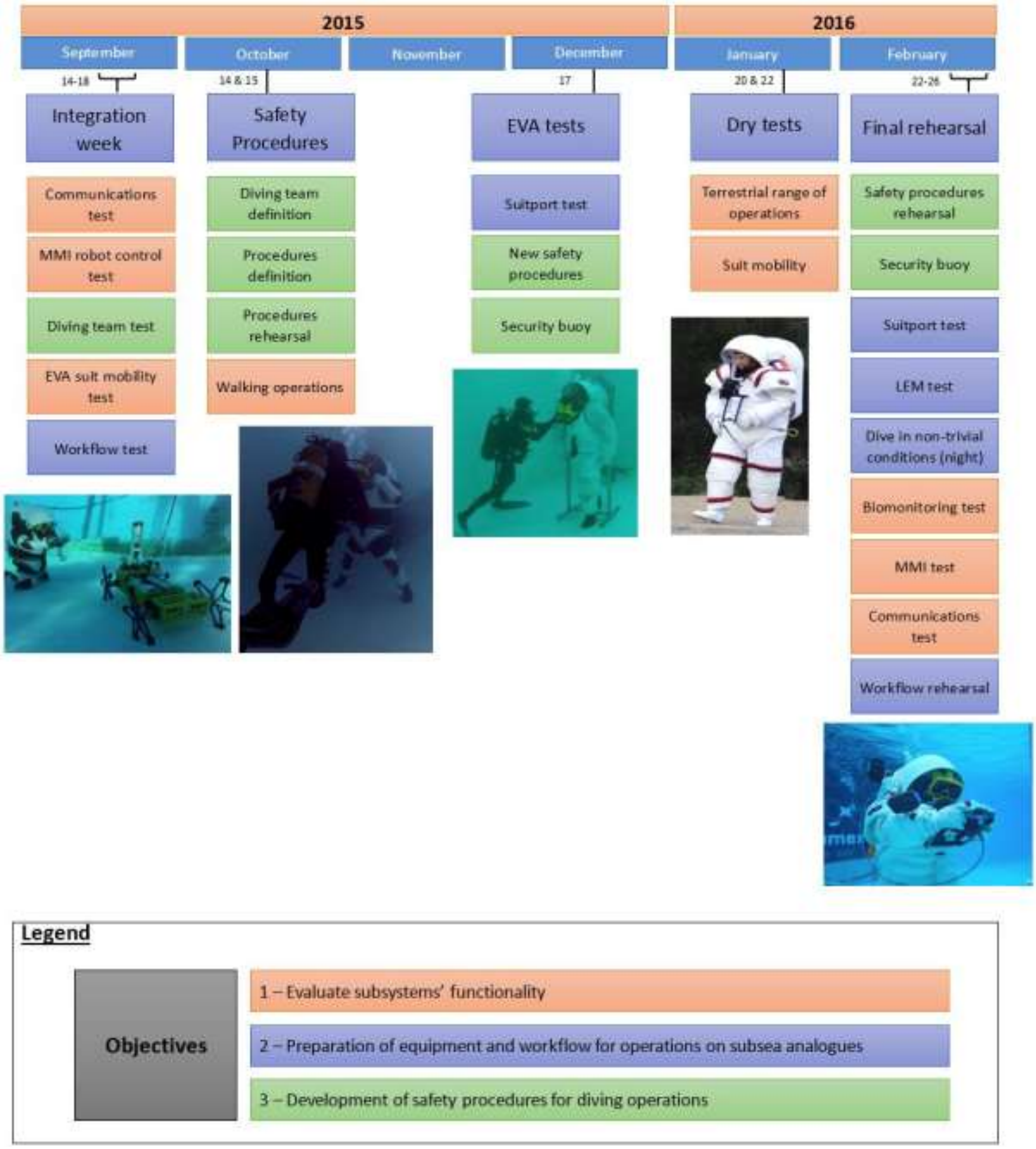


Figure 29 : Set-up of Marseille pool tests

Gandolfi II test results (December 2015, January + February 2016): The Gandolfi II suit was tested during all three simulations in 2015 and 2016. In the first pool test in December 2015, the focus was on testing the suitport, safety procedures and the safety buoy. Results indicated that the egress / ingress into the suitport was still a challenge.

This could be fixed and after some changes to the equipment and more training of the team, both the egress from the suitport and the ingress to the suitport worked fine in the pool tests in February 2016. Nevertheless, handling the MMI wired to the surface still poses a challenge to the astronauts and security divers. It was possible to successfully repeat a number of quick ingress/egress operations, which was an important pre-requisite for the sub-sea off-coast simulations.

With respect to the usability of Gandolfi II for terrestrial simulations, the results of the dry test in January 2016 indicated that the suit should not be used longer than 30 minutes, even by a young and sportive simulation astronaut. Thus the planned EVAs have to be no longer than 30 minutes, or several astronauts have to take turns in one EVA, changing the suit in between.

Even though a longer EVA could be performed, the 30 min limit was set for reasons of comfort and to reduce the risk of an accident due to too much strain on the astronaut. These were important findings that had to be taken into account in the planning of the EVAs for Rio Tinto.

Figure 30: Astronaut-diver evolving in lunar gravity during a night dive

Bio-Monitoring system: The software and hardware elements of the bio-monitoring system were integrated with the suit and the SCA. Tests in February 2016 were successful and the bio-monitoring equipment worked as expected. Some aspects of the system, however, were not fully integrated yet and could not be completely tested (e.g. the networking interfaces between the bio-monitoring software and the MCC).

Man-Machine Interfaces: The communication system and MMI were tested during the February tests. This included extensive voice communications tests. Communications between the test subject in water immersion and Mission Control were successfully achieved. A communication infrastructure consisting of Field Control Centre (FCC), the mission control centre (MCC), and EV1 (the astronaut) with SCA1 (the communication box in the suit) was tested. Neither the Remote Science Center (RSC) nor EV2 and SCA2 were included in the tests. Due to a hardware malfunction that could not be repaired during the test period, the Rover and Rover Emergency Control could also not be included in the communication test.

2.7.4 T 7.2 Pool-tests Robot + EVA Suit

Task Lead: DFKI

DFKI performed tests of the underwater robot in the Maritime Exploration Facility in Bremen before the robot was sent for the integration week and the second round of pool tests to Marseille. In addition, the robot was tested in an open-sea environment during an excursion to the Italian Island of Volcano in June 2015 (reported already in the Second Progress Report). The tests proved the general functionality of the robot in an underwater environment. This included the on-board parts of the communication system and the omnicam camera system.

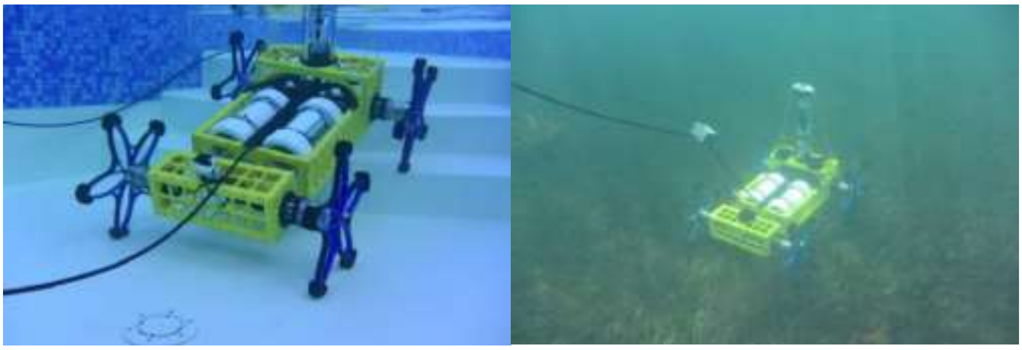


Figure 31: Pool-tests and sea-test on Vulcano

Further tests in conjunction with the EVA suit were done during the integration week in Marseille in September 2015 (see second Progress Report).

These were complemented by a second round of tests in Marseille in February 2016. Unfortunately, due to unexpected hardware failures that could not be repaired on-site, this second round of tests was not fully successful. Some tests, in particular of the integration of the robot in the communications and command infrastructure, could not be performed as planned. Other tests, like tests of the sensors under water and the testing and calibration of machine vision algorithms worked fine.

For more information on the robot testing, please refer to D7.2

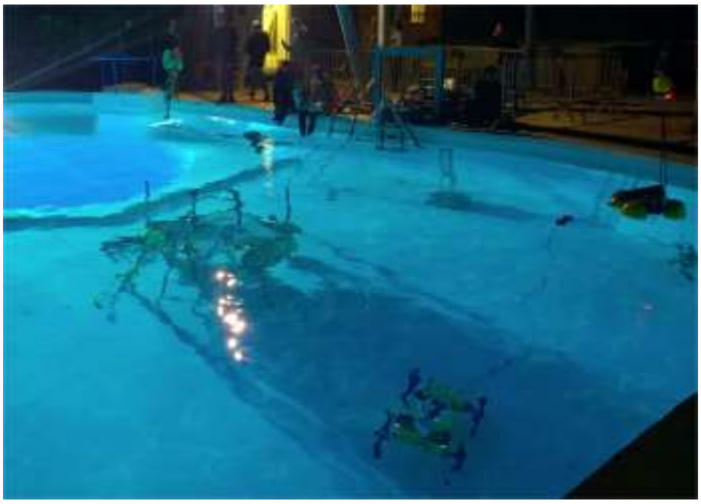


Figure 32: Robot in the COMEX pool, February 2016

2.7.5 T7.3 – Lab-tests Control Center

Task Lead: SPACE

Prior to the underwater tests in Marseille, the functionality of the control center and communication links was extensively lab-tested in the lab at the premises of SPACE in Brussels. During the first integration week in Marseille, these tests were continued and proved that the robot in the COMEX pool can be successfully controlled via satellite link from the MCC in Brussels. The tests were continued during the second round of pool tests in February 2016, but due to the hardware failures mentioned above, a high level of integration with the robotic system could not be reached as planned.

Details of the Communication System testing can be found in D7.3

Figure 33: Mission control center in Brussels

2.8 WP 8 – Analogue Simulations

WP lead: INTA

Objective: The objective of WP 8 was to organize two simulation campaigns, in Rio Tinto and in Marseille, to test and validate the technical concepts, the equipment and the EVA procedures for future missions to Moon and Mars developed in the project.

The planning of the simulations was initiated in the fall of 2015. Initially it was planned to first organize the lunar simulation in Marseille, followed by the Mars simulation in Rio Tinto. Given the overall planning of the project, the availability of equipment and staff, and the expected weather conditions, two suitable time slots in May and June 2016 were identified. However, because there is a risk of high winds and rough seas in May in Marseille, the sequence of simulations was reversed, with the terrestrial simulation first, followed by the underwater simulation.

This change of plan was a good decision as the weather conditions Marseille were indeed much better in June than in May. In addition, the terrestrial simulations proved to be a better platform to test technical equipment and identify technical shortcomings than the underwater simulations.

A detailed description of the simulations, including a description of the test plans and the simulation results, is provided in D8.1 and D8.2.

Table 12: WP 8 - List of deliverables

Deliverable Number	Deliverable Description	Lead beneficiary
D8.1	**Report on Marseilles Analogue Simulations** Report on the trials in open sea with the two EVA suits in different configurations (robot-astronaut, astronaut-astronaut, robot-astronaut-astronaut).	COMEX
D8.2	**Report on Rio Tinto Analogue Simulations** Report and evaluation of the Rio Tinto earth-analogue simulations.	INTA

Short description of work done in each task

3.2.1 T8.1 – Experimentation plan and procedures preparation

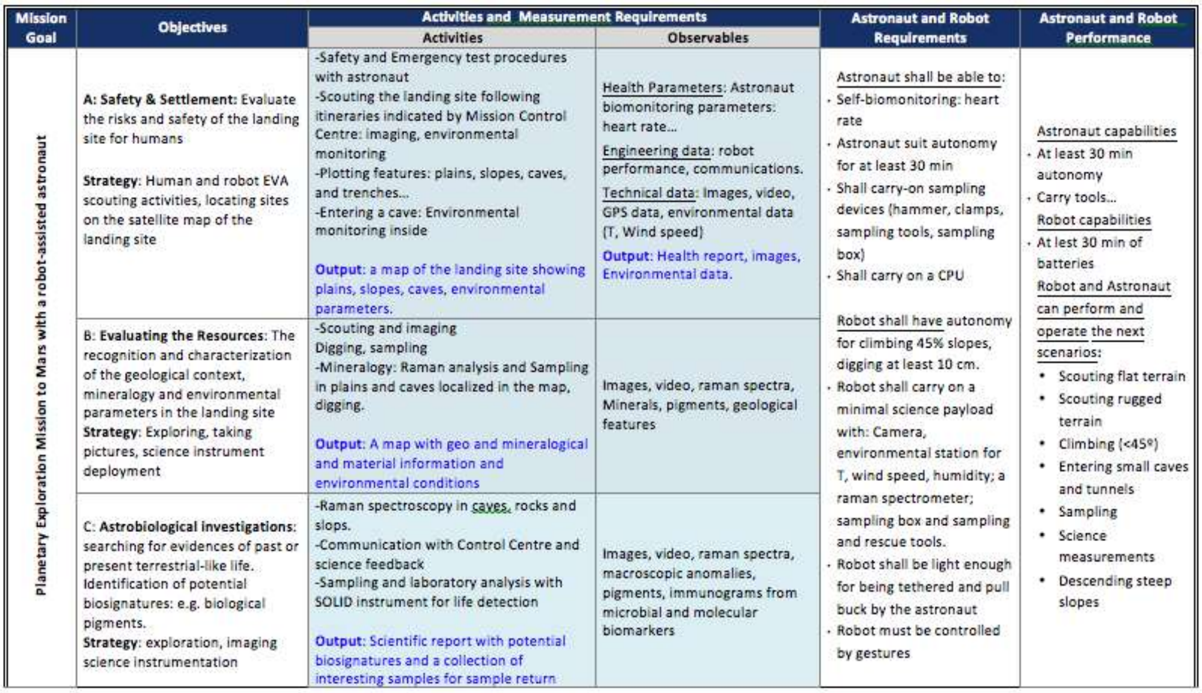
Task lead: INTA

This task, led by INTA but with strong contribution of several partners, in particular COMEX and LSG, had a focus on the preparation of detailed operation plans and procedures for the two analogue missions.

