MOONWALK
ASTRONAUT-ROBOT COOPERATION DURING SURFACE EVA

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ABSTRACT

The objective of the European Commission Project "MOONWALK" (H2020) was to develop robot-astronaut cooperation techniques and test those in two specific analogue missions: one in Rio Tinto, Spain and another one underwater offshore Marseilles. In the frame of the project, a team of seven partners developed a simulation architecture including space suit simulators ("GANDOLFI"), a robotic scout vehicle ("YEMO"), biomonitoring techniques, sampling tools and a communication architecture allowing communication with a distance Mission Control Centre (MCC) based in Zaventem, Belgium.
The paper and presentation will report on the mission simulations in Rio Tinto (Mars Mission) and Marseilles (Lunar mission). It will show the results of the project and give a vision on future work in this field where the test platforms developed in MOONWALK could be used for research or astronaut training.

1. INTRODUCTION AND OBJECTIVES

The MOONWALK project was a 3-year cooperative R&D project funded by the European Commission under the 7th Framework Programme. The project started in September 2013 and concluded in August 2016.
The objective of the project was the development and validation of concepts, operations and technology for future exploration missions (Lunar and Martian EVA) in Earth analogue environments. This includes the development of new methods for teamwork between humans and robots in EVA related to planetary exploration (robot-assisted EVA) and the development of Earth-analogue simulation equipment to train future astronauts in robot-assisted EVA related to geological and exobiological investigations in extreme environments. The equipment and methods developed were verified in two field simulations: in an underwater analogue in simulated reduced gravity, and in a terrestrial analogue with extreme environmental conditions and exobiological significance.

MOONWALK has developed technologies supporting future exploration missions, including technologies for astronaut-rover collaboration and wearable EVA Information System (EVAIS), as well as an EVA training suit based on future EVA spacesuits (NASA's Z-1 architecture). Time delay in communication to MCC was integrated in both campaigns (from a technical point of view); but this aspect is more of relevance for Martian mission simulations.
One major goal of the project was to develop and evaluate robot-astronaut cooperation by using the DFKI YEMO robot to assist the astronaut in certain activities. It is the purpose of the project to evaluate the impact of a robot companion in the EVA team (potentially versus a human companion) and to derive cooperation and control methodologies that lead to a real asset in manned surface EVA.

The combination of two analogues with specific gravity factors allow to study i) the influence of the reduced gravity in the EVA operations (by man and machine). The combination of mixed teams of astronauts and robots allows to study ii) the impact (positive or negative) that a robotic buddy has to the efficiency of the operations. Both team structures (astronaut-astronaut

and astronaut-robot) needed to be tested in both simulations campaigns (Marseilles and Rio Tinto); by using similar tasks (to assure fair comparison).

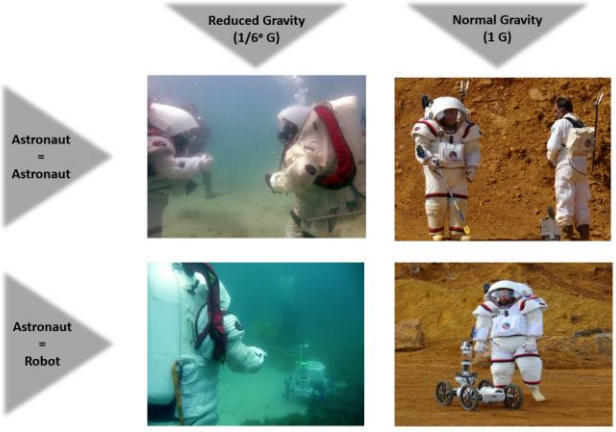

Figure 1: The factors of simulated gravity and team composition during the final simulations in Marseilles (left) and Rio Tinto (right).

2. ARCHITECTURE DEVELOPMENT

The earth-analogue simulations focused on evaluating the feasibility and efficiency of co-operation scenarios involving astronauts -equipped with EVA suits- including sampling tools, and supported by an assistant-robot (scout rover). The hardware developed in the frame of the project will be presented in the following sections.

