SURFACE EXPLORATION ANALOGUE SIMULATIONS WITH A CREW SUPPORT ROBOT

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ABSTRACT

Robots are likely to play an important part as support for future human exploration missions on Mars and Moon. Robotic assistants have the potential to improve the efficiency and safety of human surface activities. The control of robots in space is non-trivial because astronauts are limited in their movements by a bulky spacesuit and missing or reduced gravity. The EU funded project Moonwalk investigates technologies for robotic crew assistance and methods for performing earth analogue simulations. A hybrid leg/wheel system is used as the robotic platform, which is equipped with an omnidirecional camera to monitor the astronaut. The robot can be controlled by gestures which are detected with sensors attached to the human. In this paper we present the requirements, progress and outlook on the robotic system and the supporting technologies.

Key words: Field Robotics, Analog Missions, Moon, Mars.

1. INTRODUCTION

The last time a human has performed extraterrestrial surface activities was during the Apollo missions in 1972. Since then robotic technologies have advanced significantly. They will likely play an important role when it comes to revisiting the Moon, exploring an asteroid or going to Mars [1]. The control of robots in space is non-trivial because astronauts are limited in their movements by a bulky spacesuit and working under reduced gravity [2]. This paper discusses the progress of the EU funded project Moonwalk, which develops new, practical methods for the interaction between astronauts and robots [3]. One of the challenges in earth-analogue simulations of missions to Moon or Mars are the operational constraints such as the reduced gravity or the communication delay between the astronauts on a planetary surface and mission control on Earth.

In the project Moonwalk, two analogue simulations are planned for the conditions that astronauts will encounter during future extravehicular activities (EVA) on Moon or on Mars: The project will conduct simulations offshore the coast of the French city of Marseille, where an EVA on the lunar surface under reduced gravity will be simulated [2]. A second simulation will be conducted in the Spanish region of Rio Tinto, where operations are focusing on exobiological sampling and sampling procedures under extreme environmental conditions [4].

The paper contains a general overview of the Moonwalk project. Special emphasis is put on the design and construction of the robot, which is used as a companion to the astronaut in the analogue missions. Further, a gesture based method is proposed, which is used to control the robot in-situ by the astronaut. In the paper we discuss the design constraints for the rover, and provide details on the final design including an omnidirectional camera as part of the sensor setup. The rover is based on the Asguard[5] system, which has already been evaluated in a number of terrestrial settings [6]. An additional difficulty is introduced by the system to be operable at the environmental pressure at the subsea analogue site in Marseilles, and the dusty environment in Rio Tinto.

2. SIMULATION SCENARIOS

The MOONWALK project incorporates two simulation campaigns; one at the Subsea Analogue Site in Mar-

Figure 1. Subsea Analogue Site in Marseilles, France

Figure 2. Mars Analogue Site in Rio Tinto, Spain

seilles, France (see Fig. 1) and one at the Mars Analogue Site in Rio Tinto, Spain (Fig.2).

The Subsea Analogue Site will be used to simulate activities of a robot-supported crew on the lunar surface in reduced gravity ($1/6\,\mathrm{g}$). The tests will be performed in water depths between $-5\,\mathrm{m}$ and $-15\,\mathrm{m}$ and require all equipment to comply with the boundary conditions of this water depth. The site offers different types of geological morphologies such as crater-like formations (subsea sinkholes), plains with sediment and cliffs.

The Mars Analogue Site in the Rio Tinto acidic basin is emplaced in the south western area of Spain, the Huelva province. The most interesting area to test MOONWALK is in the north, which is comprised of Rio Tinto, Nerva, Berrocal, La Palma del Condado and Niebla localities. It is here where the river shows a closest analogy to Mars. This area is characterized by highlands ($100\,\mathrm{m}$ to $660\,\mathrm{m}$) and a high stability in the hydro-chemical parameters such as pH, which remains between 0.9 and 3 (mean value of 2.3), and a high concentration of iron in solution (between $1.5\,\mathrm{g\,l^{-1}}$ to $20\,\mathrm{g\,l^{-1}}$).