A detailed description of the planning for the Rio Tinto and the Marseille simulations can be found in D8.2 and D8.1, respectively. Operation procedures for Rio Tinto are listed in Annex II of D8.2.

The planning was focused to fulfil the requirements on the science traceability matrix that summarizes the objectives, the measurable parameters and the requirements and expected performance of the different systems and subsystems developed in MOONWALK.

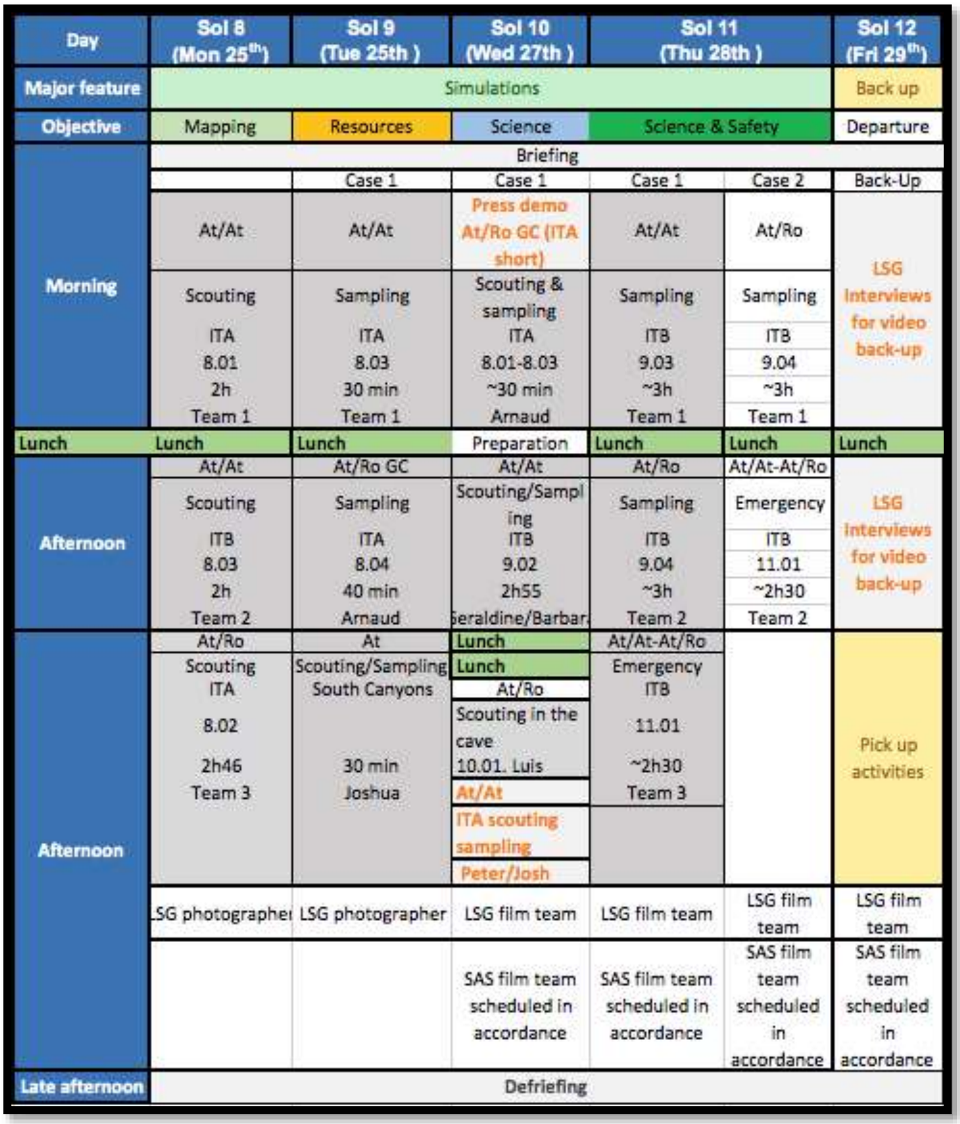
Table 13: Science traceability matrix (Rio Tinto)



Mission Goal	Objectives	Activities and Measurement Requirements		Astronaut and Robot Requirements	Astronaut and Robot Performance
		Activities	Observables		
Planetary Exploration Mission to Mars with a robot-assisted astronaut	**A: Safety & Settlement:** Evaluate the risks and safety of the landing site for humans **Strategy**: Human and robot EVA scouting activities, locating sites on the satellite map of the landing site	-Safety and Emergency test procedures with astronaut -Scouting the landing site following itineraries indicated by Mission Control Centre: imaging, environmental monitoring -Plotting features: plains, slopes, caves, and trenches... -Entering a cave: Environmental monitoring inside **Output**: a map of the landing site showing plains, slopes, caves, environmental parameters.	Health Parameters: Astronaut biomonitoring parameters: heart rate... Engineering data: robot performance, communications. Technical data: Images, video, GPS data, environmental data (T, Wind speed) **Output**: Health report, images, Environmental data.	Astronaut shall be able to: · Self-biomonitoring: heart rate · Astronaut suit autonomy for at least 30 min · Shall carry-on sampling devices (hammer, clamps, sampling tools, sampling box) · Shall carry on a CPU Robot shall have autonomy for climbing 45% slopes, digging at least 10 cm. · Robot shall carry on a minimal science payload with: Camera, environmental station for T, wind speed, humidity; a raman spectrometer; sampling box and sampling and rescue tools. · Robot shall be light enough for being tethered and pull buck by the astronaut · Robot must be controlled by gestures	Astronaut capabilities · At least 30 min autonomy · Carry tools... Robot capabilities · At lest 30 min of batteries Robot and Astronaut can perform and operate the next scenarios: • Scouting flat terrain • Scouting rugged terrain • Climbing (<45º) • Entering small caves and tunnels • Sampling • Science measurements • Descending steep slopes
	B: **Evaluating the Resources**: The recognition and characterization of the geological context, mineralogy and environmental parameters in the landing site **Strategy**: Exploring, taking pictures, science instrument deployment	-Scouting and imaging Digging, sampling -Mineralogy: Raman analysis and Sampling in plains and caves localized in the map, digging. **Output**: A map with geo and mineralogical and material information and environmental conditions	Images, video, raman spectra, Minerals, pigments, geological features		
	C: **Astrobiological investigations**: searching for evidences of past or present terrestrial-like life. Identification of potential biosignatures: e.g. biological pigments. **Strategy**: exploration, imaging science instrumentation	-Raman spectroscopy in caves, rocks and slops. -Communication with Control Centre and science feedback -Sampling and laboratory analysis with SOLID instrument for life detection **Output**: Scientific report with potential biosignatures and a collection of interesting samples for sample return	Images, video, raman spectra, macroscopic anomalies, pigments, immunograms from microbial and molecular biomarkers		

The planning for the simulations comprised of

- **Mission Plan (MP)**. The MP captures the basic planning approach in terms of scheduling and activity allocation. It was a coarse approach and underwent several iterations during the pre-mission planning process, serving as the underlying structure for the AP.
- **Activity Plan (AP).** The AP was the detailed plan for each day of the actual mission. It scheduled field activities based upon a 1-3 h roster for each field crewmember, associated resources, and other information.
- **Test Plan (TP).** The TP contains a detailed list of the different type of tests and measures that need to be done to carry out the activities on the plan.
- **Operation procedures (OP).** The OP describes step by step how to proceed to achieve the objectives planned in the AP. The OP describes the order of execution of the different tests to fulfil the AP (see Annex II of D8.2). The format of the OP followed a standard format used by NASA. During the EVA, the procedures were displayed to the simulation astronauts through the HMI (chest-mounted display).



Day	Sol 8 (Mon 25th)	Sol 9 (Tue 25th)	Sol 10 (Wed 27th)	Sol 11 (Thu 28th)		Sol 12 (Fri 29th)
Major feature	Simulations					Back up
Objective	Mapping	Resources	Science	Science & Safety		Departure
Morning	Briefing					
		Case 1	Case 1	Case 1	Case 2	Back-Up
	At/At	At/At	Press demo At/Ro GC (ITA short)	At/At	At/Ro	LSG Interviews for video back-up
	Scouting ITA 8.01 2h Team 1	Sampling ITA 8.03 30 min Team 1	Scouting & sampling ITA 8.01-8.03 ~30 min Arnaud	Sampling ITB 9.03 ~3h Team 1	Sampling ITB 9.04 ~3h Team 1	
Lunch	Lunch	Lunch	Preparation	Lunch	Lunch	Lunch
Afternoon	At/At	At/Ro GC	At/At	At/Ro	At/At-At/Ro	LSG Interviews for video back-up
	Scouting ITB 8.03 2h Team 2	Sampling ITA 8.04 40 min Arnaud	Scouting/Sampling ITB 9.02 2h55 eraldine/Barbar	Sampling ITB 9.04 ~3h Team 2	Emergency ITB 11.01 ~2h30 Team 2	
Afternoon	At/Ro	At	Lunch	At/At-At/Ro		Pick up activities
	Scouting ITA 8.02 2h46 Team 3	Scouting/Sampling South Canyons 30 min Joshua	Lunch At/Ro Scouting in the cave 10.01. Luis At/At ITA scouting sampling Peter/Josh	Emergency ITB 11.01 ~2h30 Team 3		
	SG photographe	LSG photographer	LSG film team	LSG film team	LSG film team	LSG film team
			SAS film team scheduled in accordance	SAS film team scheduled in accordance	SAS film team scheduled in accordance	SAS film team scheduled in accordance
Late afternoon	Defriefing					

Figure 34: Example of Activity Plan (AP) for Rio Tinto simulation

Table 14: Exerpt from a Rio Tinto Test Plan (TP) – for astrobiological sampling

Test No	Tested elements or actions	Verification
1	Install the SHEE	Check and test
2	Verify SHEE sealing	Check pressure, etc
3	Ingress and egress the SHEE	
4	AS health. Biomonitoring parameters	
5	EVA suit status and equipment	
6	Docked to suitport	Check and test
7	RS1 suit ingress	
8	Voice communication	Communications to BCC and LCC
9	Chest display	Procedure and map visualization
10	Wrist display	Screen set

11	Video camera	
12	Bio-monitoring	Check health parameters
13	TM data	Data transmission to LCC
14	Sampling marker flags (10x)	Check and count
15	Suit computer	Display map
16	HMI tool	Communicate with Ro
17	Communication delay	Communications to BCC and LCC
18	Check terrain by AS	Visual inspection
19	AS stress level	Check health parameters
20	Identification of RRS and RSS	AS training on Geology and biology
…	…	
51	Life detection experiment in the lab…	SOLID experiment

For each simulation, an organizational structure was developed, assigning specific persons to specific tasks and organizing the support teams for the MOONWALK technical components (see Figure 35 as an example for the Rio Tinto simulation)

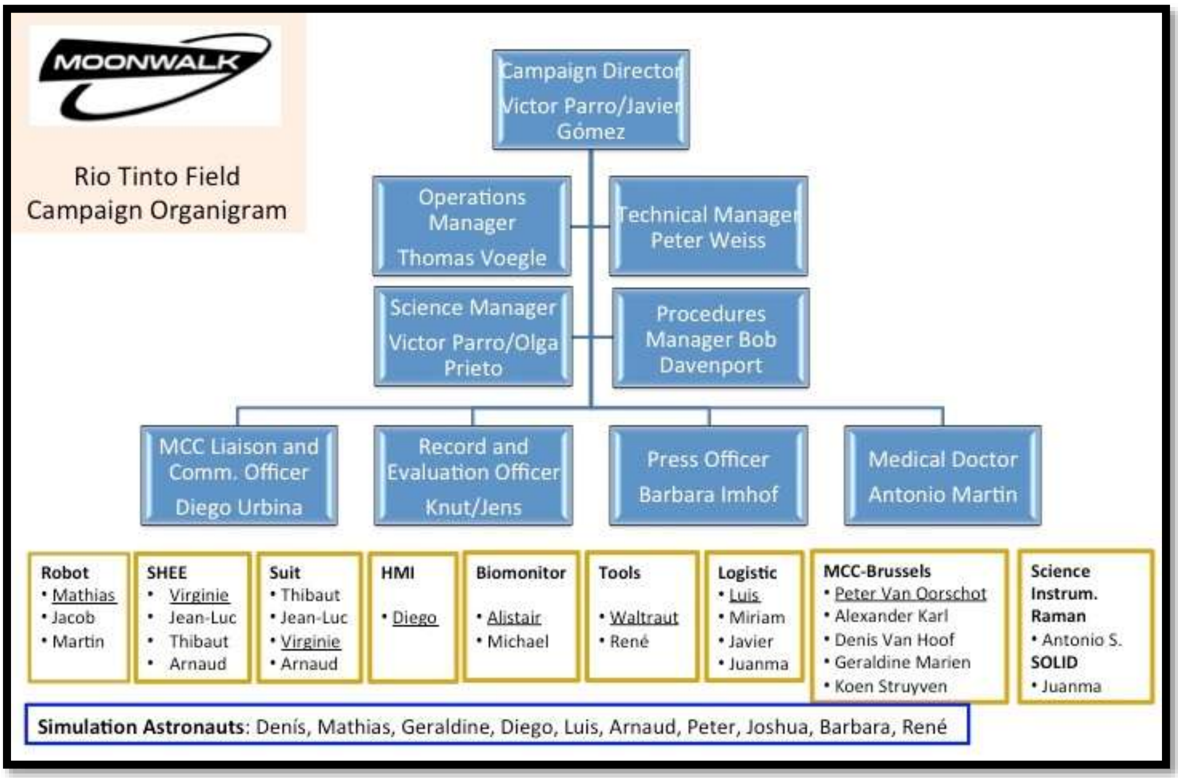


Figure 35: Assignment of responsibilities for Rio Tinto Simulation

3.2.2 T8.2 Moon simulation (Subsea Marseille)

Task lead: COMEX

The objective of this task was to organize and conduct a lunar analogue simulation underwater, off the coast of Marseille, France. The objective of the simulation was to validate the MOONWALK technology for human-robot interaction under low-gravity (1/6 G) conditions, as well as to demonstrate and evaluate the technology and infrastructure, and the performance of a hybrid astronaut-robot team in a natural, EVA-like outdoor environment.