2.1 The COMEX EVA simulation suit

A first EVA training suit, based on the ORLAN spacesuit, was available to the project ("Gandolfi" developed by COMEX) and the fabrication of a new second suit allowed to include novel devices, such as the EVA Information System (EVAIS) for robot control and means for communication/visualisation. Together with the already existing suit, the new suit also allowed to perform subsea simulations with two astronauts. These two training suit are designed for “wet” use (i.e. with a diver and its life support system inside). Nevertheless, the Gandolfi-2 allows a terrestrial utilization too.

The Gandolfi-2 concept has three main drivers: take into account ergonomics aspects of the NASA Z-1 suit, simulate constraints of movements as in a real pressurized space suit, and put the astronaut/diver into neutral buoyancy or reduced gravity. (This function is only available in underwater configuration.)

With a rear-entry concept, the design of the novel EVA suit is based on the next generation NASA spacesuits concept, namely “Z series”, that aims at increasing astronauts mobility. The EVA training suit is now completed and incorporates an exoskeleton made of hard parts in composite materials (fiberglass or carbon) and soft parts in neoprene, and bearings. The bearings location is directly inspired by the Z1 series spacesuit to allow rotations of shoulders, arms, thighs and pelvis. The final prototype of the novel COMEX EVA astronaut training suit is shown in the figure below. In order to simulate the movement constraints caused by the use of a pressurized spacesuit, the movement amplitudes of the Gandolfi-2 have been limited by the design itself and comply with the Z1 spacesuit movement constraint specifications. 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 via torsion springs, which are sized to be the closest to the Z1 spacesuit movement resistances. The current weight of the training suit is 33 kg in the air and around 6 kg underwater. Being assumed that the COMEX suit is a Z1 simulator with a total mass of 73kg during orbital or planetary missions, the target mass for the moonwalk training suit underwater is around 12kg for a lunar simulation (1/6 G). It should be noted that in terrestrial simulations, this concept does not make sense since a reduced gravity cannot be simulated in the air.

Figure 2: The COMEX EVA astronaut training suit during underwater trials in pool (left) and during terrestrial trials (right).

2.2 Man-Machine Interfaces and Mission Control

The project developed an innovative user-friendly EVA Information System (EVAIS) for efficient robot control under highly restrictive conditions (movement restriction through EVA suit, low visibility, etc.). Developed by Space Applications, the EVAIS was designed 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. The EVAIS includes a robot control sub-system and a data interface integrated in the EVA suit. The EVAIS features Operations Data File (ODF) procedure viewing, telemetry display, payload/robot operations, text/media/voice communication. It also has a special

screen for communications during emergencies.
A helmet camera streams video of the approximate current field of view of the astronaut. The EVAIS assumed three possible configurations: a wrist display, a chest display and a heads-up display, which are implemented for a comparability study. The EVAIS operated in conjunction with a Mission Control Centre in Brussels, Belgium. When operating in wrist display mode, the subject has the possibility of controlling the interface with a push button array that initially would be located on a retractable tether on the torso. The suit computer assembly (SCA) that manages data and communication was installed on the rear door of the training suit. This equipment has two versions: one for subsea trials and another one for terrestrial trials. The Mission Control Centre consists in a console for three positions (FLIGHT, CAPCOM and ROBO), manned by a group of experienced ISS flight controllers, who interacted with the suited test subjects during the EVA.

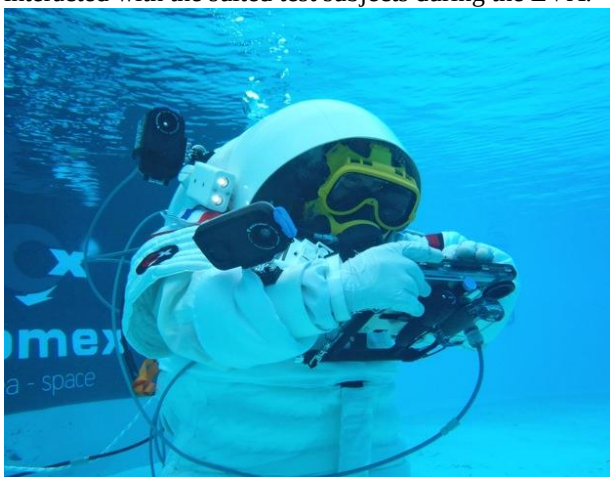

Figure 3: Test of the EVAIS during pool trials at COMEX.

