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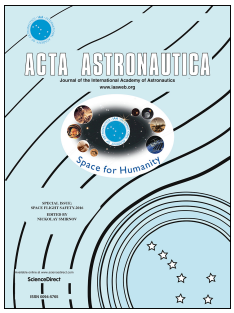

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Analysis of a Moon outpost for Mars enabling technologies through a Virtual Reality environment

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Abstract

The Moon is now being considered as the starting point for human exploration of the Solar System beyond low-Earth orbit. Many national space agencies are actively advocating to build up a lunar surface habitat capability starting from 2030 or earlier: according to ESA Technology Roadmaps for Exploration this should be the result of a broad international cooperation. Taking into account an incremental approach to reduce risks and costs of space missions, a lunar outpost can be considered as a test bed towards Mars, allowing to validate enabling technologies, such as water processing, waste management, power generation and storage, automation, robotics and human factors. Our natural satellite is rich in resources that could be used to pursue such a goal through a necessary assessment of ISRU techniques.

The aim of this research is the analysis of a Moon outpost dedicated to the validation of enabling technologies for human space exploration.

The main building blocks of the outpost are identified and feasible evolutionary scenarios are depicted, to highlight the incremental steps to build up the outpost. Main aspects that are dealt with include outpost location and architecture, as well as ISRU facilities, which in a far term future can help reduce the mass at launch, by producing hydrogen and oxygen for consumables, ECLSS and propellant for Earth-Moon sorties and Mars journeys. A test outpost is implemented in a Virtual Reality (VR) environment as a first proof-of-concepts, where the elements are computer-based mock-ups. The VR facility has a first-person interactive perspective, allowing for specific in-depth analyses of ergonomics and operations. The feedbacks of these analyses are crucial to highlight requirements that might otherwise be overlooked, while their general outputs are fundamental to write down procedures. Moreover, the mimic of astronauts' EVAs is useful for pre-flight training, but can also represent an additional tool for failures troubleshooting during the flight controllers' nominal operations. Additionally, illumination maps have been obtained to study the light conditions, which are essential parameters to assess the base elements location. This unique simulation environment may offer the largest suite of benefits during the design and development phase, as it allows to design future systems to optimize operations, thus maximizing the mission's scientific return, and to enhance the astronauts training, by saving time and cost.

The paper describes how a virtual environment could help to design a Moon outpost for an incremental architecture strategy towards Mars missions.

Keywords: Virtual Reality, Moon outpost, Illumination analysis, Incremental exploration architecture

Acronyms/Abbreviations

Two-Dimensional (2D)
Three-Dimensional (3D)
Four-Dimensional (4D)
Assembly Integration and Test (AIT)
Augmented Reality (AR)
Ames Research Centre (ARC)
Computer-Aided Design (CAD)

Crew Module (CM)
COllaborative System Engineering (COSE)
Digital Elevation Model (DEM)
Deep Space Gateway (DSG)
European Astronaut Centre (EAC)
Environmental Control and Life Support System (ECLSS)
Earth-Moon Lagrangian point 1 (EML1)
Earth-Moon Lagrangian point 2 (EML2)
European Space Agency (ESA)
Extra Vehicular Activity (EVA)
Fluid Science Laboratory (FSL)
Graphical User Interface (GUI)
Habitat Demonstration Unit (HDU)
Hubble Space Telescope (HST)
Initial Mass to Low Earth Orbit (IMLEO)
Italian Mars Society (IMS)
In Situ Resource Utilization (ISRU)
International Space Station (ISS)
Japan Aerospace Exploration Agency (JAXA)
Johnson Space Center (JSC)
Laser ALTimeter (LALT)
Low Earth Orbit (LEO)
Lunar Orbiter Laser Altimeter (LOLA)
Lunar Reconnaissance Orbiter (LRO)
Model Based System Engineering (MBSE)
Molten Oxide Electrolysis (MOE)
National Aeronautics and Space Administration (NASA)
OpenSG Binary (OSB)
Personal Computer (PC)
Pressurized Lunar Rover (PLR)
Stand Alone Power System (SAPS)
SELenological and ENgineering Explorer (SELENE)
Small Missions for Advanced Research in Technology (SMART-1)
Space Transportation System (STS)
Thales Alenia Space Italia (TAS-I)
Technology Readiness Level (TRL)
Technology Research Office (TRO)
United Space Alliance (USA)
Virtual Environment (VE)
Virtual European MaRs Analogue Station for Advanced Technologies Integration (V-ERAS)
Virtual Environment Research in Thales Alenia Space (VERITAS)
Virtual Interactive Environment Workstation project (VIEW)
Virtual Visual Environment Display project (VIVED)
Virtual Reality (VR)
Virtual Reality Modelling Language (VRML)
eXtensible Markup Language (XML)