A detailed description of the Marseille simulation can be found in D8.1.

Nine potential lunar analogue sites were identified in an area near Marseilles, in the Calanques National Park. They were selected mainly for their geomorphological similarity with some interesting spots on the lunar surface.

Among those sites Port de Pomègues was been selected for the MOONWALK lunar surface EVA simulations because it hosts several geological features of interest (a crater-like structure with steep slopes), because its exposition to wind is low, and because a preliminary survey on the strength of communication signals showed a good coverage.

Prior to the simulations, the site was explored to identify several sampling and scouting locations, an appropriate spot for the Lunar Exploration Module (LEM) mock-up “landing”, and a slope that could be used to test astronaut/robot collaboration while scouting an uneven terrain.

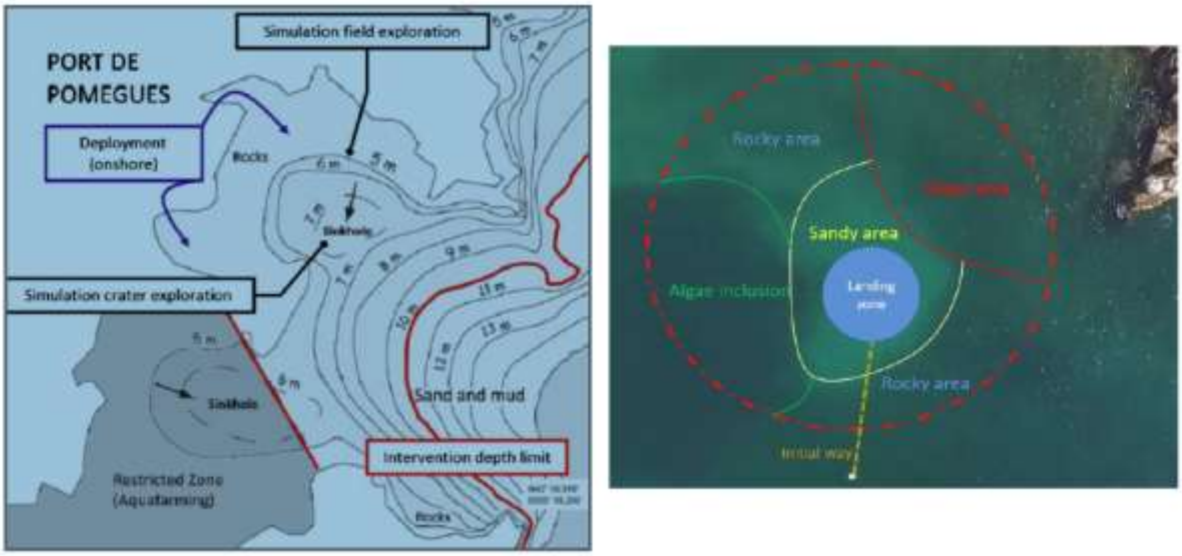


Figure 36: (Right) Moon analogue site selection on the coast of Frioul Island, Marseilles bay [RD1]. (Left) Delimination of the simulation zone with the different areas for scouting and sampling operations.

Because the possible EVA scenarios were limited due to time constraints and the small size of the site, no strict itineraries for the individual EVAs were developed. The simulation-astronaut(s) had to reach the specific areas in a given order, but not following a precise path made of points of interest like it was the case in the Rio Tinto simulations. Unfortunately, due to the algae inclusion, the “crater-like” shape of the sinkhole was occasionally unclear. Similarly, a problem encountered when simulating lunar environment underwater is the changing conditions in the sea in terms of visibility. Even though it strengthens the feeling of evolving in an extreme environment, it is not relevant with regard to lunar environment.

EVA pool trials in preparation of the off-shore simulations were held from May 30th to June 3rd at COMEX. These were necessary for a last integration and test of the equipment and to train the divers who were selected as simulation astronauts (particularly for security procedures rehearsal). Nevertheless, press, a public day and outreach activities were organized as well during this week.

Figure 37: Impressions from the Marseille pool trials before the offshore simulations

The second week from June 6th to June 10th was devoted to the actual subsea analogue simulation. The COMEX research vessel MINIBEX was used to ship crew and equipment to analogue site near the Port de Pomègues. With favourable weather conditions, the simulation proceeded as planned. Only towards the end of the last day, a strong breeze forced the simulation to be stopped prematurely.

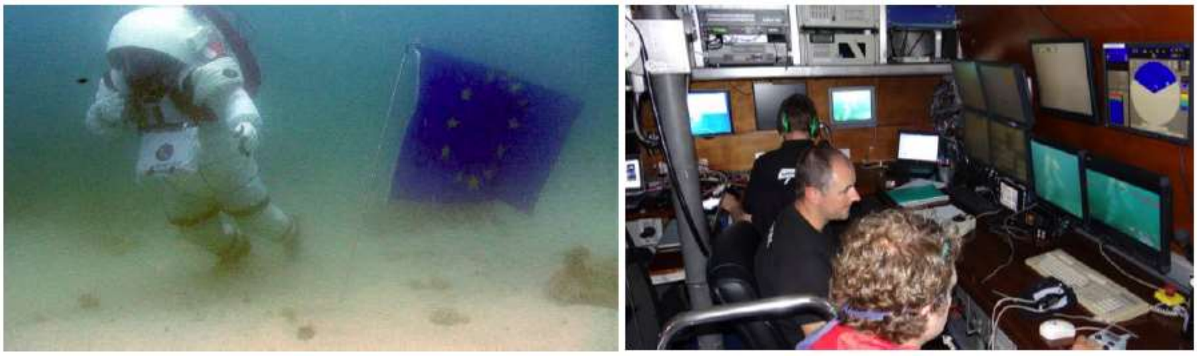


Figure 38: Astronaut in the sub-sea simulations off the coast of Marseille (left), CapCom on-board the MINIBEX (right)

The simulation environment included several elements that were installed on the sea-bed (a Lunar Exploration Module mock-up (LEM), the flag and its pole, sampling tools and scientific payload mockups (ALSEP)) and the robot (deployed beforehand). Both robot and astronaut were linked to buoys on the surface. The buoys functioned as relays for data- and voice communications. A remotely operated vehicle (ROV) was used to monitor the simulations (with video-feed to the MINIBEX).

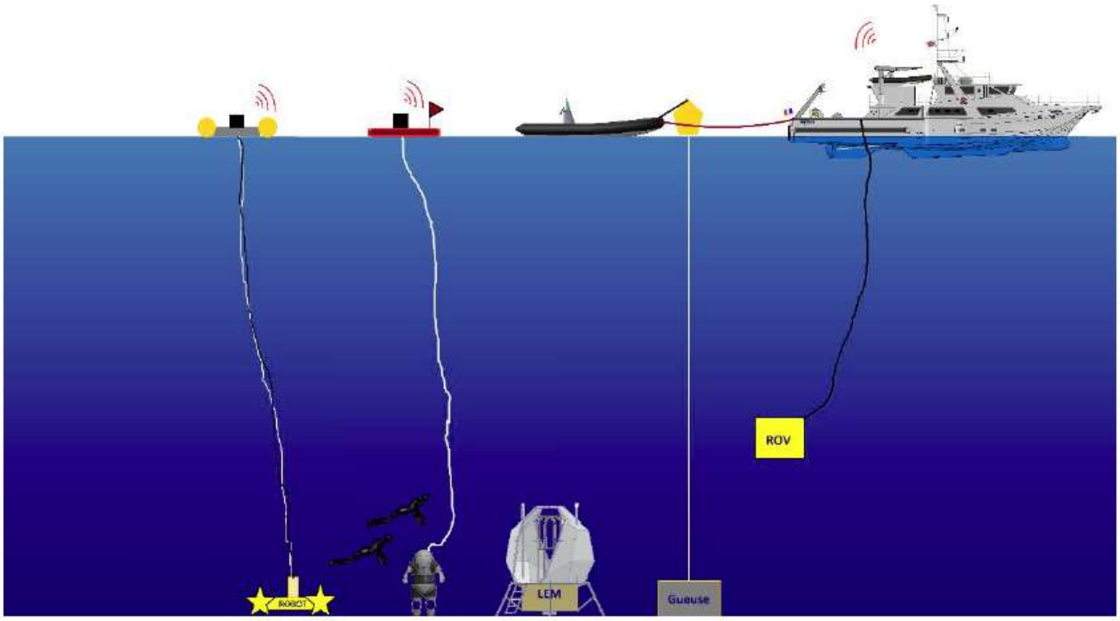


Figure 39: Schematic representation of the Marseille subsea analogue simulation set-up.

Underwater simulations in general and sub-sea simulations in the open sea in particular require specific security measures. During each EVA simulation, a team of experienced safety divers was present. They were trained to give support to the astronauts and rescue them in case of any unforeseen situation. The simulations thus commenced with a rescue exercise, in which the safety divers trained the procedures required to bring an astronaut to the surface in case of an emergency.

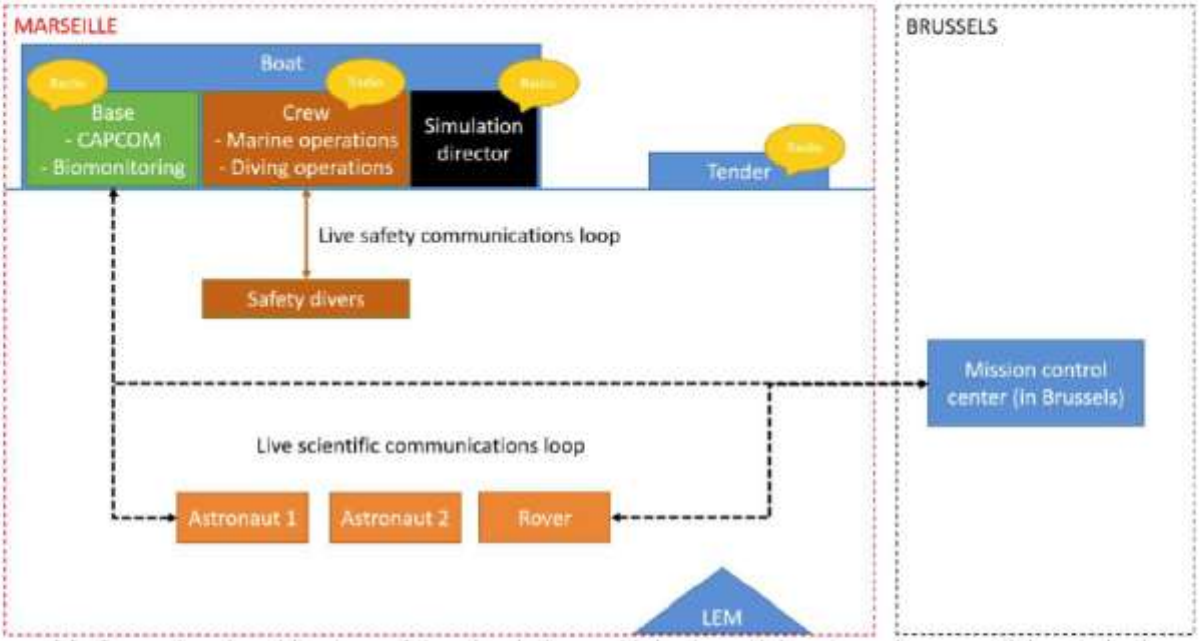
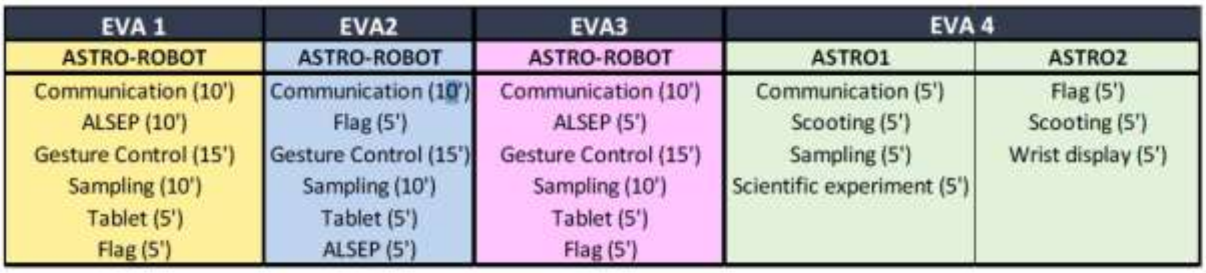


Figure 40: Schematic of distribution of roles during Marseille simulation

With one day needed for set-up and one day for wrap-up, three active days for EVA simulations were available. In addition, an emergency procedure rehearsal under real conditions was performed on the first day. As a result, a total of four EVA simulations could be conducted (according to plan). Three EVAs involved one astronaut in the Gandolfi II suit and the robot for cooperation activities. The last EVA involved two astronauts, with the second astronaut using the Gandolfi I training suit.

The duration of each EVA simulation was around 55 min for Robot/Astronaut cooperation. The Astronaut/Astronaut experiment lasted only 15-20 min due to the weaker autonomy of the Gandolfi I LSS compared to the Gandolfi II.

Table 15: Overview of EVA simulations in Marseille



EVA 1	EVA2	EVA3	EVA 4	
ASTRO-ROBOT	ASTRO-ROBOT	ASTRO-ROBOT	ASTRO1	ASTRO2
Communication (10')	Communication (10')	Communication (10')	Communication (5')	Flag (5')
ALSEP (10')	Flag (5')	ALSEP (5')	Scooting (5')	Scooting (5')
Gesture Control (15')	Gesture Control (15')	Gesture Control (15')	Sampling (5')	Wrist display (5')
Sampling (10')	Sampling (10')	Sampling (10')	Scientific experiment (5')	
Tablet (5')	Tablet (5')	Tablet (5')		
Flag (5')	ALSEP (5')	Flag (5')		

3.2.3 T8.3 Mars simulation (Rio Tinto)

Task lead: INTA

The mars analogue simulation in Rio Tinto was performed during the two weeks between April 16th and April 30th. The location (Las Zarandas), which was identified by a MOONWALK delegation during a scouting trip to the area in November 2015, was located close to the village of Nerva, which was used as a logistics base.