Figure 4: The Mission Conrol Centre located at Space Applications in Brussels, Belgium.

2.3 Scout Robot YEMO by DFKI and IMU control

The robot used in MOONWALK was equipped with limited autonomous behaviour to be able to assist the astronaut in EVA with a minimum of user interaction. Inertial Measurement Units (IMU) were integrated in the suit's joints and allowed the astronaut to control the robot by arm movements.
YEMO was based on the ASGUARD and COYOTE robot family of DFKI. Each robot features hybrid-legged wheels and a passive body joint between the front and rear axis for maximum mobility in uneven terrain. This robot is the first one of this model capable of underwater operations. It films its environment with a panoramic camera mounted on the front. It provides in each frame a 360 degree panoramic picture with a vertical opening angle of approximately 90 degrees. Tracking of the astronaut can be performed in parallel to observations by scientist located on Earth or in a habitat. For interaction purposes the robot carries a full colour LED ring, consisting of 48 individual controllable LEDs. This allows the system to communicate different states and/or answers to the astronaut. The rover is capable in assisting the astronaut by e.g. providing floodlights as light sources, carrying a weather station during surface operations and acting as a tool carrier with the payload box. The data connection to the MCC was established via a Wi-Fi-Link during surface operation. During underwater operations the rover is tethered with a cable to the surface.

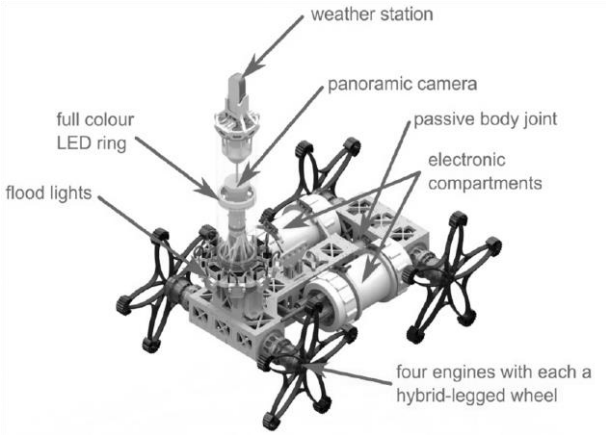

Figure 5: The YEMO Scout robot for EVA assistance developed by DFKI.

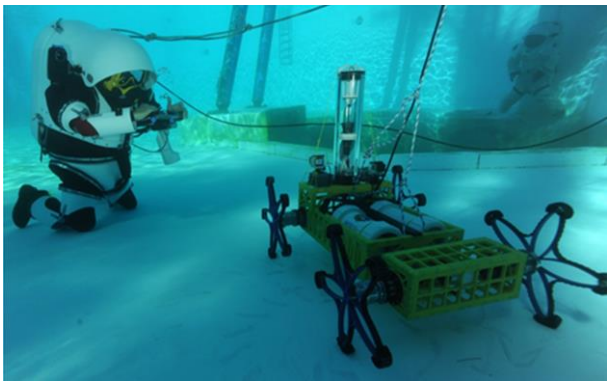

Figure 6: Robot control tests with the "astronaut" during pool trials.

The Gandolfi-2 features a gesture control architecture that allows to control the scout robot accompanying the astronaut without the use of a dedicated joystick but by gestures of the arms and upper body. The gesture control sensing is achieved by IMU distributed over the arms and upper body of the astronaut, those are fixed on the diver suit or shirt of the subject (for Marseilles and Rio Tinto respectively). The project evaluated the interaction of local (astronaut) and remote control of the robot under various time-delay conditions. Bio-monitoring equipment integrated in the EVA suit as well as gesture and pose recognition implemented on the robot enabled the monitoring of the astronaut's state of health. In case of emergency, the robot would be able to support the MCC in rescue operations.