1. Introduction

A rising interest for the Moon has flourished again in recent years after the *space race* decades: Clementine by U.S., Small Missions for Advanced Research in Technology (SMART-1) by Europe, Kaguya/SELenological and ENgineering Explorer (SELENE) by Japan, Chang'e 1 by China, Chandrayaan-1 by India, etc. are just few examples of unmanned missions which already visited the Moon. Other probes have been designed by national space agency and will be launched in the 2020-2030 timeframe for assessing lunar resources to enable the coordinated human and robotic exploration of our natural satellite. For instance, there are are the National Aeronautics and Space Administration (NASA) cubesats Lunar IceCube, Lunar FLASHLIGHT, and LunaH-Map, the Japanese Aerospace Exploration Agency (JAXA) SELENE-2 mission and the jointly effort spacecraft of the Luna-Glob program by Roscosmos and the European Space Agency (ESA).

The Moon vicinities and surface could then appear to be very appropriate to assess critical milestones such as technologies and operations in low gravity environments, as suggested by the purposed future exploration scenarios in [1]-[6]. Test campaigns in this valuable environment could enable Martian sorties with reduced effort, development cost and enhanced confidence, if compared with direct missions. Maximizing the scientific return with those preparatory survey missions could help to extend the human presence beyond the Low Earth Orbit (LEO) as the ISS is currently doing. In fact, if an evolutionary path for the human spaceflight is considered, a human long-term presence on the Moon surface could be considered a natural stepping stone to progressively pave the way to human exploration of the Red Planet and the Solar System in general. In this sense, ESA has been proposing the visionary concept of the "Moon Village", where multiple stockholders should collaborate in an ISS-like international framework to progress towards lunar exploration [7].

The purpose of this work is to detail a novel approach to support space mission design, where a lunar human base has been used as a mission concept test case. Some light has been cast also on how In Situ Resource Utilization (ISRU) techniques could be integrated into the mission architecture to produce consumables for the Environmental Control and Life Support System (ECLSS), such as oxygen and water, food, and propellant to refuel spacecraft. To assess and validate some parts of the decision-making process in this large and complex exploration context, a Virtual Reality (VR) environment has been used. In particular, preliminary estimates on illumination rates led to identify favourable locations for the outpost. A first draft example of lunar base elements where created into an interactive virtual scene as a proof-of-concepts of the final scope of this project. Also, a Martian scene has been reproduced with

the VR tool to show its the great reconfigurability and its potential use for future Martian mission design.

An overview of a potential general lunar mission scenario has been described in section 2, where some emphasis on the incremental approach has been given, also for supporting first sorties to the Red Planed.

The VR application has been characterized in section **Error! Reference source not found.**: after an introduction on how the software works, a use case has been detailed.

Section 4 illustrates the first results obtained with the set-up conceived for the case study.

Finally, conclusions are drawn in section 5, highlighting also the future development plans for this research activity.