The location is well suited for the simulations because it features several interesting natural features similar to martian features and well-suited to evaluate the technical sub-systems of MOONWALK. This includes

- a large, sandy plain with some small canyons and moderate slopes (EZ_A)
- a dune-area and a small cave-like structure (EZ_B)
- large canyons with steep slopes (EZ_C)
- multiple mineralogical analogies to the Meridiani Planum on Mars

The simulations were organized in two weeks. The first week was devoted to setting up, testing and training all the equipment and procedures. The actual planetary exploration mission simulation wproject as performed during the second week.

From a technical point of view, the main sub-systems that were evaluated during the simulation were the GANDOLFI2 astronaut training suit, the helper robot YEMO, robot-control by gestures (captured through integrated IMU sensors) and other astronaut-mounted devices (e.g. chest-mounted tablet), an EVA information system and direct as well as time-delayed communications, scientific instrumentation for astrobiological investigations, instrumentation for bio-monitoring of the astronaut, and manual tools for sampling of soil and rocks.

Figure 41: Rio Tinto simulation site

In addition to this and to the initial plan described in the DoW, the MOONWALK consortium managed to convince the coordinator of another FP7 funded project, the SHEE project, to make the main outcome of this project, the *Self-Deployable Habitat for Extreme Environments* (SHEE) available for the Rio Tinto simulations. Nevertheless, the deployment of the SHEE habitat, which had to be transported by truck from the International Space University ISU near Straßburg, France, to Rio Tinto required a considerable amount of extra work.

Figure 42: Rio-Tinto simulation set-up, including robot, astronaut and SHEE habitat

By including SHEE in the simulations, it was possible, for the first time in Europe, to perform a fully integrated mission simulation, including donning/doffing of the astronaut, egress/ingress of the astronaut from/to a planetary habitat, and subsequent robot-assisted EVA for the exploration of flat surfaces, canyons, slopes and caves.

An average of 25 persons from the different partners of the MOONWALK consortium participated directly in the different aspects of the campaign. In addition, a medical team consisting of a military doctor, two assistants and an ambulance truck could be organized for the full 2-weeks of simulations.

External experiments: The Announcement for Opportunities and call for external experiments issued before the simulations resulted in numerous proposals for external experiments out of which the following were selected (see also :

- **ADAPA 360** - 360-Degree VR Video Camera System for Space Suit and Helmet. The team of Ali Zareiee, ADAPA, Norway documented the Rio Tinto simulation using the ADAPA 360-Degree Camera.
- **Cave Explorer** - Assessment of performance for the wearable electro-optical diagnostic health assistant system. The team of the Human Spaceflight Department, OHB System AG and the Medical Engineering Department, IMES University of Applied Sciences Würzburg-Schweinfurt) conduceted tests with a new, mobile, digital diagnostic system for medical monitoring astronauts during manned space missions (CAVExplorer 2.0). With electrodes worn on the body of an astronaut and sensor detectors on the earlobe, the CAVExplorer 2.0 measures electrical signals and monitors the health of the heart and circulatory system.
- **SCALE - Shared Cognitive Architecture for Long-term Exploration.** In this project, which was funded by NASA and included contributions from the, a team lead by Dr. Leslie DeChurch (Georgia Tech) and including participants from the NASA Behavioral Health & Performance Department, from Northwestern University and from the Universtiy of Florida, the communications by the EVA crew, the habitat crew and the MCC were logged for analysis by the SCALE team. The goal was to develop new methodologies and technologies to improve shared cognition during space missions. In addition, Mission control was handed over from MCC in Brussels to Georgia Tech / SCALE for the afternoon of the 28th of April 2016 during the Rio Tinto simulations. This demonstrated the capability of involving international teams into the modular MOONWALK simulation architecture.
- **Psychobot - Human Psychological Relationship with a Planetary Exploration Robot.** The team of Yvett Mikola, who is a PhD student at the University of Madrid (UCM) Madrid, Spain, did an empirical survery on the participants of the simulations. The objective of the experiment was to prove the possibility that humans develop an emotional attachment to their robotic "working partners" when interacting with them on a daily basis. To measure the qualitative and quantitative changes in the human-robot teams, four questionnaires were developed to be used with a pre-post method for each simulation astronaut.

NASA involvement: In addition to the SCALE experiment, NASA was involved in the Rio Tinto trials through by a NASA delegate, Matt Deans from NASA Johnson Space Center. He visited the simulation site during the second week and stayed for several days. His role was that of an official NASA observer. Unfortunately the experiment that was initially planned to be contributed by NASA was not possible because of problems raised by the NASA administration.

ESA involvement: ESA was involved in the simulations through by observers from the EAC in Cologne (Dr. Victor de Maria) and by former ESA astronaut, Jean-Francois Clervoy. Both observers stayed for several days during the second week and provided valuable comments to the MOONWALK team about the set-up of the simulations and the usability of the simulation suit and human-machine interface.

The simulation infrastructure set up in Rio Tinto is shown in Figure 43. The infrastructure on-site included the SHEE habitat and three containers, one of which hosted Mission Control Center 1 with the Science Team and the Procedure Manager. The other two were used as workshops for the robot team and the CST. INTA deployed a field-truck as exobiology lab and the medical team was present with a medical truck.

CapCom was installed in the SHEE habitat, which also hosted the suit-port. Thus a very realistic simulation scenario could be established: The astronauts were donned in the SHEE habitat, entering the space suit attached to the suit port from the inside of the habitat. They then rejoined the robot, which was parked in the vicinity of the habitat, and performed the EVA. After the EVA, the astronauts docked to the suit-port and entered the habitat, where the de-briefing took place.

Throughout the EVA, the astronauts were in voice contact with the CapCom in the habitat and sent video- and bio-monitoring data to the CapCom. The robot was also connected to CapCom and the control of the robot was performed by the astronauts via the connection to CapCom. Direct control of the robot from CapCom was also possible.

CapCom was permanently in contact with the MCC in Brussels (and in the US, during the SCALE experiment). This communication link was delayed by 7 min. The on-field mission control center and science team was also hooked up to this connection.

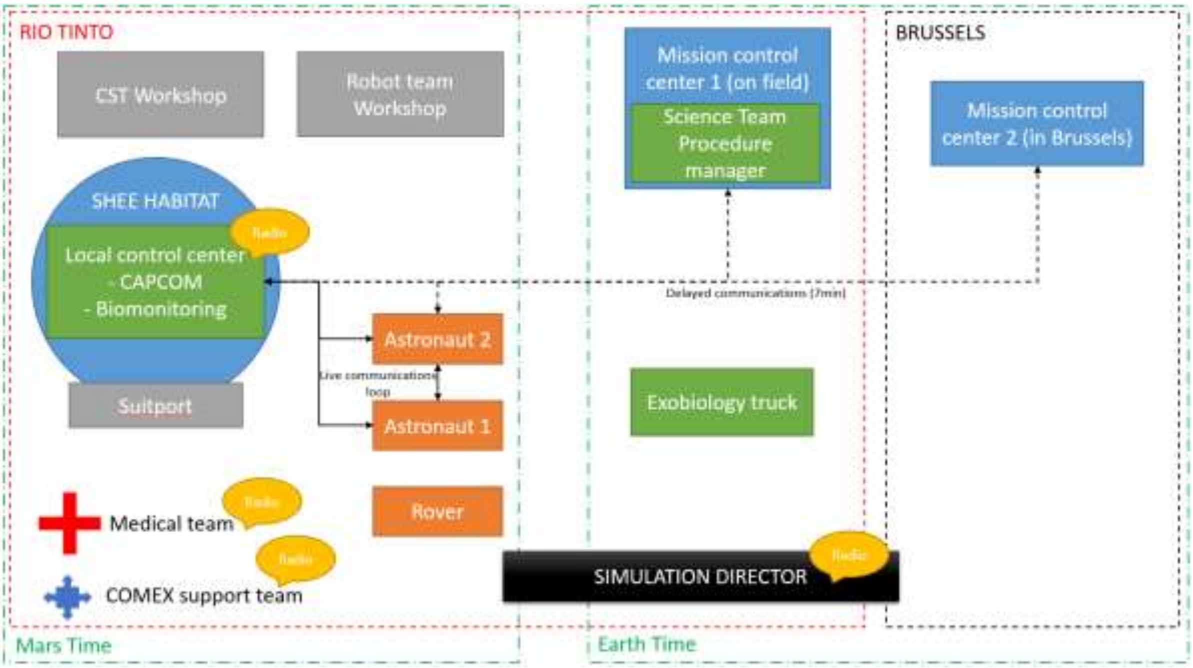
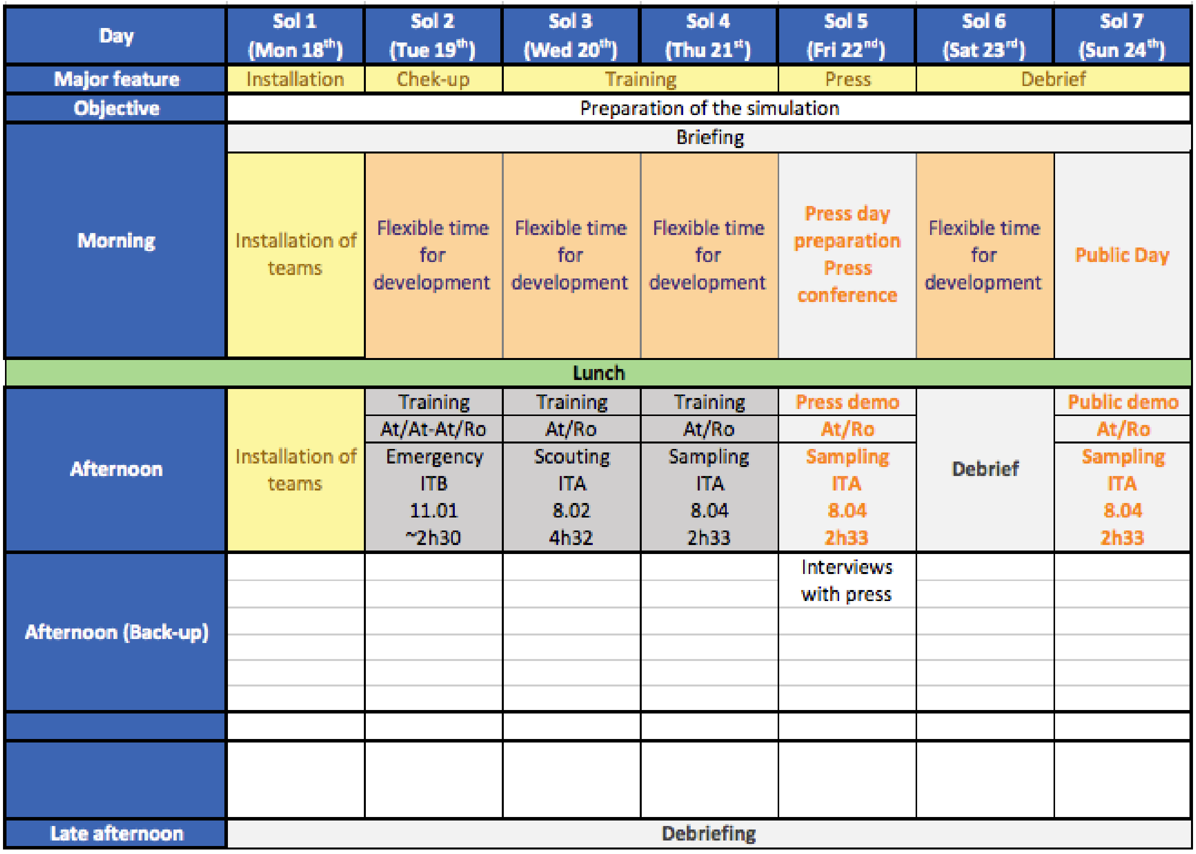


Figure 43. Operational architecture of the simulations with both participants and non-participants in the scientific simulation process. The term CAPCOM was used here for the individual on-site (inside SHEE) communicating with the EVA team (in contrast with the « CAPCOM » in the Space Program who is located at the flight control center on Earth

The Rio Tinto simulations were organized in two weekly stages:

Stage 1 Set-Up: Week 1 (April 18th to April 24th) was organized as a training week, dedicated to the testing of equipment and crew and the resolution of final technical problems.