2.4 EVA sampling tools by LIQUIFER

Manual tools for EVA support a range of astronaut-robot interactions of various degrees of complexity. The tools used in MOONWALK were manually operated by the astronaut and included the following items: an Astronaut Rescue Tool, an Astronaut Tether Control, Pantograph Sampling Tool, Foldable pick-up Claw.
The Astronaut Rescue Tool is for astronaut assistance should he/she fall over. It is a manual tool which is positioned in a separate compartment of the Payload Box. 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 device with adapted handle and anti-slip elements along the stick. The Astronaut Tether Control is the manual control for the rover scouting a steep slope. It is developed from an off-the-shelf retractable tether system with adapted control buttons and has a 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 is a retractable sampling tool which can be used single handed to collect samples directly into a sample box and feed them into the YEMO payload box. The design is derived 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 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.

2.5 EVA suit Biomonitoring system

The Biomonitoring system of MOONWALK consists of a heart rate measurement system that allows to derive different grades and types of stress (in function of heart rate variability). The sensor measuring the heart rate is placed directly on the skin of the subject. It communicates with a receiver unit placed in proximity. Both units are COTS systems and are supposed to be able to communicate underwater (short distance). The receiver unit is communicating with the SCA via an umbilical with USB connection. The elements itself are watertight since encapsulated (including the batteries; the whole element is replaced when the batteries are empty).

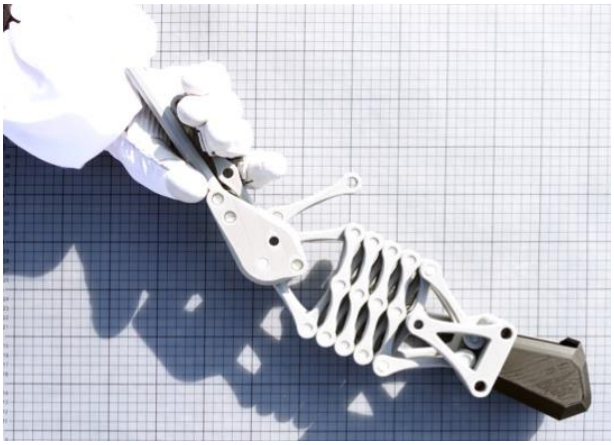

Figure 7: The Panotgraph Sampling tool for EVA developed by LIQUIFER

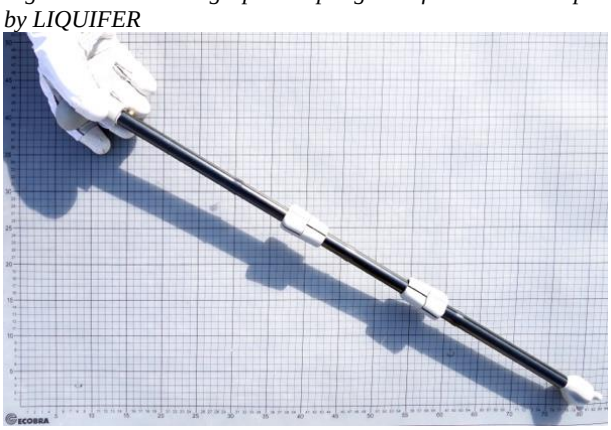

Figure 8: Astronaut Rescue Tool for assitsance when fallen over.

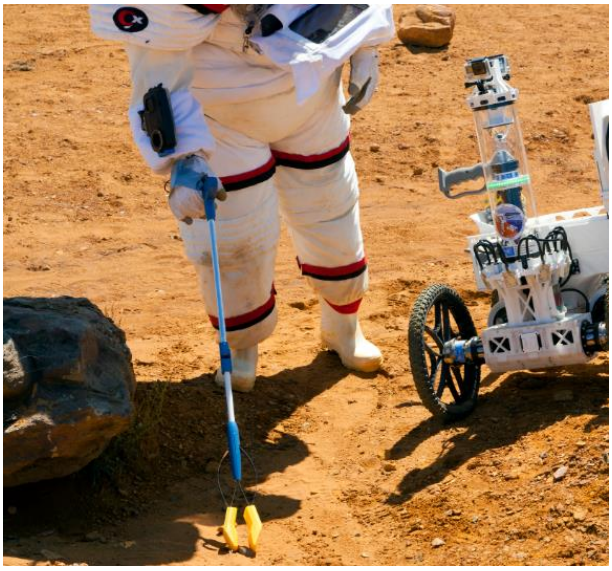

Figure 9: The Foldable Pick-up Claw used by the astronaut during the Rio Tinto simulations (photo: B. Stubenrauch)