The two analogue sites offer;

- an opportunity to study the behaviour of equipment, involving simultaneous usage of instruments by a human astronaut fitted with EVA suit
- a platform for testing various hardware, tools and techniques for scouting, imaging, monitoring, mapping, analysing and sampling the terrain
- the possibility to study iron-sulphate containing minerals (jarosite, hematite) and rocks as a model for their Martian counterparts
- the possibility to test EVA procedures and operations in reduced gravity conditions (neutral buoyancy)
- a platform for testing support teams in a remote location

Six simulation scenarios were designed, casting the robot rover an essential role in assisting the astronaut with exploration, scouting, sampling and construction activities. Furthermore, the robot is able to aid the fallen astronaut in emergency situations. All scenarios will be tested at both analogue sites and will be compared and evaluated thereafter. Specificities of selected scenarios showing the capabilities of the Asguard rover in joint activity with the astronaut will be discussed.

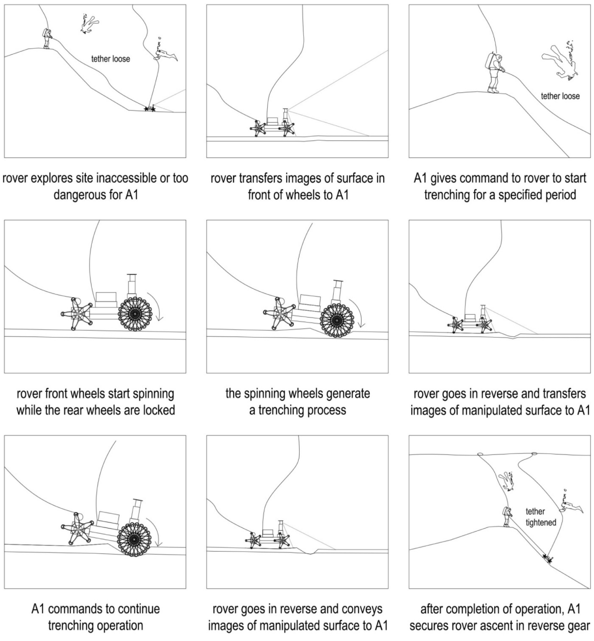
A generic challenge of robot designers is one of uncertainty of the specific task that the robot will be required to execute. New methodology to support the design and development of space robotic systems working side by side with humans in a dynamic exploration setting have been developed as part of Moonwalk project [7].

Although it is largely understood by the scientific community in the field of exploration that in a real-case-basis of EVA, a minimum of two astronauts will go on EVA, and will very likely be assisted by a large piece of equipment such as a buggy or even pressurized rover - Moonwalk focuses on the less explored possibilities of cooperation between a small rover and an astronaut. Moonwalk intends to show that, even under these operational scenarios, scientific exploration of the Lunar and Martian surface can be conducted in sensible and useful ways.

When exploring unknown terrain on extra-terrestrial surfaces, the range of an astronaut is limited due to his Life Support supplies, the capabilities of the bulky suit and the availability of rescue measures in case of emergency. Exploration of sites which can jeopardize the safety of an astronaut will be avoided by all means possible.

The Asguard rover is made to explore a wide range of rugged and uneven terrain and permits research in regions deemed unsafe for the human astronaut. The robot can assist the astronaut in exploring these sites via camera and measuring devices, such as the Raman spectrometer.

Thus, the rover can support the astronaut in evaluating the potential of astrobiological or geological research interests in regions un-explorable by the astronaut, such as a steep-sloped crater. The Asguard is tethered so in the