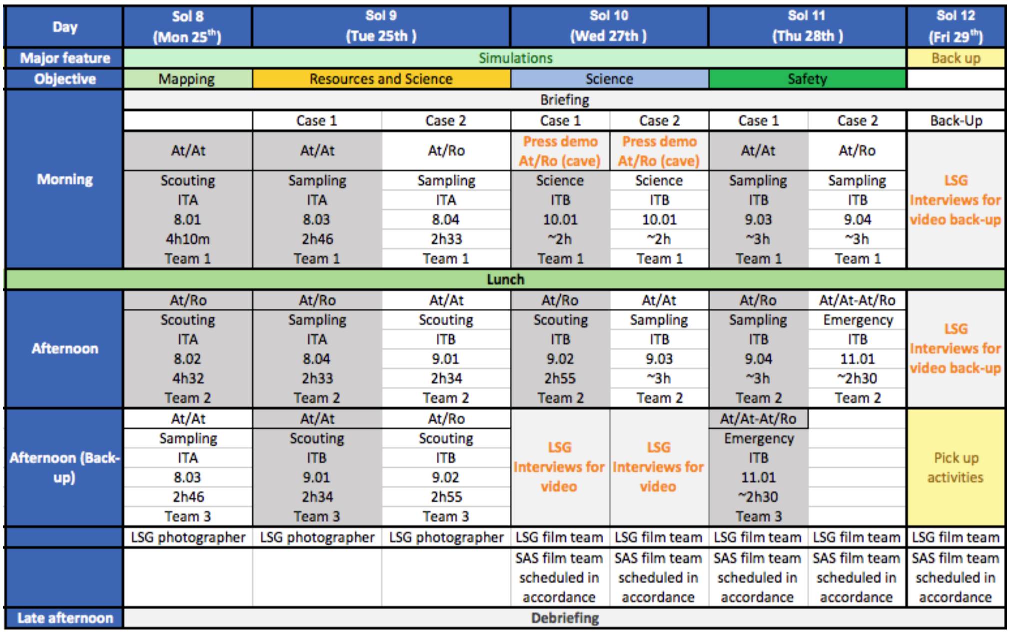


Day	Sol 1 (Mon 18th)	Sol 2 (Tue 19th)	Sol 3 (Wed 20th)	Sol 4 (Thu 21st)	Sol 5 (Fri 22nd)	Sol 6 (Sat 23rd)	Sol 7 (Sun 24th)
Major feature	Installation	Chek-up	Training		Press	Debrief	
Objective	Preparation of the simulation						
Morning	Briefing						
	Installation of teams	Flexible time for development	Flexible time for development	Flexible time for development	Press day preparation Press conference	Flexible time for development	Public Day
Lunch							
Afternoon	Installation of teams	Training At/At-At/Ro Emergency ITB 11.01 ~2h30	Training At/Ro Scouting ITA 8.02 4h32	Training At/Ro Sampling ITA 8.04 2h33	Press demo At/Ro Sampling ITA 8.04 2h33	Debrief	Public demo At/Ro Sampling ITA 8.04 2h33
Afternoon (Back-up)					Interviews with press		
Late afternoon	Debriefing						

Figure 44 : Plan for the first Rio Tinto Week

Stage 2 Simulation: Week 2 (April 25th to April 29th) was dedicated to the EVA simulations. In the initial plan, a maximum of three EVAs per day (one in the morning, two in the afternoon) were scheduled, with SOL10 (April 27th) also foreseen for dissemination (press and video). As a result, the initial plan had foreseen 18 EVA simulations, seven of which performed by astronaut-astronaut (At/At) teams, nine by astronaut-robot teams (At/Ro), and two by a combination of both (At/At-At/Ro).

During the simulations it became obvious that the initial plan had to be adopted to the requirements of the simulations, cause both by environmental constraints (in particular rain) and unforeseen technical issues (hardware failures, communication problems). The red Rio Tinto dust, which is rich in ferrous oxides, proved to be a challenge both to the hardware of the robot and communication modules, as well as to the general reliability of the communication network.



Day	Sol 8 (Mon 25th)	Sol 9 (Tue 25th)		Sol 10 (Wed 27th)		Sol 11 (Thu 28th)		Sol 12 (Fri 29th)
Major feature	Simulations							Back up
Objective	Mapping	Resources and Science		Science		Safety		
Morning	Briefing							
		Case 1	Case 2	Case 1	Case 2	Case 1	Case 2	Back-Up
	At/At	At/At	At/Ro	Press demo At/Ro (cave)	Press demo At/Ro (cave)	At/At	At/Ro	LSG Interviews for video back-up
	Scouting	Sampling	Sampling	Science	Science	Sampling	Sampling	
	ITA	ITA	ITA	ITB	ITB	ITB	ITB	
	8.01	8.03	8.04	10.01	10.01	9.03	9.04	
	4h10m	2h46	2h33	~2h	~2h	~3h	~3h	
	Team 1	Team 1	Team 1	Team 1	Team 1	Team 1	Team 1	
Lunch								
Afternoon	At/Ro	At/Ro	At/At	At/Ro	At/At	At/Ro	At/At-At/Ro	LSG Interviews for video back-up
	Scouting	Sampling	Scouting	Scouting	Sampling	Sampling	Emergency	
	ITA	ITA	ITB	ITB	ITB	ITB	ITB	
	8.02	8.04	9.01	9.02	9.03	9.04	11.01	
	4h32	2h33	2h34	2h55	~3h	~3h	~2h30	
	Team 2	Team 2	Team 2	Team 2	Team 2	Team 2	Team 2	
Afternoon (Back-up)	At/At	At/At	At/Ro	LSG Interviews for video	LSG Interviews for video	At/At-At/Ro		Pick up activities
	Sampling	Scouting	Scouting			Emergency		
	ITA	ITB	ITB			ITB		
	8.03	9.01	9.02			11.01		
	2h46	2h34	2h55			~2h30		
	Team 3	Team 3	Team 3			Team 3		
	LSG photographer	LSG photographer	LSG photographer	LSG film team	LSG film team	LSG film team	LSG film team	LSG film team
				SAS film team scheduled in accordance	SAS film team scheduled in accordance	SAS film team scheduled in accordance	SAS film team scheduled in accordance	SAS film team scheduled in accordance
Late afternoon	Debriefing							

Figure 45: Plan for the second week at Rio Tinto

The sequence of events for a typical EVA simulation is shown in Figure 46.

Figure 46: Schedule of a typical EVA simulation

Summary of results of the Rio Tinto simulation: Overall, the Rio Tinto campaign was successful

- Multiple EVA simulations involving only astronauts or hybrid astronaut-robot teams were carried out to test and execute the tools, procedures and scenarios developed during the MOONWALK project, including gesture-controlled astronaut-robot scouting, sampling, or exploring inaccessible sites by any of them separately.
- A realistic Mars exploration mission simulation was performed with the main objectives achieved: the landing site was explored and mapped, different resources were identified, and microbial markers (evidences of life) were detected in the collected samples.
- Extensive outreach and dissemination of the campaign both in the field and through press, TV, radio, both national and international (See also D9.6).

During the two weeks, or 12 “Sols” of the Rio Tinto Simulation, more than 50 EVAs were performed. About half of them were for training purposes, and the other half for EVA simulations involving Astronaut-Robot (At/Ro) and Astronaut-Astronaut (At/At) teams. Each EVA simulation had a duration of 0,5 up to 1,5 hours, and a total of 14,5 hours was spent for the EVA simulations. The astronauts and the robot covered a total distance of 12,3 km in the simulations.

The duration of the EVA simulations was limited not by the energy-autonomy of the robot, but by the physical strain that was put on the simulation astronauts by the Gandolfi II suit, which weighed more than 35 kg. It was decided that to avoid any health risks, each astronaut should not be in the suit for more than 30 minutes. Thus the simulations were either scheduled for 30 minutes, or the astronaut was replaced after 30 minutes by a colleague and the EVA was continued.

Overall, all MOONWALK technological components were deployed and could be tested in the field. This included the space suit Gandolfi II, the small amphibian helper robot YEMO, a set of manual sampling tools, the biomonitoring system, the communication set up, and the unique scientific instruments for astrobiology research SOLID3.1 and the prototype of the ExoMars RAMAN spectrometer. In addition, the outcome of another FP7 funded project, the Self deployable Habitat for Extreme Environment (SHEE) (http://www.shee.eu/main), was successfully integrated in the simulation scenarios.

The analogue simulations showed that a robotic helper can be useful to support an astronaut, or a team of astronauts, with the exploration of planetary surfaces, in particular of areas that are difficult to access (e.g. slopes, canyons, caves).

The simulations provided prove that innovative methods for robot control, such as control by gestures, are indeed useful as user friendly and simple methods to control the movements of a small helper robot. Many of the technologies demonstrated, including the SHEE habitat, the astronauts, the versatile exploration robot, and the scientific instrumentation, may also be useful for the exploration of extreme environments on Earth.

The performance of the technology was tested using a set of realistic mission scenarios and procedures. A Planetary Exploration Mission simulation was carried out in realistic scenarios with a hybrid team consisting of an astronaut and a gesture controlled helper robot.

The EVA performed by the As/As and As/Ro teams provided valuable material and information to roughly address the main mission simulation objectives (see mission plan)

In the Rio-Tinto simulation, three scientific-technological fields met in a single planetary exploration simulation campaign: human exploration, robotic exploration, and astrobiology science. Our experience demonstrated that collaboration among these fields has to be improved to prepare future manned planetary exploration missions.

The simulations achieved an excellent coverage by local, national, and international media, including press and TV.

3.2.4 T8.4 Control Center Operations

Task lead: SPACE

The design and implementation of the communications network was a critical elements for the simulation campaigns. In MOONWALK, an EVA information system was developed. The purpose of this system was to

- exchange information between the Astronaut, Mission Control, and a science team during EVAs,
- allow the control of payloads and robots on the planetary surface,
- improve the situational awareness and autonomy of the Extravehicular Crew.

The EVA information system was implemented on an interactive touchpad inspired by the Krechet-94 Soviet Moon suit control panel that, instead of using mechanical buttons and analogue displays, makes use of modern display and interaction capabilities. The touch display hardware and user interface take into account the use of pressurized gloves to operate the display, both from a layout and a mechanical/electrical perspective. The touchpad was mounted on the chest of the Gandolfi II suit ("chest-display").

The technical features of the EVA Information System and the chest-display include

- synchronized procedure viewing (with intravehicular crew and MCC)
- telemetry and Caution & Warning (C&W) display
- video streaming (including video from a helmet camera, and scouting robot with anmomnidirectional camera)
- a voice loop communications system
- text communications
- robot control through push buttons
- voice recorded communications

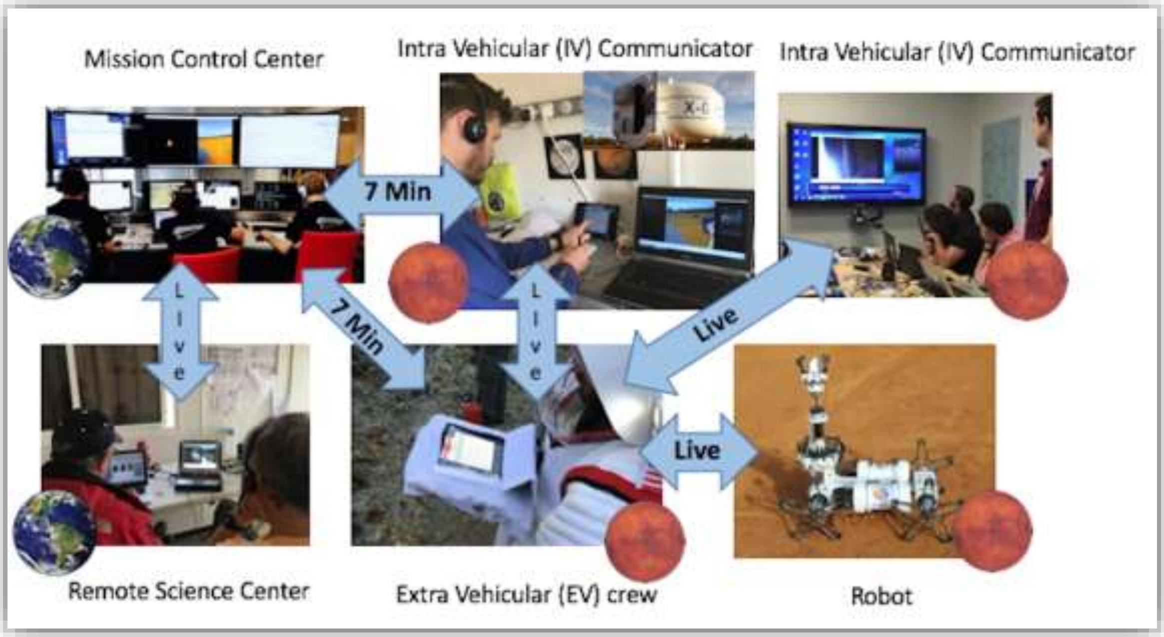


Figure 47: Communication set-up during Rio Tinto

Figure 48. Efficient communication system for MOONWALK Rio Tinto campaign. The FLIGHT director was at the MCC in Brussels and the Science Director and team was in a remote Science Center in the field, with live communication**.**

Through the EVA information system, the astronaut was connected to a communication infrastructure that consisted of the following components:

Mission Control Center (*Callsign: MCC or Brussels):* MCC was located in Brussels and simulated a remote (i.e. terrestrial) center in charge of performing and coordinating science activities for the surface operations.

Local Intravehicular (IV) communicator (*Callsign: CAPCOM or Base):* The local IV crew was in charge of dictating the pace at which the surface operations were made. It coordinated closely with the EV crew the execution of the procedures.

Extravehicular Activity Crew (EV) (*Callsigns EV1 and EV2):* Crew simulating EVAs on the planetary surface. During Mars simulations, EV1 had the Gandolfi II suit simulator, and EV2 was shirtsleeve.

Robot (*Callsign Ro*): The robotic rover, linked to CAPCOM for data up- and download. Control of the rover was by EV1 via connection through CAPCOM.

Remote science center (RSC, SCIENCE) (*Callsign: SCIENCE):* Participants in charge of leading the science activities. They requested science to be performed by the EV crew, always communicating through the MCC.

SCALE Intravehicular (IV) Communicator (*Callsign: SCALE*): External experiment run by Georgia Tech / NASA assumed the same role of the local IV communicator during dedicated slots in the simulation.