2. Mission scenario

Considering the long-term plans of the future human space explorations scenarios, a hypothetical self-sustaining modular outpost [8]-[11] is described in this research work. The main purposes of the base should be to offer a valuable platform for technologies validation and scientific activities, offering also potential commercial opportunities among the framework of multinational cooperation. A broad coordination among the different potential stakeholders involved in this endeavour is desirable, with common goals and shared scopes.

The outpost should be scalable and upgradable for both equipment and crew to enhance the overall mission flexibility. Furthermore, it will be geared to actively support Mars expeditions, proving a valuable environment where to test critical technologies and new mission elements. Preparatory missions [6] could help to evaluate critical aspects related to the extended astronauts' Extra Vehicular Activities (EVAs) and surface science operations, to be used both for lunar and Martian endeavours.

Precursor robotic missions under development by national agencies, involving autonomous and teleoperated rovers, could enhance the preparation process to set and achieve the full operational capabilities of the permanent station on the Moon. Deepening the knowledge of our natural satellite, where sample returns probes could play a major role in highlighting the missing key elements to cope with its harsh environment, is mandatory to enable permanent stays.

Moreover, a cis-lunar station, i.e. the Deep Space Gateway (DSG) currently under development by NASA and commercial partners, could host astronauts in the first crewed campaigns, be a scientific platform for running experiments akin to the ISS, and actively support telerobotic, acting as gateway between lunar surface and our planet. The Space Launch System (SLS) and the Orion Crew Module (CM), heritage elements of the shelved NASA Constellation program, could be used for crew rotation, and for supplies and infrastructures transportation. The additional logistic support needed could be provided by an electric space tug [12]. All those elements should be part of the same architecture, which should aim to the creation of a lunar permanent surface settlement.

The human base elements which should be present and placed in convenient positions are: launch/landing pad, lunar lander/ascent vehicle, a habitat element with airlocks for EVAs, a science module, radiation shelters, transportation equipment, a lunar consumables and storage depot, a communication terminal, and rovers both pressurized and unmanned [8], [13], [14].

The permanent settlement could also be useful to test disruptive solution to limit the Earth-dependability, enabling a new way to conceive long stay missions. In-situ raw materials processing is one of the most promising technique and could be one of the main drivers for the next generation of space mission design. The more elements are manufactured with ISRU, the lower the Initial Mass to Low Earth Orbit (IMLEO). Site preparation, structure and equipment construction, in-situ repair and use, power generation with He-3, and cosmic radiations shielding, are only few examples of what regolith processing could led to. Furthermore, the lunar soil resources, conveniently mined, processed, and exploited, could directly contribute not only to the self-sustainment of the human base, but could also fulfil the needs for the future Red Planet journey. Additionally, oxygen production could lead to a complete closure in the ECLSS, while, together with hydrogen, could also support propellant production, and regeneration for fuel cell consumables. For both Mars and Earth-LEO-Moon sorties, propellant could be delivered to a space depot located at the Earth-Moon Lagrangian point 1 (EML1) or 2 (EML2) [15], [16], where lower ΔVs are required for station-keeping, reducing mass to be launched and improving mission adaptability.

The other essential elements when dealing with crewed missions is water. It is essential for life support, but could also be used for radiation shielding and regenerative fuel cell supply. Since water plays a major role in the site selection strategy, the wished location for the settlement should be chosen near places where this resource is present and accessing it is fairly easy. Following the recent fashion, the lunar south pole permanently shadowed areas have been postulated to engrave icy water deposit, as observed by radio telescopes [17], and probes like Clementine [18] and the Lunar Reconnaissance Orbiter (LRO) [19], [20]; another hypothesis, suggested by [21], has proposed the hydrogen atoms excess observed as trapped solar wind protons from the Earth's magnetotail plasma. However, recent developments in data analysis from the Chandrayaan-1 orbiter, suggest a widespread occurrence

of water in pyroclastic materials sourced from the deep lunar interior, and thus an indigenous origin [22]. Hence, the equatorial regions of the Apollo landing sites may represent another favourable location for water deposit.