3. SIMULATION CAMPAIGNS

The project aimed at simulating a planetary exploration mission to Mars or to the Moon and followed the architecture of the figure below.

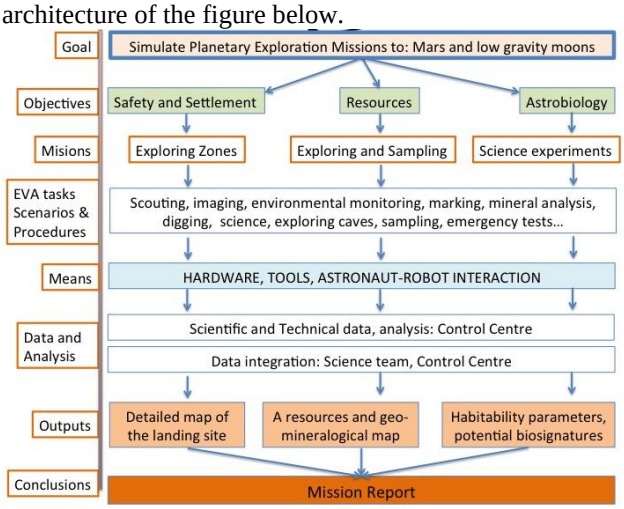

Figure 10: Architecture of the two mission campaigns

3.1 Rio Tinto Mars simulation

The Rio Tinto simulation campaign had been set up accordingly to one of MOONWALK project's task definition: "The objective is to simulate future mission by astronauts and robots to the surface of Mars." Contrary to the Moon mission, this scenario included exobiological procedures to search for remnants of life. Sampling techniques (robotic and manual) were tested during this campaign. It also included the use of a space habitat simulator developed by the SHEE project (www.shee.eu) during these trials.

The main objective of the Rio Tinto simulation were:

A) Perform EVA simulations of planetary exploration on Mars, in both Astronaut-Astronaut and Astronaut-Robot configurations, for the evaluation and comparison of their respective ability to perform a set of predetermined tasks gathered in a number of scenarios.

B) From the SHEE habitat, Astronauts or Astronaut-Robot teams will perform EVA among a predetermined itinerary in which they will use their HMIs and the communication with the CAPCOM hosted in the habitat to follow a specific procedure. Astronauts will be bio-monitored from the habitat and will exchange scientific data and instructions with a control centre- figuratively on Earth- with a time delay of 7 minutes each way.

Figure 11 shows a satellite image of the itineraries that were performed during 39 EVAs.

Three distinct communication loops were used to simulate remote collaboration between a crew on Mars and a control center back on Earth:

- Communication loop 1: Live voice communication between CAPCOM, Astronaut 1 and Astronaut 2
- Communication loop 2: Delayed communications between CAPCOM, Astronaut 1, Mission Control 1 (in Rio Tinto) and Mission Control 2 (in Brussels)
- Communication loop 3: Live communication between Mission Control 1 and 2 thanks to screen sharing

Figure 11: Rio Tinto itineraies

The COMEX suit simulated the weight of a potential future spacesuit on Mars (in Martian gravity). The project delivered therefore results on the performance that can be expected from astronauts on that planet using such equipment, and certain limitations that could be a design driver for novel surface EVA suits of the future. Following table shows the "records" of the simulations: maximal distances, maximal mission durations and maximal speeds.