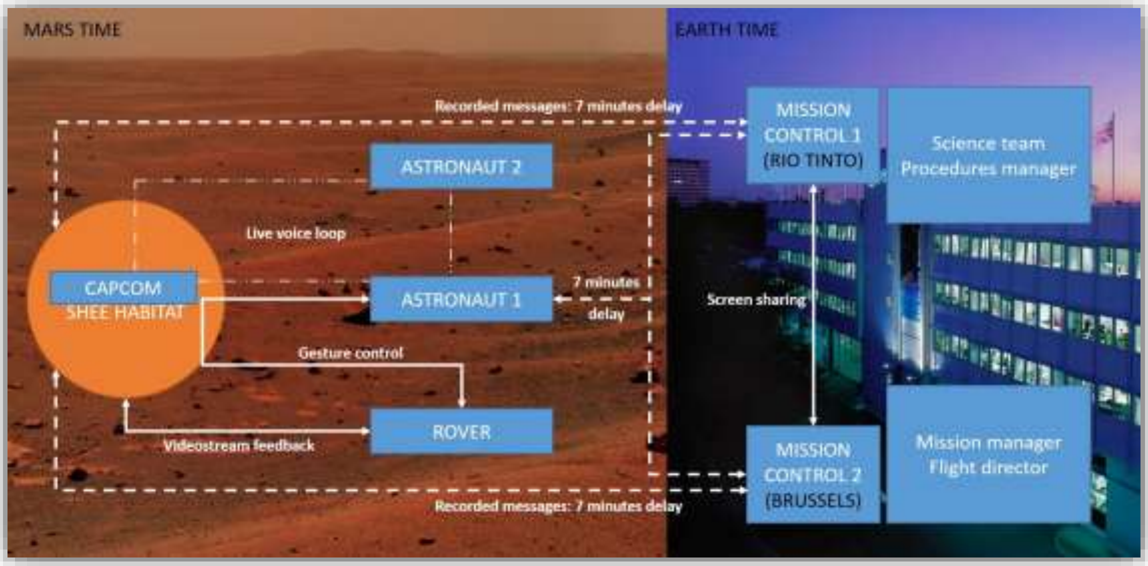


Figure 49: Communication setup during Rio Tinto (schematic)

During the simulations, several data streams were logged, including

- Voice (Stream Recordings) (voice communication recordings of EVAs among IV, EV1, EV2, SCALE and Robot team)
- VCOM (Voice recordings between flight controllers (CAPCOM, FLIGHT and SYSOPS) that were recorded using the VCOM communications matrix.
- Video (Video recordings of EVA, belonging to either the EV1 helmet camera or the Robot)
- Chat (chat interactions via the EVA information system from MCC, IV and SCALE)

3.2.5 T8.5 Evaluation of analogue missions

Task lead: NTNU

During both the Rio Tinto and the Marseille simulations, extensive data were gathered. This included

- Recordings of the voice stream between astronauts and CapCom / MCC
- Recordings of the video streams from the helmet cams of the astronaut and the 360 degree omnicam mounted on the rover
- Bio-monitoring data of the astronaut recorded during the EVA
- Empirical data on user experience collected through interviews with the astronaut(s) directly after the EVA simulation.

However, although the amount of data gathered during the simulations was significant, it has to be pointed out that the relative low number of EVA simulations possible during the five days in Rio Tinto and the three days in Marseille (longer simulation campaigns were not covered by the project budget) does not support a scientifically sound statistical analysis. Thus the evaluation of the simulations is more qualitative than quantitative.

The core objectives of an evaluation of the empirical data performed by NTNU and documented in an appendix of D8.2 was to analyze the analogue missions with respect to human factors and evaluate and compare the astronauts versus the astronaut-robot team in terms of performance and psychological impact.

The analysis tries to prove a twofold hypothesis: 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.

Prior to the simulations a data collection and evaluation plan was prepared (RD5). The objective with this plan was to identify and plan the data collection from, and the evaluation of, the MOONWALK simulation campaigns. We referee to this document for details about the data planned to be data collected (RD5). The subjects responding to the surveys and interviews were anonymized by replacing the subject names with subject numbers. The key is held by the partner NTNU.

The dataset collected through the survey is comprehensive, including a great amount of questions and categories of respondents. Both because some respondents gave multiple answers, and because the respondents belong to different categories, new variables for sorting the responses needed to be created. Primarily the dataset is differentiated by five main categories of respondents:

- Rio Tinto training week,
- Rio Tinto simulations,
- Marseille Pool Tests,
- Marseille subsea simulations and
- HMI training survey.

The survey collected 52 lessons learned, 33 comments about the different simulations, 55 comments about the tools, 63 comments about the HMI, 39 comments about the suit. The simulations generated several types of data including video and audio recordings, GPS tracking, biomonitoring, written logs and questionnaires and interviews. Of these, mainly the written logs (CAPCOM), questionnaires and interviews were used in the evaluations performed by NTNU.

Details on the results of the mission evaluation can be found in Annex II of D8.2.

The MOONWALK analogue simulations evaluated the human performance and the effect of robot-human cooperation in very different environments. The desert like environment in Rio Tinto and the underwater site in Marseille provide gravity level, pressure and temperature conditions that challenge the human performance. One objective of MOONWALK was to see how hybrid astronaut-robot teams perform when the human part of the team is put under stress.

The evaluations show that using the robot was not seen as a burden by the astronauts. There was little evidence that the interaction with the robot in a At/Ro hybrid team created more stress /

different responses from the simulation astronauts than the interaction with the other simulation astronaut in an As/As team. This shows that, although the robot was very simple and had a low level of capabilities (e.g. no manipulation capabilities) and decisional autonomy, it is a useful tool for planetary exploration. It can be expected that more powerful and “intelligent” robots will do an even better job.

2.9 WP9 – Outreach and Dissemination

WP lead: LSG

Objectives:

The general goal of the outreach and dissemination WP is to increase the visibility of MOONWALK, to improve the public recognition of the project, and to educate the public about possibilities of working with machinery in extreme environments. The objective is also to point out applications of space technologies on earth and also attract future research, academic and industrial partners for further development.

Another goal of this WP is also to search for marketing possibilities while securing intellectual property rights of all consortium partners. The latter aim will be tackled in the further development of the project.

Table 16: WP 9 - List of deliverables

Deliverable Number	Deliverable Description	Lead beneficiary
D9.1	Webpage including secured intranet site	LSG
D9.2	Children Competitions Report	LSG
D9.3	Project Flyer + Dissemination material	LSG
D9.4	Dissemination Plan	LSG
D9.5	Exploitation and IPR Plan	DFKI
D9.6	Final Dissemination Report	LSG
D9.7	Draft Exploitation Plan	DFKI
D9.8	Newsletter 1	LSG
D9.9	Newsletter 2	LSG
D9.10	Newsletter 3	LSG

Short description of work done in each task

The work in WP 9 started right at the beginning of the project and will be continued until the end of MOONWALK (and, through the exploitation planned by the MOONWALK partners, beyond the project duration).

2.9.1 T9.1 - Dissemination of the results

Task lead: LSG

Website: The MOONWALK website has been updated regularly throughout the year, documenting:

- ***News*** related to MOONWALK, intended to highlight where and how information on project MOONWALK has been shared / disseminated and includes, conferences, media coverage, exhibitions, workshops and events.
- The ***Galleries*** section which illustrates the progress of the project and offers additional information on consortium meetings and major milestones achieved and this report period included the February 2015 - MOONWALK Consortium Meeting and Workshop in Trondheim, MOONWALK storyboards / final simulation scenarios and most recently in Galleries is the documentation of the first test campaign carried out in Marseilles.
- ***Publications*** lists the various conferences and papers consortium members have contributed.

Dissemination Material: Under the lead of LSG, a number of high-quality dissemination material was created in MOONWALK. This includes posters, flyers, image renderings, videos (see T9.4), but also a MOONWALK sticker and mission patch, and a project T-shirt.

Figure 50 : MOONWALK Mission Patch left: sticker, right: embroidered patch

Newsletters: Within MOONWALK, a total of three newsletters were produced and distributed among a wide audience in the space research community and general public.

To achieve optimal dissemination and outreach results, the initially planned delivery dates of the newsletters were adapted to the actual project stages, which formally resulted in delays. However, these delays did not have a negative impact on the reception and outreach effect of the newsletters.

Table 17: Re-timing of MOONWALK Newsletters 1, 2 & 3

Newsletter No.	Timing when the newsletter is scheduled to be published	Deliverable No.

Newsletter #1	Published in month 20 (May 2015) and served as the MOONWALK Announcement of Opportunity (AO) for researchers.	D9.8
Newsletter #2	Published in month 31 (March 2016) in connection with the (then) forthcoming simulations at subsea Marseilles and Rio Tinto.	D9.9
Newsletter #3	Published in month 34 (June 2016) near the end of the project summarizing the project accomplishments.	D9.10

The newsletters were used to publish the ‘Call for participation’ in various outreach activities and to disseminate the concept and results of the analogue simulations. For this purpose, visual renderings of the simulation scenarios were developed (see below).

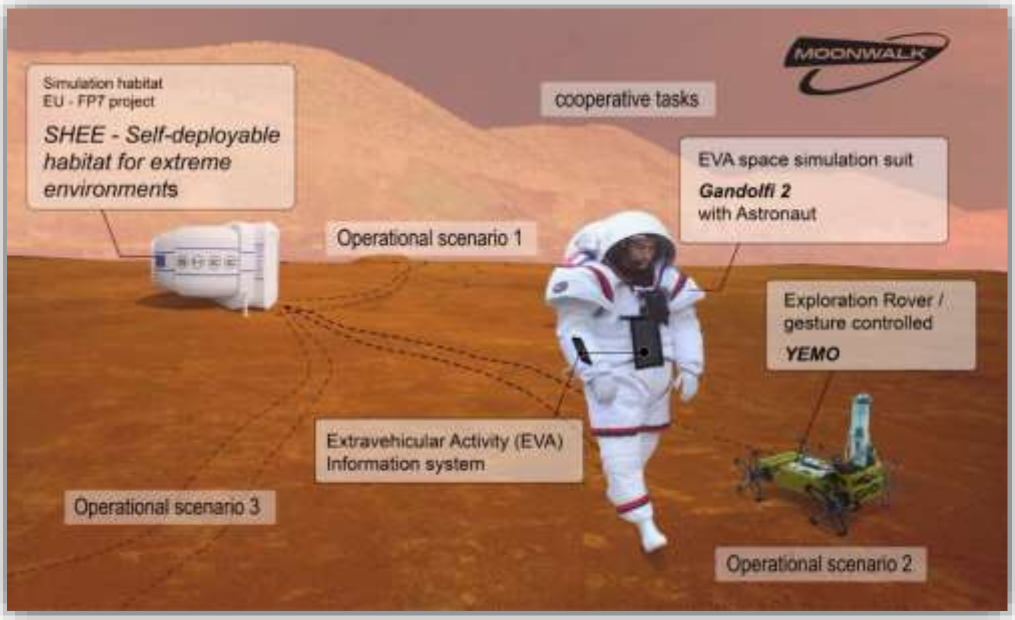


Figure 51: MOONWALK visualization – simulation diagram Rio Tinto (NL2)

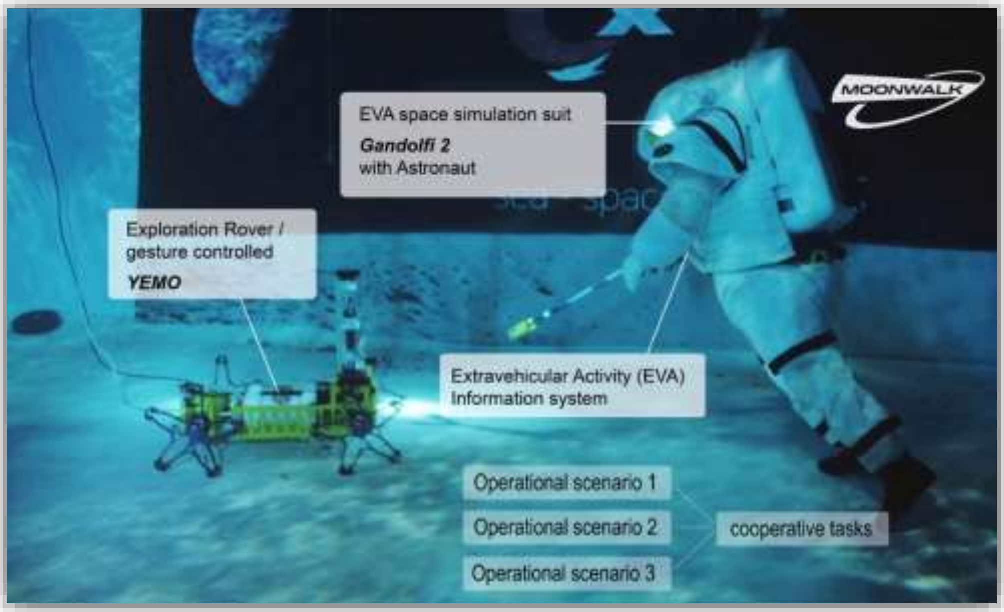
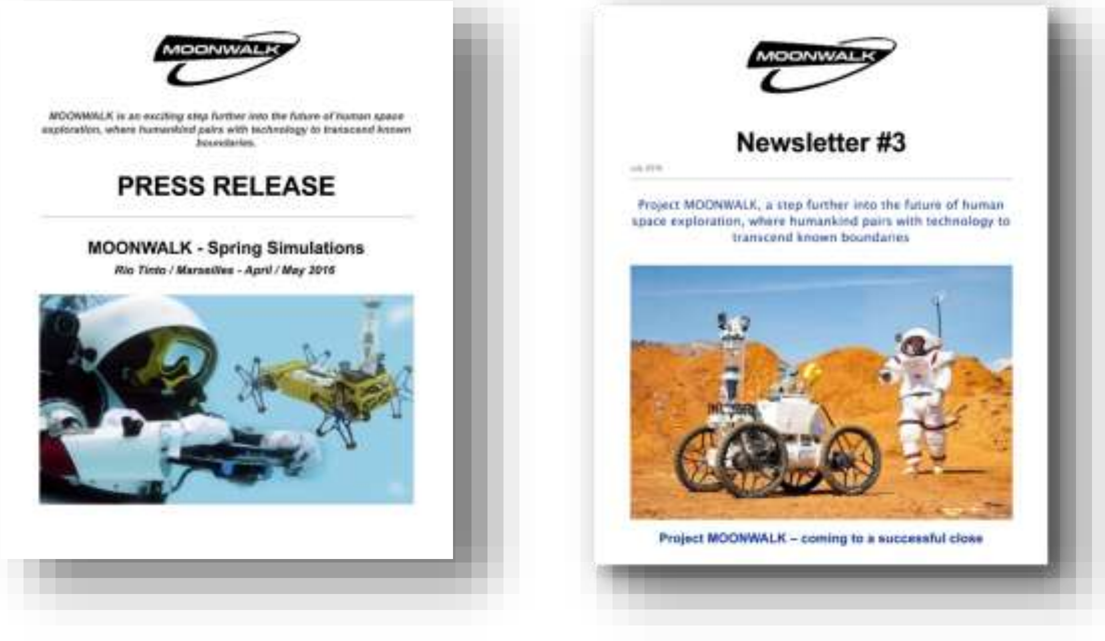


Figure 52: MOONWALK visualization – simulation diagram subsea Marseilles (NL2)



MOONWALK is an exciting step further into the future of human space exploration, where humankind pairs with technology to transcend known boundaries.