Nevertheless, the lunar south pole has been strategically chosen in this work to combine the possibly water access with peculiar light conditions, as further discussed in section 3.3.

Accessing the grains where regolith and water are mixed or where an ice thin coat is present on the rocks of shadowed craters, could represent a huge turning point for the procurement of habitat by means of ISRU techniques. Alongside other already developed methods to extract O_2, H_2, and H_2O with higher Technology Readiness Level (TRL), e.g. ilmenite reduction, oxygen extraction from cold traps would require far less energy: according to [23], the regolith should be firstly dried out before starting to separate soil and water. This process requires to heat it up to 50°C, allowing the vapour phase to be formed and separated from the rest of the mixture. Then, it is possible to liquefy water for storing or for producing oxygen and hydrogen via electrolysation. An interesting integration concept could be to use heat losses during the ilmenite reduction process (reaction is triggered with temperatures above 1050°C) for melting the ice-soil mixture, as proposed by [9]. Those losses in the main reaction chamber could then be used to estimates the additional plant hardware parts and their masses. Whereas ilmenite reduction is more suitable to apply to titanium-rich regolith, typical of lunar maria in near-equatorial regions, and despite it has not the highest yield, it could be the most suitable process to begin supporting the mission. Actually, it has a higher TRL than other solutions like reduction with methane, vapour phase pyrolysis, sulphuric acid reduction, electrolysis of solid lunar regolith, and Molten Oxide Electrolysis (MOE). Once the knowledge of permanently shadowed craters for cold traps exploitation will eventually be assessed with data collection and preliminary studies on samples, it will be possible to start the oxygen production and use it as the primary procurement source. The secondary one will remain the ilmenite reduction, if no other more interesting and energy-saving concepts for regolith processing would be discovered or optimized.

Another crucial aspect to deal with is power generation: the extreme conditions of deep space or long duration mission have led several spacecraft to adopt nuclear power system. However, for the settlement of a lunar base, their utilization is still questionable, mainly for safety reasons [24], [25]. Small plants could be tested on the Moon in early campaign phases to assess critical issues (e.g. nuclear waste processing): only after this phase is possible to decide whether incorporate them as standard for exploration architecture, or if the outpost should rely only on other type of power systems. In this sense, a very promising idea is to use a hybrid closed-loop device, like a Stand Alone Power System (SAPS). This system has been firstly developed for terrestrial application [26], but its feature to supply power without being connected to an electric grid is particularly useful for planetary space exploration missions, as currently investigated by the ESA European Astronaut Centre (EAC), within the *Spaceship EAC* initiative [27], with lumped parameter models and hardware-in-the-loop simulations [28]. Specifically, the system proposed in this work is a photovoltaic-hydrogen SAPS, composed by: solar panels, fuel cells, batteries, electrolyser, and tanks. During sunlit periods, the solar panels will be used to supply the base loads and to electrolyze water. During eclipse periods, fuel cells will be active, fed by O_2 and H_2 previously compressed and stored in tanks: a liquefier may not be required, if oxygen and hydrogen are stored in cold traps in a cryogenic state [29]. Ni-H_2 batteries will be used for energy storage and to absorb peak loads: they will be recharged by photovoltaic arrays. Electric convertor devices will be also required to meet every systems' element specifications (tension and current). A schematic view of the SAPS is depicted in Fig. 1.