rover explores site inaccessible or too dangerous for A1

rover transfers images of surface in front of wheels to A1

A1 gives command to rover to start trenching for a specified period

rover front wheels start spinning while the rear wheels are locked

the spinning wheels generate a trenching process

rover goes in reverse and transfers images of manipulated surface to A1

A1 commands to continue trenching operation

rover goes in reverse and conveys images of manipulated surface to A1

after completion of operation, A1 secures rover ascent in reverse gear

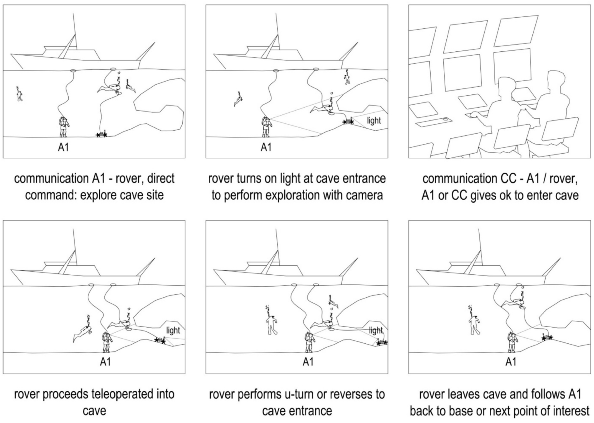
Figure 3. Storyboard of the trenching scenario to be evaluated during our field trials in 2016

case it cannot autonomously accend the crater wall, the astronaut has the potential to assist the rover, pulling it upwards.

Another important part of exploration is taking samples. New astronaut suits for future exploration will be more ergonomic and will allow the suited person to bend down and to kneel; however, the risk of loosing balance and falling down especially under partial gravity remains present. The rover robot can assist the human with sampling; in trenching (see Fig. 3) part of a selected area to enable the astronaut to take a sample and to have access to the soil below the cover layers; or by providing the astronaut with data from the Raman spectrometer and in the form of rover camera images from areas hard for the astronaut to access. The rover can be helpful in both cases; hard to reach areas, such as a crater or, on flat terrain where the astronaut can take samples from the terrain and utilize the rover's payload box for its storage capacity.

An unexplored cave (see Fig. 4), either too narrow or too dangerous, is another example, where a small robot can aid an astronaut in sampling. A robot that can traverse challenging terrain and is small enough to access hard to reach regions within caves is ideal for taking pictures or spectrometer measurements; information which can be transferred to the astronaut for evaluation. Thus, the very first scouting activity can determine the scientific value of a particular cave site without endangering a human.

Constructing a shed for tools, machinery parts or for samples can be useful either to protect the samples against the dust or to shield them from sun exposure. As depicted in the Figure below the Asguard offers fixings for poles so that one astronaut can construct simple devices on his or her own without the help of a second astronaut.



communication A1 - rover, direct command: explore cave site

rover turns on light at cave entrance to perform exploration with camera

communication CC - A1 / rover, A1 or CC gives ok to enter cave

rover proceeds teleoperated into cave

rover performs u-turn or reverses to cave entrance

rover leaves cave and follows A1 back to base or next point of interest

Figure 4. Storyboard of the cave scenario

Apart from nominal situations and planned activities also off-nominal situations and emergencies can arise. One instance is when an astronaut loses his/her balance and falls down. The Life Support backpack is heavy and hinders the astronaut to easily get back up. The rover is equipped with a deployable stick which it can bring to the astronaut so s/he can easily grab it and pull him/herself up again. More serious emergencies such as a broken leg requires the aid of another astronaut and/or a larger vehicle where the astronaut can sit and be taken to the nearest base.

3. ROVER

The scenario and project design of Moonwalk incorporates a robotic rover, to assist and support the astronaut during the simulations. In section 1 we introduced some scenarios, we are planning to test during our simulations in 2016. Based on this scenarios the main requirements for the rover are defined as:

- Follow the astronaut in his/her natural speed ($\approx 1.5\,\mathrm{m\,s^{-1}}$).
- Survey the environment with a omnidirectional camera or a pan/tilt unit.
- Carry a payload of 5 kg and provide assistance in exploration.

For the second point, we decided to use an omnidirectional camera. This allows a permanent surveillance of the entire surroundings. Further details of the camera construction are discussed in section 7.