PRESS RELEASE

MOONWALK - Spring Simulations

Rio Tinto / Marseilles - April / May 2016

Newsletter #3

Project MOONWALK, a step further into the future of human space exploration, where humankind pairs with technology to transcend known boundaries

Project MOONWALK – coming to a successful close

Figure 53: Press release 4.16 and Newsletter 3

Press releases: Press releases were electronic templates for distribution by all consortium partners to their respective contacts. They highlighted the key milestones within the project and were intended to generate an excitement over the project. Press releases were generally shorter than their newsletter counterparts, but offered a quick, concise reminder for people to look further into MOONWALK. Press releases were developed in Word format and pdf versions were distributed to project partners to further circulate. A digital version was also created using the online service Mailchimp, used internationally by businesses for marketing emails and targeted campaigns. LSG’s contact list alone reaches over 1000 people/organizations. The average ‘open’ rate for press releases sent by LSG via Mailchimp, is between 5 and 22 percentage points greater than the industry average.

- **Press Release – Children Competition:** The Children Competition press release was a document inviting children from around the world to participate in the MOONWALK Children Competition. The press release advertised the MOONWALK comic book designed especially for the competition, it gave overall details on the competition including prizes to be won and provided directions on where to go to find out more, as well as contact information. Dated 24.2.2016, it was released and titled: MOONWALK Children Competition. It was sent to children museums all over Europe through the Vienna Children museum ZOOM (Ms. Elisabeth Menasse) and to European schools through the network of the outreach department (Ms. Michaela Gitsch) of the Austrian Aerospace and Space Agency. Further each consortium member distributed it through their networks and facebook.
- **Press Release – LANDED! MOONWALK – Simulation – Rio Tinto** was electronically distributed on 19. April, 2016 announcing the beginning of simulation in Rio Tinto. Stunning imagery was captured of the simulation trials including astronaut and rover in a landscape resembling Mars, performing exo-biological tasks. A reminder was given to persons of the public and press to register for visiting the site during the two-week simulation period.

LANDED !

MOONWALK - Simulation - Rio Tinto

19. April 2016

Members of the MOONWALK team and project equipment have arrived in Rio Tinto this past weekend, as groundwork for the analogue tests were prepared. Logistic items such as power units, tents, toilets and crew cabins were installed at the test site. SHEE, Self-Deployable Habitat for Extreme Environments (a European Union Seventh Framework project), has already arrived and will provide shelter for the test subjects in the mission scenarios.

On Monday, safety procedures and instructions were provided to everyone on site and all instruments and equipment were given a final check in preparation for the mission tests to begin on Tuesday.

Today, Tuesday, 19. April, MOONWALK begins its first Earth-Analogue simulation to test the hardware and various spacewalk scenarios that have been developed by the MOONWALK team over the last 2.5 years.

Successful communication has been established with Mission Control Centre in Brussels and our simulation astronauts are ready to go. Next update to be reported soon!

Figure 54: Press release 19.4.16

- **Press release MISSION ACCOMPLISHED!** was electronically distributed on 29. April, 2016 announcing the end of the simulation campaign in Rio Tinto. This press release summarized the events which occurred at Rio Tinto near Seville, Spain between 16 and 29 April 2016. New imagery was presented, information on public and press turn-out was related, winner of the Children Competition for ‘first phrase to be spoken on Mars’ was featured, visiting guest researchers that were part of the simulations were credited and lastly, a reminder to register for the upcoming simulations in Marseilles was included, for those that had missed out on visiting the Rio Tinto campaign, or intended to visit both.

Press Release
29.4.2016

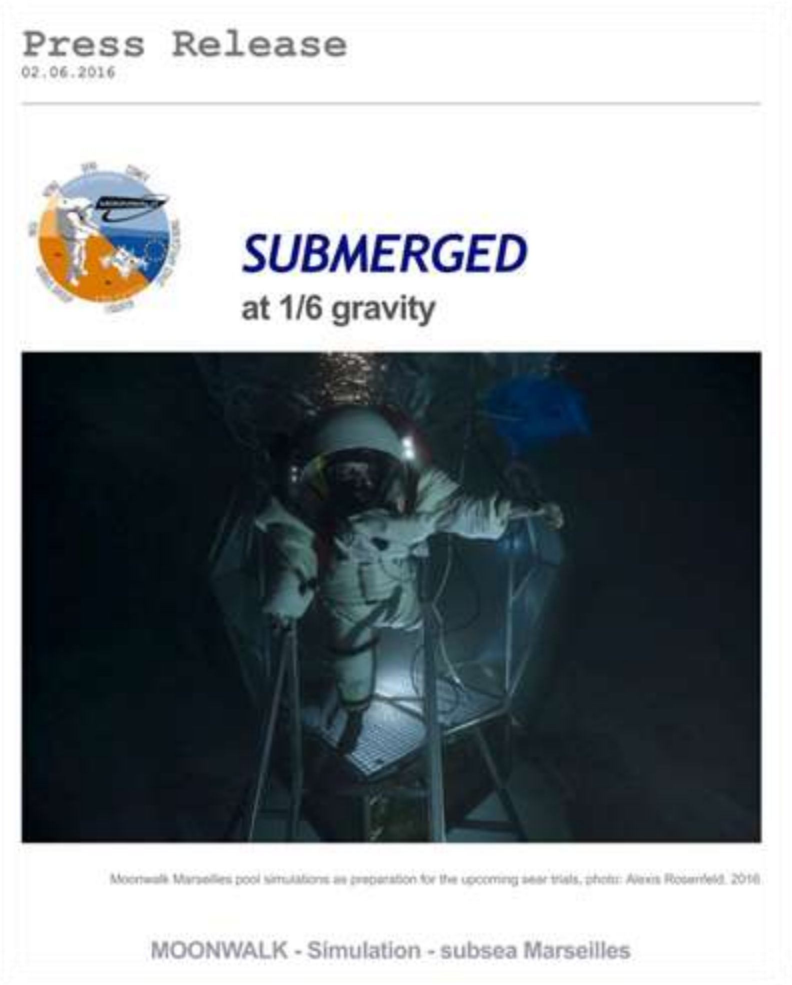
MOONWALK - Simulation - Rio Tinto

MISSION ACCOMPLISHED

MOONWALK is an exciting step further into the future of human space exploration, where humankind pairs with technology to transcend known boundaries.

Figure 55: Press release 29.4.16

- **Press Release – SUBMERGED at 1/6 gravity** was electronically distributed on 02. June, 2016 announcing the success of the underwater Gandolfi II spacesuit and underwater communications between astronaut / rover / mission control at the simulation campaign in Marseilles. Photos of the MOONWALK systems and equipment during the pool trials at COMEX, leading up to testing in the open sea were featured. Descriptions of the testing site and facilities were relayed. External researchers were again mentioned and the winner of the Children Competition in Marseilles, with the task to design a new flag to be planted on the moon was mentioned.



Press Release

02.06.2016

SUBMERGED

at 1/6 gravity

Moonwalk Marseilles pool simulations as preparation for the upcoming sear trials, photo: Alexis Rosenfeld, 2016

MOONWALK - Simulation - subsea Marseilles

Figure 56: Press release 2.6.16

Brochures and flyers:

- **Project flyer:** The MOONWALK project flyer is a three-folder. It was created already in 2014 and was regularly distributed to the research community and members of the public at venues visited by consortium partners. Similarly, the flyer was made available for free download on the project website under “PUBLICATIONS.”

MOONWALK
Enabling astronaut-robot partnerships for future Moon-Mars surface exploration

Seven partner organizations are bringing their expertise to MOONWALK:
DFKI Robotics Innovation Center, Germany / Project Coordinator, Robotic platform, Robot-control Interface;
COMEX, France / Technical Coordination, EVA training suit, Subsea simulation;
Airbus Group Innovations, Great Britain / Biomedical monitoring for EVA;
LIQUIFER Systems Group (LSG), Austria / Scenario design, EVA training suit, EVA tools design support;
Space Applications Services, Belgium / System architecture, and EVA human-machine interaction technology;
NTNU Centre for Interdisciplinary Research in Space, Norway / Human dependability, simulation campaign evaluation;
Instituto Nacional de Técnica Aeroespacial (INTA) - **Centro de Astrobiología** (INTA-CSIC), Spain / Astrobiological Field Support, Rio Tinto Mars analogue

Figure 57: MOONWALK brochure

- **Project Brochure:** A final brochure describing the MOONWALK project will be completed at the end of the project. The brochure is a booklet with close to 40 pages in length. It provides ample information and imagery on MOONWALK targeted towards a large public audience. It was printed by an on-demand printing company in Austria and copies will be distributed to project partners for limited distribution.

Press Coverage at relevant publications: Since the pool trials at COMEX in February 2016, MOONWALK has received an extraordinary amount of press from near and far. The trend continued during the simulation campaigns in both Rio Tinto and subsea Marseilles. Please see Annex for an extensive, although not inclusive list, of publicity (media) channels MOONWALK has been featured.

Figure 58: Selection of images taken from press coverage of MOONWALK project

- **Press Packages:** Given the overwhelming demand for information on the MOONWALK project, LSG, made Press Packages for each of the simulation sites. Each Press Package can be downloaded from the website with free access to use all material with proper credit given to the author of the images. http://www.projectmoonwalk.net/moonwalk/?cat=14
- **Press Conferences:** Press Conferences were organised as 'public days' for each of the analogue simulations sites at Rio Tinto and subsea Marseilles. Persons of the press were allowed the opportunity to speak individually with project partners during this time. The public day in Rio Tinto was offered on Sunday 24. April, 2016 and in Marseilles on Wednesday 1. June 2016.

Announcement of Opportunity (AO) and call for external experiments: Research opportunities for conducting scientific experiments and investigations in conjunction with project MOONWALK was offered in MOONWALK's Announcement of Opportunity (AO). From the submissions received, the following experiments were selected:

- **ADAPA 360** - 360-Degree VR Video Camera System for Space Suit and Helmet (Team: Ali Zareiee, ADAPA, Norway). Documented Rio Tinto using ADAPA 360-Degree Camera. Provided excellent footage of site and MOONWALK project.
- **Cave Explorer** - Assessment of performance for the wearable electro-optical diagnostic health assistant system (Team: Human Spaceflight Department, OHB System AG; Medical Engineering Department, IMES University of Applied Sciences Würzburg-Schweinfurt). Tests were conducted for a new, mobile, digital diagnostic system for medical monitoring astronauts during manned space missions called the CAVExplorer 2.0. Comprised of electrodes worn on the body of an astronaut and sensor detectors on the earlobe, the CAVExplorer 2.0 measures electrical signals and monitors the health of the heart and circulatory system.

Figure 59: Video still from ADAPTA 360 (left), CAVExplorer 2.0 (Photo: Walter Kullmann, 2016)

- **Lunar Lander Pivot Beam Support System** (Team: Aedel Aerospace Unipessoal, Portugal): A mock-up of a structure with a pivoting arm showing one activity as part of construction operations was tested in subsea Marseilles.

Figure 60: Lunar Lander Pivot Beam Support System Mock-Up underwater, Sarah Pell as the simulation astronaut (photo: Comex 2016)

- **SCALE - Shared Cognitive Architecture for Long-term Exploration** (Team: Leslie DeChurch (Georgia Tech), Noshir Contractor (Northwestern), Jeff Johnson (U. of Florida); NASA Behavioral Health & Performance): Communications by EVA crew, habitat crew and MCC were logged for analysis by the SCALE team in order to develop new methodologies and technologies to improve shared cognition during space missions. In addition, Mission control was handed over for the afternoon of the 28th of April 2016 to Georgia Tech during the Rio Tinto simulations, demonstrating the capability of involving international teams into the modular MOONWALK simulation architecture.

Figure 61: SCALE, Georgia Tech Mission Control Centre; (Photo: Georgia Tech, 2016)

- **Psychobot - Human Psychological Relationship with a Planetary Exploration Robot** (Team: Yvett Mikola, PhD student, Complutense University of Madrid (UCM). Madrid, Spain): The experiment tried to prove the possibility that humans develop an emotional attachment to their robotic "working partners" when interacting with them on a daily basis. To measure the qualitative and quantitative changes in the human-robot teams, four questionnaires were developed to be used with a pre-post method for each simulation astronaut.

Children Competition: A competition for school children, aged 6-14 was envisaged to involve the next generation of space explorers in the two MOONWALK simulations - subsea Marseilles and Rio Tinto. As both simulations were conducted within a two-month period, the originally conceived two separate competitions were integrated into one Internet Children Competition. It was agreed by the MOONWALK consortium to develop a comic book to achieve multiple goals: to convey basic knowledge of space exploration, to raise interest in space related research and development, to inspire creativity and to supply identification potential.

The comic book was developed around the story of four children between 7 and 12 years who travel to moon and Mars, accompanied by their personal pet robots. Within the pages of the comic book, the tasks were revealed asking children to create an international flag for the return to the moon and to propose a significant phrase to be spoken upon arrival on Mars. One winner for each task was selected.

For the detailed report see D9.2 – Children Competition Report

Public events: Public events took different forms and included press conferences, public access days, professional events and festivals. See press conferences above in the press section.

Figure 62: Group picture of the extended MOONWALK team on the public day in Rio Tinto during the Mars simulations (Photos: Comex, 2016)

Table 18: List of Public events in 2016

Date	**List of Public events**	**Description**
May 2016	**MOONWALK Simulation site subsea Marseilles** **COMEX**, France	Public / Press day – various activities and information about the project for participants
April 2016	**MOONWALK Simulation site Rio Tinto** **Rio Tinto,** Quarry, Spain	Public / Press day – various activities and information about the project for participants
March 2015	**beSPACE space dinner 2015** Brussels Planetarium, Belgium	Space Application Services introduces the MOONWALK project
November 2014	**Festival du Film Sous-mari** COMEX Café, France	Exhibition on MOONWALK by COMEX
June 2016	**Colloque Mer et l’Espace -L’homme face aux frontières du XXIe siècle,** 23.06.2016 Paris	Presentation on MOONWALK by COMEX
September 2016	**„Wandzeitung“,**artists’ studio Steinbrenner, Dempf & Huber, 12. September 2016, Vienna	Exhibition of project Moonwalk photo and video footage by LIQUIFER

Workshops: Periodic workshops were organized for selected attendants, including, but not limited to, the participation of consortium members, representatives from EC, other relevant European organizations, space agencies, members of the Scientific Advisory Board (SAB) and university students. Four workshops were foreseen at tentative dates as described in the DoW.