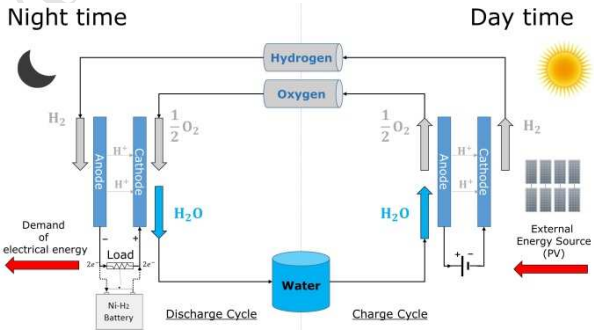

Fig. 1. Photovoltaic-hydrogen SAPS

Regulation and transition between sunlight conditions and eclipses should not be overlooked: the solar panels positioning and pointing is fundamental to obtain a high conversion efficiency and optimal performances from the overall SAPS. Similar constrains could be applied to the base elements. A VR tool, further described is section 3.2, has been used to analyse those aspects.

3. Virtual Reality simulations

The design process of the future space missions will take advantage of the recent discoveries in the technology. One of the most promising in this sense is VR: its application could be a key element in all the product life cycle stages of a space system.

VR applications in the space domain were quite pioneering considering that the VR concept is dated back in the late 1960's and 1970's, with the first devices patented starting from the mid-1980s [30]. In fact, NASA was one of the first institution that started to actively work on VR with research projects*: since the early 1990s a VR laboratory was established at the Johnson Space Center (JSC) to help the human spaceflight program, especially for EVAs in microgravity environments.

The first successful practical use of a Virtual Environment (VE) was the crew training for the Space Transportation System (STS), i.e. the U.S. Space Shuttle program, Hubble Space Telescope (HST) repair and maintenance mission (STS-61) [31]. A more recent example for astronaut training purposes is the case study based on laptop usage in the Fluid Science Laboratory (FSL) inside the ISS Columbus module [32].

Also, other operational processes endorsed the VR technologies usage: familiarizing and assessing several design solutions are parameters of interest and benefit in human spaceflight simulation training. United Space Alliance (USA) has deployed a virtual tool for both spacecraft assembly and ground processing operations design and training on the Orion CM [33].

Another critical aspect of crewed space mission is stowage and payload accessibility: optimization is desirable to not waste time in retrieving objects and tools, and to operate with them. Successful examples of VR implementation in this field are confirmed by [34]-[36], where the ISS Columbus module has been used as case study. An additional potential application in this specific area is Augmented Reality (AR), where a virtual world is superimposed over the real one to provide useful information to the user which is performing a task. This other branch has been recently investigated by the "Sidekick" project by NASA and Microsoft®, which has been tested the HoloLens device on-board the ISS to potential aid astronauts in the daily scientific activities [37].

The wide variety of devices currently present on the market, ranging from Oculus Rift to HTC Vive to Sony PlayStation VR, each characterized by different strengths and weaknesses, has push both VR and AR to gain momentum in several scientific domains including the space sector. Thus, integrating virtual tools in some phases of the product life cycle, including operations and training, could results in major benefits, even though their implementation in standardized industrial process is not yet simple. In this paper, a possible VR proof-of-concept to be adopted for a permanent lunar base design has been detailed.

* NASA Ames Research Centre (ARC) started the Virtual Visual Environment Display project (VIVED) and later the Virtual Interactive Environment Workstation project (VIEW), in partnership with VPL Research.

3.1 Methodology

The approach to be used to analyse future space exploration scenarios is to adopt a solution where VR systems are interfaced with standard design tools, responsible for quantitative physical analysis of the different aspects and components of mission. Not only the spacecraft itself, but all the necessary engineering processes involved from the early stage of mission definition will benefit the improved productivity and communication effectiveness of the new methodology. A collaborative environment, where the Model Based System Engineering (MBSE) is adopted, is the ideal area where to develop and test this cutting-edge idea, allowing users and designer to better shape products in a smarter and optimized way. Different design solutions could be studied and discussed by experts of different disciplines, always accounting for ergonomics and user operations: all the new design solutions could be then tested to verify the compliance with the requirements. Validation and verification phases of the project could be partially substitute by virtual tests in a near future, also for the Assembly Integration and Test (AIT) procedures. TRL level rising will be shorter compared with standard approaches: shorten the time-to-market will help industries to quicker satisfy customers and agencies to shrink programs duration.