The CAD rendering in Fig. 5 shows the final configuration of the rover, as it is currently planned to be used in 2016. Main components of the rover are highlighted:

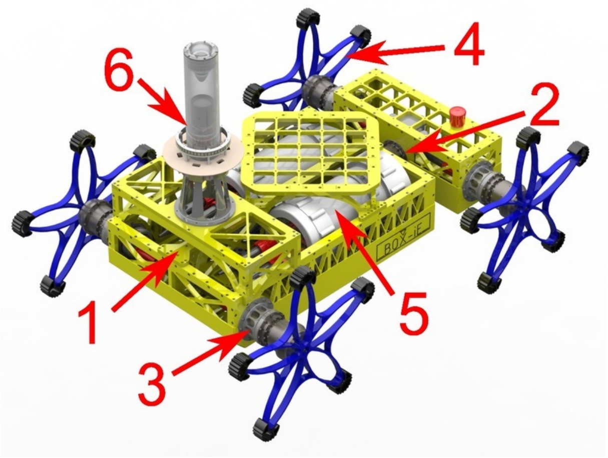


Figure 5. CAD rendering of the MOONWALK rover

Main frame (1) – The main frame is made from 10 mm thick polyethylene sheets. Each individual part was water jet cut and screwed together. Perpendicular mounting of the sheets stiffens the frame and allows to applied higher loads to it. In addition standard mounting points, 3 mm in diameter and spaced in a 50 mm × 50 mm grid, allow flexible mounts of different sensors and/or equipment.

Passive joint (2) – The passive joint connects the front and rear frame. It allows a passive rotation of the rear frame along the longitudinal axis of the rover. The rotation allows all four wheels to have ground contact in uneven terrain, but it is on the other hand limited to 30° to either side.

Motor modules (3) – Each motor module is enclosed in an individual pressure housing. A module is constructed of the brushless DC motor with a 1:50 reduction gear attached. To protect the seals from the dust thrown up by the wheels, a dust protection is applied too.

Hybrid legged wheel (4) – Each wheel is driven by a single motor. The wheel design allows the rover to climb over obstacles, that are higher than the wheel radius (e.g. stairs). This increased mobility capabilities allow access to difficult to reach areas and increase the operational range of the rover. Additionally the wheels provide dampening of the main frame.

Pressure housing (5) – PVC pressure housing. One will contain the on-board computer, where the other one contains the main battery.

Omnidirectional camera (6) – Further discussion in Section 7.

The entire rover will have a size of 700 mm × 700 mm × 650 mm, and a final mass of ≈ 23 kg on land.

Since the rover will be operated in salt water and on land, we chose corrosion resistant materials. The main parts, such as the frame and pressure housing, are made of plastics. Mechanically stressed parts are made of titanium, such as the motors and the passive joint. Parts made of different types of metals are isolated from each other, to reduce the risk of contact corrosion. We use standard stainless steel screws for most of the housing.

Another reason for the choice of polyethylene as the main frame material: Its density is close to 1, which makes it nearly neutral buoyant in water. In our case, we need to achieve as specific weight underwater, compared to the weight in air, if we want to simulate lunar or martian gravity. Due to the density of near 1, the frame does only have a minimum weight under water and does not interfere too much with the gravity compensation.

4. BUOY

Acoustic sub-sea communication is limited to ≈ 50 kbit/s This small bandwidth is not sufficient to allow transmission of live video data from the rover, as discussed in Section 3. To circumvent this problem, we will be using a surface buoy, as shown in Figure 6, with Wi-Fi access point. The buoy itself will be connected with an umbilical to the rover. This setup provides high-speed broadband data transmission from and to the rover. It also helps to localize the rover from the supply vessel, since the buoy marks the rough spot of the rover on the sea floor.

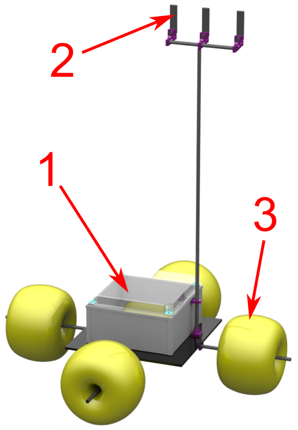


Figure 6. Rendering of the surface Wi-Fi buoy

Main features of the buoy are annotated in Figure 6. These are:

Electronics compartment (1) – The watertight box holds all required electronics for the operation of the buoy. In essences these are the router and a battery. For logging purposes a GPS receiver may be added, if need be. Also additional batteries for the rover may be added here to increase the operational time of the rover.