During the course of the project the following workshops were conducted:

- involve the younger generation - students (five workshops at the ISU summer schools),
- two events for professionals and stakeholders (during simulations in Rio Tinto and Marseilles),
- two workshops for professionals and stakeholders (Newport and Trontheim).

This way the MOONWALK Consortium reached out to a wider range of people than originally anticipated.

Table 19: MOONWALK workshops

Workshop No.	**Location / Period**	**Brief Description**
Workshop #1 (M 8)	NEWPORT, UK In conjunction with M2 after the presentation of WP3 (Concept Definition & Architecture).	EXTENDED MOONWLK CONSORTIUM Invited experts from the SAB and NASA joined the meeting via video conference. Feed-back and insight was given by experts based on their relevant projects. (NEEMO mission hardware and D-RATS campaigns)
Workshop #2 Cluster focussing on simulation	1. Activity with HEC Montreal Summer School on Management of Creativity and Innovation July 1– 11, 2014 2. ISU Space Studies Program (SSP) 2014, Montreal, Canada; 3. SSP 2015 Athens, Ohio, USA; 4. SSP 2016 Haifa, Israel. 5. ISU Master of Space Studies MSS 2014/15, MSS 2015/16. Strasbourg, France.	WORKSHOPS ON 'SIMULATION OF INTERPLANETARY MISSION – PLANNING AND EXECUTION' Five workshops were run by SPACE at the International Space University on 'Simulation of interplanetary mission' with a focus on remote /delayed communications. Participants were split into two teams, one acting as mission control centre, the other as Mars base team with setup similar to MOONWALK. Included planning, hardware familiarization, risk identification and mission execution.
Workshop #3 (M17)	Trontheim, NO	ANALOGUE EXPERIENCES The workshop took place at the NTNU premises in Trontheim, Norway on February 5th 2015. The workshop featured talks from external experts (Gernot Grömer, ÖWF; William Carey, ESA) and MOONWALK consortium members, and a visit to the CIRiS Control Room. The thematic focus of the WS was on the exchange of experiences with the organization and management of earth analogue simulations.
Workshop #4 (M 32)	Rio Tinto, Spain	EXTENDED MOONWLK CONSORTIUM SAB, NASA, ESA and EU participants were invited, for individuals open workshop upon registration.
Workshop #5 (M 33)	COMEX, Marseilles	EXTENDED MOONWLK CONSORTIUM ESA and EU participants were invited, for individuals open workshop upon registration. Also the scientists and engineers of the selected experiments from the Announcement of Opportunity were present.

Conferences: Consortium partners have attended and will keep attending international workshops and conferences in order to disseminate information on the project goals and achievements. LSG, with help from the other consortium partners prepared a public presentation.

Table 20: Participation in conferences

#	Conferences relevant to MOONWALK
1	65th International Astronautical Congress (IAC) 29 September – 3 October 2014, Toronto, Canada [presentation and paper]
2	7th IAASS International Space Safety Conference 20-22 Oct 2014, Friedrichshafen, Germany [presentation and paper]
3	ASTech International Conference Space Exploration 2014 29-31 October 2014, International Space University (ISU), Strasbourg, France Organized by: International Space Exploration Coordination Group (ISECG) [presentation]
4	Astrobiology Science Conference 2015 15-19 Jun 2015, Chicago, Illinois, USA [presentation and paper]
5	AIAA Space 2015 31 August – 2 September 2015, Pasadena, California [presentation and paper]
6	ESREL 2015 7-10 September 2015, Zürich, Switzerland [presentation and paper]
7	66th International Astronautical Congress (IAC) October 12–16, 2015, Jerusalem, Israel [presentation and paper]
8	International Symposium on the Moon 2020-2030 December 16, 2015, ESTEC, Netherlands [presentation]

Scientific publications: During MOONWALK, a number of scientific publications in conference proceedings and journals were published. In 2015 and 2016, the following publications were submitted and published:

Thomas Vögele, Barbara Imhof, Peter Weiss (2016): **PROJECT MOONWALK – WORKING WITH ROBOTS TO TRANSCEND KNOWN BOUNDARIES**, ROOM Journal, Issue: #3 (9) Autumn 2016 (Published: 31 August 2016), https://room.eu.com/

K. Fossum, B-E. Danielsen, A.B. Mohammad, S.O. Johnsen (2015): **LAYING THE BASIS FOR RESILIENT HUMAN-ROBOT INTERACTIONS IN FUTURE SPACE EXPLORATION MISSIONS**, ESREL 2015

V. Parro-García, F. Puente-Sánchez, O. Prieto-Ballesteros, Centro de Astrobiologia, T. Vögele, M. Höckelmann, B. Imhof, B. Davenport, W. Hoheneder, P. Weiss, V. Taillevot, D. Urbina, F. Fossum, A. Nottle (2015): **THE MOONWALK PROJECT: PREPARING FOR HUMAN SUPPORTED SCIENCE ON MARS AND THE MOON**, Astrobiology Science Conference 2015

Diego A. Urbina, Tom Hoppenbrouwers, Hemanth K. Madakashira, Vladimir Albert, Keshav Chintamani, Xavier Martinez-Gonzalez, Boris Van Lierde, Ngoc-Diep Ho, Nicolae Mihalache, Jakob Schwendner, Mathias Hoeckelmann, Martin Schroeer, Peter Weiss, Virginie Taillebot, Thibaud Gobert (2015): **MOONWALK – PROTOTYPING THE SPACESUIT HUMAN INTERFACES OF THE FUTURE FOR TEST IN WATER IMMERSION PARTIAL GRAVITY SIMULATION,** 66th International Astronautical Congress (IAC 2015)

Barbara Imhof, Waltraut Hoheneder, Stephen Ransom, René Waclavicek, Robert Davenport, Peter Weiss, Bernard Gardette, Virginie Taillebot, Thibaud Gobert, Diego Urbina, Tom Hoppenbrouwers, Thomas Vögele, Mathias Höckelmann, Jakob Schwendner, Knut R. Fossum, Victor Parro-García (2015): **MOONWALK – HUMAN-ROBOT COLLABORATION MISSION SCENARIOS AND SIMULATIONS,** AIAA Space 2015

Susmita Mohanty, Barbara Imhof, Alistair Nottle, Thomas Vögele, Jakob Schwendner, Weiss Peter, Virginie Taillebot, Bernard Gardette, Thibaud Gobert, Mr. Yashodhan Nevatia, Diego Urbina, Mr. Knut Fossum, Victor Parro-Garcia, Olga Prieto-Ballesteros (2014): **OPERATION SCENARIOS AND CONSTRAINTS FOR JOINT HUMAN-ROBOT SURFACE EVA MISSIONS ON MOON AND MARS,** 5th International Astronautical Congress (IAC 2014)

Knut Robert Fossum, Abdul Basit Mohammad **(2014): APPROACHING HUMAN-ROBOT INTERACTION WITH RESILIENCE,** 7th IAASS International Space Safety Conference 2014

Peter Weiss, Bernard Gardette, Virginie Taillebot, Thibaud Gobert, Thomas Vögele, Mathias Höckelmann, Jakob Schwendner, Alistair Nolte, Matthew Roberts, Barbara Imhof, Waltraut Hoheneder, Stephen Ransom, Robert Davenport, René Waclavicek, Diego Urbina, Tom Hoppenbrouwers, Knut Robert Fossum, Victor Parro-García, Olga Prieto-Ballesteros (2014): **THE MOONWALK PROJECT ASTRONAUT-ROBOT COOPERATION IN EUROPEAN SPACE ANALOGUE SIMULATIONS,** ASTech International Conference Space Exploration 2014

In addition, the following papers are under preparation.

Víctor Parro, Peter Weiss, Thomas Vögele, Barbara Imhof, Mathias Höckelmann, Martin Schröer, **ASTRONAUT-ROBOT COOPERATION PROCEDURES FOR PLANETARY EXPLORATION AND LIFE DETECTION ON MARS;** in preparation, to be submitted to Astrobiology Journal (IF 2.6)

Victor Parro et. al., **LIFE DETECTION ON MARS WITH A ROBOTIC MOBILE LAB** (working title), to be submitted to Astrobiology Science Conference 2017

Thomas Vögele, Barbara Imhof, Peter Weiss et. al.; **PLANETARY EXPLORATION WITH ROBOTIC TOOLS** (working titel), to be submitted to the 48th Lunar & Planetary Science Conference, LPSC2017

3.3.1 T9.2 - Training for test-bed deployment and utilization

Task lead: COMEX

The objective of this task was to train selected personnel in how to operate and maintain the systems of the MOONWALK training suit and rover. This includes “guests” from the associated partners in MOONWALK (e.g. NASA, members of SAB).

Prior to the Rio Tinto and the Marseille simulations, a number of male and female simulation astronauts were selected and trained in the handling of the Gandolfi II space suit, as well as in the use of the gesture control to steer the robot. The astronauts were mainly recruited from within the consortium, but external guest were also invited.

One of them was Dr. Sarah Jane Pell, Simulation Astronaut and Professional Diver from Australia. She participated in one of the As/As EVA in Marseille.

Figure 63: Sarah Pell preparing for the astronaut-astronaut scenario, before diving into the space simulation suit Gandolfi-2 (Photos: LIQUIFER Systems Group, 2016)

3.3.2 T9.3 – Exploitation, management of knowledge and IPR issues

Lead: DFKI

The objective of this task was to describe exploitable results of the MOONWALK technology and to identify potential markets. IPR issues were also to be addressed. For this purpose, an Exploitation and IPR Plan (D9.5), combined with a Draft Exploitation Plan (D9.7) were developed.

3.3.3 T9.4 - Visualizations, images, animations, videos

Task lead: LSG

The objective of this task was to develop images and videos that document the technical components of MOONWALK as well as the analogue simulations. This objective has been fully achieved, as a large number of high-quality images, graphs and videos were produced during the project. Examples are:

Images: A number of visualizations were developed to illustrate the project and the analogue simulations. These images were used mainly for dissemination and outreach (e.g. in the newsletters).

Figure 64: MOONWALK blended visualization Subsea Marseilles / Rio Tinto

Video Documentary: The MOONWALK video documentary was completed at the end of August. The video is a short documentary on the overall achievements of the project and was filmed and edited by the film studio in Vienna. Working in close relationship with LSG, the concept of the film and its various contents were conceptualized and realization of the ideas were brought to fruition by RaumFilm. Most the of the video coverage comes from the simulations in Rio Tinto due to the greater accessibility of that test site in comparison to the simulations in Marseilles, where limited access to the site was a reality. In Rio Tinto, project partners were interviewed and the documentary provides from each statements and an explanation of their respective contributions. The imagery in the video, focuses on the Rio Tinto and Marseilles simulations and provides a rich textural background for the project and the development of technologies. Through this overview, the particularities of the project and its developments are explained. The video, approximately 10 minutes in duration, will be made available online for public viewing.

3. Summary and Outlook

MOONWALK (http://www.projectmoonwalk.net) developed innovative technologies for human-robot interaction and co-operation in Extra Vehicluar Activities (EVAs) in the context of the exploration of Moon and Mars (robot-assisted EVA). The MOONWALK scenario foresees one or two astronauts equipped with EVA suits (e.g. space suits) and special tools (e.g. for exobiology sampling) that are supported by a small, all-terrain assistant-robot (rover).

In addition to the technology development, MOONWALK built capacities and know-how related to European infrastructures for Earth analogue simulations. Such infrastructures are needed to validate European Space technologies under realistic environmental conditions while still being affordable.

The main technical achievements of MOONWALK were the development of core components needed for a robot-assisted EVA mission, including a simulation EVA space suit, a small helper robot, a user-friendly man-machine-interface (MMI), EVA information- and communication system system, a number of manual and robot-mounted tools to collect scientific samples, and a device to improve the online monitoring of the astronaut's vital signs.

The MMI was of particular interest, as it is needed to enable an astronaut in a heavy space suit to efficiently interact with the robot. The space suit severely restricts the mobility, the dextrosity, and the visual prerception capabilities of the astronaut. To overcome these restrictions, the MMI uses manual gestures for robot control and a data interface integrated in the EVA suit.

To demonstrate and validate the project results, two earth analogue simulations were conducted in the last year of the project. The first one was in Rio Tinto, Spain. In this campaign, a robot-assisted EVA on Mars was simulated. Rio Tinto has a morphology and a soil-chemistry that can be compared to Mars. Consequently, the focus of the mission was on exploration of the terrain and gathering of soil samples. Through a co-operation with the EU-funded SHEE project and the integration of the SHEE habitat in the simulation, a realistic EVA mission, including egress and ingress of the astronaut to a planetary habitat, could be simulated. The second analogue simulation was off the coast of Marseille, France. Here the mission scenario included the exploration of the lunar surface under simulated low-gravity conditions.

From the start, MOONWALK put a strong focus on public outreach and communication with European and international stakeholders, including ESA and NASA. Selected by a public Announcement of Opportunity, several experiments contributed by external stakeholders were integrated in the Rio Tinto and Marseille missions. Observers from ESA and NASA, including a real ESA astronaut, attended the simulations and provided valuable feedback. Through a children's competition for the best quote from the first astronaut on Mars and the best design for a Moon mission flag, the interest of the young generation in Space exploration and human spaceflight was ignited. Overall, the massive public and media interest in the MOONWALK simulations is proof that Space exploration is still a fascinating topic and that earth analogue simulations in Europe are not only valuable to validate key technologies, but also to efficiently promote human space flight .