The aim of this work is to create a virtual shared environment, easy accessible and to be hosted in Concurrent Design Facilities (CFD) rooms, where the "digital mock-up/virtual prototype" and all the data of interest could be seen and intuitively accessed by all the people present for trade-off studies or design review meeting. This approach will facilitate continuous communication and collaboration between all users involved in a certain project, from design and production, to maintenance and service, to disassembling and recycling. It is also very well suitable for collective decision-making dynamics, as proposed by [38], in the field of knowledge based system decisions.

The real system will be substituted by a computer-based virtual analogue. It is a systemic and semantic aggregation of all information, models, processes, and simulations that describe the system in evolution throughout its life cycle, whereas the human actors, the product, and the human-product environment are accounted [39].

The advantages of this method are:

- High requirement traceability and almost real-time verification of them;
- Ergonomic studies enhanced;
- Operational tasks and procedures verification;
- Great synergy and data exchange among all disciplines;

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- Optimization oriented;
- Useful for training purposes (e.g. astronauts' pre-assignment training, flight controllers' training, etc.);
- Risk assessment and reduction;
- Cost and time saving;
- Possibility of real-time failures troubleshooting.

Especially for training purposes, gradually integrating such tool into the standard processes [40], [41] will lead to positive training association and familiarisation.

A first successful case, which adopted a similar methodology, was the re-design of toolbox currently in use on ISS Columbus Module [42], [43]. Starting from the operational experience gained on board from astronauts, i.e. the end users, and sharing the knowledge among the ground personnel (engineers, designers, and flight controllers), resulted into an effective final product, optimized and ready to use by the crew on board the ISS. The process, which led to this promising result, can be well summarized in the scheme of Fig. 2.

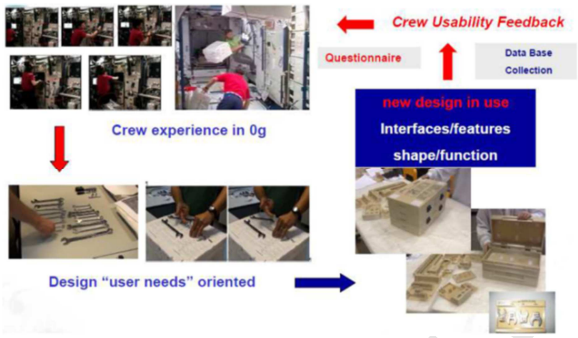

Fig. 2. Columbus toolbox crew usability feedback [43] (source: TAS-I)

Focusing more on the future astronauts' training, a successful example in this case is represented by the AMADEE-15 Mars analog campaign [44]. Analog astronauts were trained using the VR support of the European MaRs Analogue Station for Advanced Technologies Integration (V-ERAS) [45]. Developed by Mars Planet and the Italian Mars Society (IMS), which main goal is to provide an effective test bed for field operation studies in preparation for human missions to Mars, this system has been used for the familiarization phases since emulates a Martian virtual outpost combined with EVAs replica. The total immersivity has been achieved using omnidirectional treadmills and gravity-load reducing devices combined with a Microsoft Kinect and Oculus Rift.

3.2 VR tool and framework

The activity performed in this research work has been carried out at the Thales Alenia Space Italia (TAS-I) facility called COllaborative System Engineering (COSE) centre, especially in the Technology Research Office (TRO) and in the VR laboratory. This laboratory is aimed to the VR applications to the design and development activities of complex systems, including training. The application of the facility is planned to be extended towards other engineering disciplines, such as integration and testing, and the interactions among them in the concurrent design definition and verification processes [46].