Wi-Fi Antennas (2) – The antennas are mounted on a 1 m pole. This position should allow direct contact between the buoy and the ship even with minor swell.

Floatation device (3) – The floatation devices provide the necessary buoyancy for the buoy. If required, the assembly can take additional ones to achieve a least a weight to buoyancy ratio of 1:3. To prevent capsizing a small flotation device will be added to the Wi-Fi pole. This prevents upside down scenarios by limiting the capsize angle to 90°.

The umbilical will be connected to the bottom of the buoy. To prevent entanglement of the umbilical with the rover or other simulation participants, it will be tensioned with the help of a tension device. This should also help to keep the buoy located above the rover without too much drifting.

5. GESTURE CONTROL INTERFACE

The rover can be controlled in a number of ways. One of these modes is the operation by one-handed gesture commands from the astronaut.

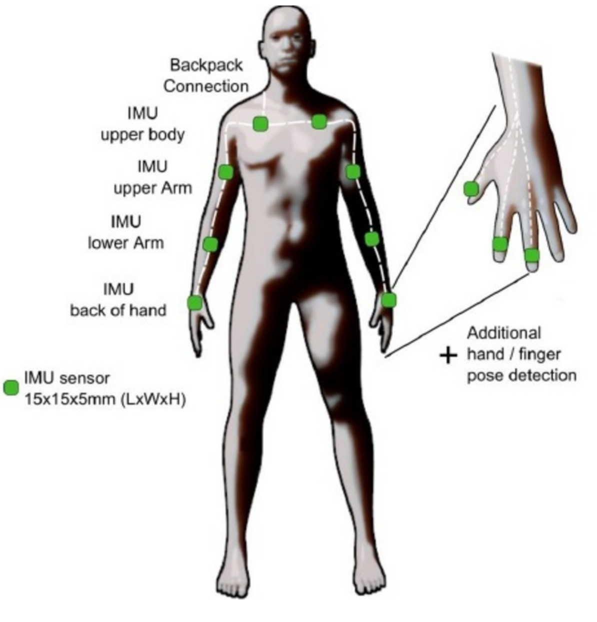


Figure 7. Physical gesture capture concept - sensor placement

To be able to record the pose and movement data of the user needed for gesture interpretation in the context given, a number of IMU sensors is attached to specific locations of the user's arm and fingers. Furthermore, to have the gesture capture setup being able to switch between arms used for issuing gesture commands - that is, using either the right or left arm for input - the sensor placement is also symmetrically mirrored to the other arm respectively (cf. fig. 7), which allows left-handedness of the potential user as well. The focus to one-handed gesture command input and the possibility to switch the particular arm used for input while performing command gestures also enables some kind of "hands-free commanding", i.e. the user is able to issue gesture commands using one arm, while simultaneously performing other tasks using the other arm as well, mostly even independently from the user's actual posture, which is achieved by using relative position changes to interpret the gesture commands issued.

The specific scenarios the gesture capture is to be performed in presents additional challenges: as the astronaut suit which is to be worn by the user within the scenario context can be expected to severely limit the freedom of movement of the user, this is also limiting the number of gestures and command movements available for controlling the robot. The underwater demonstration introduces even more constraints, as divers (which will be present in this demonstration for safety reasons) claim a certain set of special gestures for themselves (e.g. for signalling some kind of distress situation).

To cope with this constraints and challenges, a multi-level concept of gesture control has been specified, essentially consisting of *modes* and *options* (cf. fig. 8). The basic idea behind this concept is, that to issue a certain command to the robot, the user would initially perform a specific gesture sequence that chooses a corresponding *mode of operation*. Then, in succession the user is able to set *operation-specific options* by performing additional gesture sequences while in the chosen mode. E.g., to have the rover move to a certain spot, the user would at first perform a gesture sequence that sets the rover into the "direct command" mode and then perform the gestures that actually move the rover.