Table 1: "Records" of the Rio Tinto simulation

	In 1 EVA	Accumulated/peak
Distance	*780m* *Max distance for 1 EVA*	*2200m* *Max cumulative distance for 1 subject*
Time	*00:52:00* *Max time for 1 EVA*	*04:01:49* *Max cumulative time for 1 subject*
Speed	*3,05 km/h* *Max average speed*	*5,1 km/h* *Max speed peak*

One clear limitation induced through the suit itself was the weight of the system and the resulting physical effort. The movement constraints (articulations and gloves) also led to difficulties, which however were

overcome through the design of specific tools. As last element can be named the off-times, when an astronaut had to stand-by for instructions, or repetitions, when an astronaut had to go back and perform or redo tasks, through the time delay (in a Mars mission). Those can be tackled through adapted communication protocols.

Figure 12: The Rio Tinto set-up with the COMEX suit (locked to a suit-port on SHEE) and the SHEE habitat.

3.2 Marseilles Moon simulation

Marseille simulation campaign has been set up accordingly to one of MOONWALK project's task definition: "The objective is to perform a simulated Moon mission at an analogue site offshore Marseilles. The objective of these tests will be to validate the human-robot interaction architecture and to simulate various activities that future astronauts might perform on the Moon (cave exploration by robot, crater descent, installation of instruments and mock-up habitation structures)."

In (Weiss et al., 2012) nine potential lunar analogue sites have been identified in the area of Marseilles, in the Calanques National Park. At a reasonable depth they have been selected for geomorphological similarity with some interesting parts of the Moon, some geological formation being close to the shape of little craters.
Among them, Port de Pomegues has been selected because of its low exposure to the wind, its good communication data coverage, and the fact that the COMEX vessel MINIBEX can easily navigate in this zone. The site has been explored to identify several sampling and scouting locations, an appropriate spot for the Lunar Exploration Module mock-up landing, and a slope that could be used to test astronaut/robot collaboration while scouting an uneven terrain.
Figure 13 shows an aerial view of the site with all deployed surface equipment (vessels).

Among the number of EVAs conducted underwater, three fully successful and exploitable ones were conducted in the pool, and three as well in the sea, for a total time of simulation underwater of approximately 6 hours. Although in term of technical outcome, differences between pool tests and sea trials is not much, it is important when talking about human factors and immersion of the astronaut subject into an EVA scenario. The workflow is much more fluid and easy in a pool, with less operational constraints, but the few hours of simulation on the seabed harvested from three days on the sea are of a great value to reproduce the extreme environments inherent in any planetary exploration mission. Three subjects performed the simulations underwater, and all of them performed a training session in the pool before going into the sea at Port de Pomègues. This reduced pool of test subjects was due to the necessity to set up this time consuming training session, and to operational constraints on the boat.

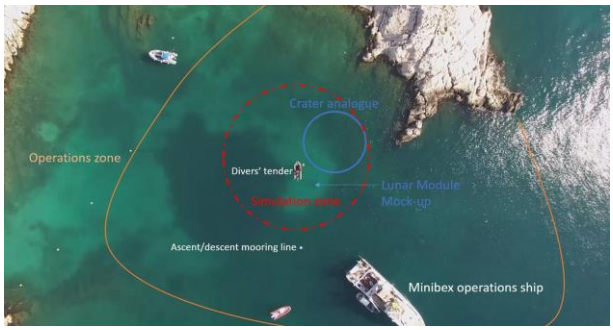

Figure 13: Aerial view of the Marseilles site during the simualtion.

Looking back at the two simulation campaigns, a tension was identified between the easiness of operations necessary to test efficiently some equipment (Rio Tinto) and the authenticity of the EVA scenario to make the most of the human factors data post-processing (Marseille, underwater). To that extent, the temporal order in which the simulation architectures were set up, first in Rio Tinto and secondarily in Marseille, appeared to be valuable. It was indeed more interesting to use Rio Tinto for troubleshooting, testing of all the equipment, rehearsal of the subsystem's synchronization, because it is an analogue environment in which the systems are easily accessible to engineers and technicians. Conversely, in Marseille, every troubleshooting would have been costly in terms of time and organization because there is very little the technical teams can do from the vessel.

While Rio Tinto was an excellent environment for engineering and testing space equipment, Marseilles is much more appropriate to train astronauts in a more challenging environment.