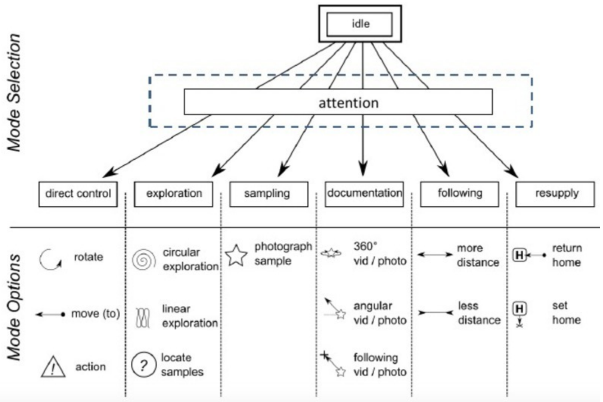


Figure 8. Outline of the gesture control concept, showing the two levels of input: modes and options. By dividing commands into this hierarchical structure, gesture sequences can be reused corresponding to different operation contexts.

Using this approach, many of the gestures from the set of available gestures, limited by the constraints of the scenario as outlined before, can be *reused*, depending on the currently chosen mode of operation, which allows the control concept to efficiently cope with this issue without loosing control options or flexibility.

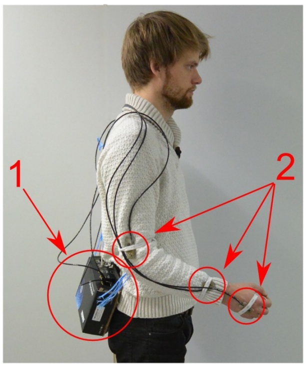


Figure 9. Prototype setup of the IMU suit, showing control device prototype (1) and sensor modules attached to certain areas of the arm (2) to be captured for gesture command recording

Additionally, there is a set of special gesture commands that will be interpreted independently of the current mode: *Stop*, *suspend* and *resume*. While the stop command allows to interrupt any operation currently performed, the two latter commands allow for e.g. making adjustments to such a operation without having to completely restart it. If, e.g. the rover is executing an autonomous exploration task and is required to continue this task at a different location, the user may simply *suspend* it by performing the corresponding gesture sequence, then switch to the "direct control" mode, move the rover, and finally *resume the former exploration task* at the target location.

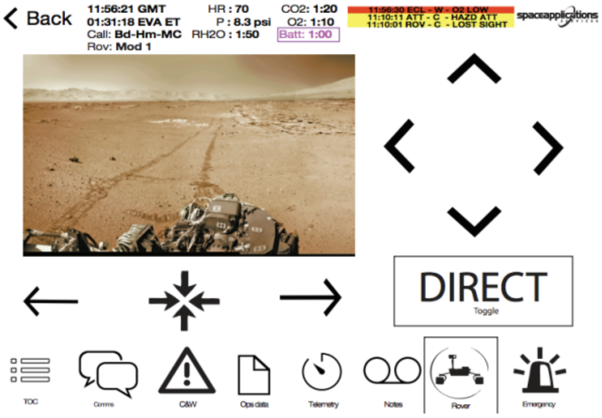
Figure 10. Image of first outdoor tests; the rover is controlled by (simplified) gesture commands - basically, after being set into a "attention" mode, the rover mimics the movements of the user's arm [e.g. it moves forward, if the arm is moved into that direction, or starts to rotate if the arm is moved sideways]

First test trials with a prototype of the gesture capture hardware (see Fig. 9) and a simplified version of the control software have been successfully performed in a outdoor situation (see Fig. 10). Those trials proved the general feasibility of the gesture control concept, but also impressively emphasised the possible benefits of using such kind of control: moving a rather complex device as the rover robot can be performed very intuitively, with minimum effort and surprisingly precise using gestures for control input.

6. OTHER ROVER CONTROL INTERFACES

Besides the gesture control interface, the Moonwalk project will also implement a few more conventional ways of commanding the rover robot: the astronaut will have the capability to command the rover via a dedicated user interface on the chest display or via a joypad which is part of the wrist display. Furthermore for the Marseille analogue simulation (lunar EVA simulation) the Mission Control Centre (MCC, located in Brussels) will have the capability to command the rover as well, taking into account a OWLT (One-Way Light Time) delay in the order of seconds. A comparative study of the usability of the different control interfaces will be performed by examining EVA tasks on test subjects (sim astronauts), during the Moonwalk analogue simulations.

On the touch screen chest display, the astronaut can select the rover dedicated User Interface (UI). When the tab is opened the *rover control activity* is started: it allows sending and receiving TC/TM to and from the rover and connecting to the rover's video stream if available. One example UI mock-up can be seen in Fig. 11. The user can toggle between different control methods: *Direct*, *Modes* and *Gestures*. Within *Modes* the user can select different (semi-) autonomous operation modes, e.g. *follow-me*. When the astronaut is controlling the rover robot via gestures, the UI on the chest display will just show the video stream sent by the rover.



11:56:21 GMT
01:31:18 EVA ET
Call: Bd-Hm-MC
Rov: Mod 1
HR : 70
P : 8.3 psi
RH2O : 1:50
CO2: 1:20
O2: 1:10
Batt: 1:00
11:56:30 ECL - W - O2 LOW
11:10:11 ATT - C - HAZD ATT
11:10:01 ROV - C - LOST SIGHT

Figure 11. View of control system when the rover is controlled directly (Forward, Left, Right, Backward)

The wrist display control interface will be similar to the chest display *rover control activity* user interface, but due to the limited space on the screen (and the astronaut's gloves) the touch screen interaction -as present in the chest display- will be replaced by physical buttons. The rover control interface available in the MCC will be similar to the one available on the astronaut's chest display.

7. CAMERA

As introduced in Section 3 we are planning to use a omnidirectional camera on the rover. This setup provides multiple advantages for our simulations:

- The rover can at all times survey its entire surroundings. This helps in tracking the astronaut and mapping the simulation area.
- Due to the single viewpoint [8] of the camera, virtual planar projections of the image can be generated, essentially providing multiple virtual pan/tilt units.
- No moving part are required on behalf of the camera, which increases the robustness of the system.
- Multiple viewers can lock onto the camera, and focus at different parts of the image.

Figure 12 shows a cut view of the camera. The light blue area marks the calculated field of view, with a viewing angle of 30° above and 60° below the horizontal plane. The camera assembly has an estimated mass of 1.5 kg with a tube diameter of 70 mm and 400 mm total height. The main parts of the assembly as marked in Fig. 12:

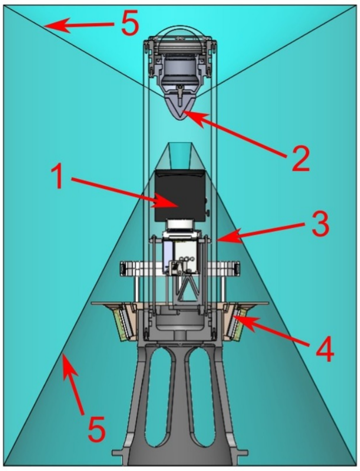


Figure 12. Cut away view of the Omnicam interior with the calculated field of view

Camera with lens (1) – The camera is a commercial of the shelf Ethernet camera with a telephoto lens. Resolution will be 4 Megapixel with a square sensor.

Hyperbolic mirror (2) – The key property of the mirror is, that all incoming light rays are mathematically collected in one point. This allows a reprojection of different virtual views.

Pressure housing (3) – As previously described for the rover, the pressure housing is here also made from plastics to reduce corrosion risks. The main tube is made of acryl for a full 360° view. While the bottom cap holds the camera assembly and the top one the mirror with a fine adjustment mechanic.

Illumination assembly (4) – The main lights help to improve lighting conditions for the camera. This is especially required for cave scenario. A second ring of color LEDs provides visual feedback on commands from and for the astronaut during the simulation.

Field of view (5) – The marked borders show the upper and lower limits of the field of view of the camera.

ACKNOWLEDGEMENTS

The project MOONWALK is financed by the EC Program SPA.2013.2.1-02 under the contract number 607346.

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