The simulations described in section 3.3 have been created using the Virtual Environment Research In Thales Alenia Space (VERITAS) [47]: it is an in-house developed and multi-software VE. It allows VR stereoscopic immersive visualizations and Four-Dimensional (4D) simulations, i.e. the Cave Automatic Virtual Environment (CAVE), from 1 to 6 screens, or for a single Personal Computer (PC). Its final goal is to have a multidisciplinary (functional and physical) representation of the system, built up concurrently, with enhanced Three-Dimensional (3D) and Two-Dimensional (2D) user-interaction, desktop or immersive-wise [46]. Therefore, the user is considered as centre and objective of the development, through the research on web-based collaboration, immersive VR and use of interaction devices (e.g. haptic devices) [46]. Thanks to all those features, this tool is particularly suitable for our scope.

The VERITAS application is based on open-source libraries and components: the virtual scenes are loaded from eXtensible Markup Language (XML) files and 3D models' data source (e.g. Computer-Aided Design, CAD) are extracted in Virtual Reality Modelling Language (VRML) or in OpenSG® Binary (OSB) format. Data coming from other simulation software (e.g. structural, thermal, aerodynamic, etc. analysis) can be displayed by using Tecplot© 3D models [47].

VERITAS functionalities can be summarized as:

- Visualization of spacecraft trajectories (having the mission data) into the Solar System, with all the planets moving correctly thanks to ephemeris calculation;
- Virtual mock-up analysis;
- Inverse kinematics, with a virtual mannequin and see it moving according to a motion-capture suit or to Jack software;
- Radiation analysis;
- Rovers and landers simulation;
- AR scenarios.

The process behind the implementation of a VR full-functioning human lunar base, can be represented by the scheme in Fig. 3.

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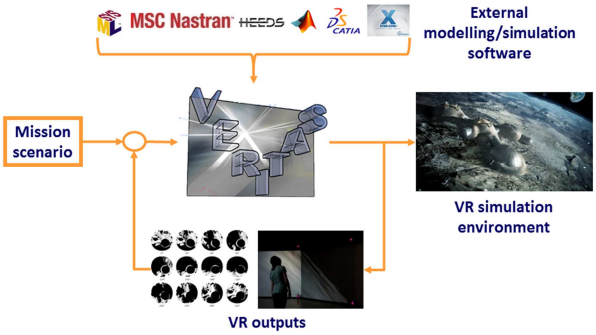


Fig. 3. Block diagram of the VE used

Once defined the reference mission scenario, this will be implemented using VERITAS, which can load external software analysis results (e.g. radiation dose, thermal gradient, 3D CAD models, etc.) as input. The final result will be a virtual outpost: data can be extracted as outputs for trade-off analysis. The improvements are then inserted again in the VR software to generate an updated version of the final product (the lunar base, or a general VR simulation environment). This loop should be iterated as long as all the experts will be satisfied for the solution obtained.

3.3 Case study

For testing the methodology and the instruments described in section 3.1 and 3.2, the illumination conditions at the lunar south pole have been studied, since it is the most probable area where to set the future outpost and it is useful for the site selection strategy. This area is of particular interest because the spin axis of the Moon is tilted by 1.54° with respect to the ecliptic plane, leaving some areas near the south pole in permanent shadow whereas other nearby regions in sunlit for the majority of the year [48].

For the terrain topography, the Digital Elevation Model (DEM) of Kaguya/SELENE mission JAXA, retrieved from [49] † and measured by the Laser ALTimeter (LALT), has been chosen. Instead of using the complete data set, the analysis has been restricted to an area extended from 88°S to 90°S in latitude (see Fig. 4) to reduce the computational cost. Longitude values are defined east-wise.

† We used the file LALT_GT_SP_NUM: it is a grid topographic data set around the lunar south pole. Altitude values were rounded off to the third decimal place. Data are ordered from -79.00390625°N to -89.99609375°N in latitude and from +0.015625° to +359.984375° in longitude. Raw altimetric range data were converted to the local topographic altitude with respect to the sphere of 1737.4 km radius based on the gravity centre of the Moon, by using the satellite orbit data.

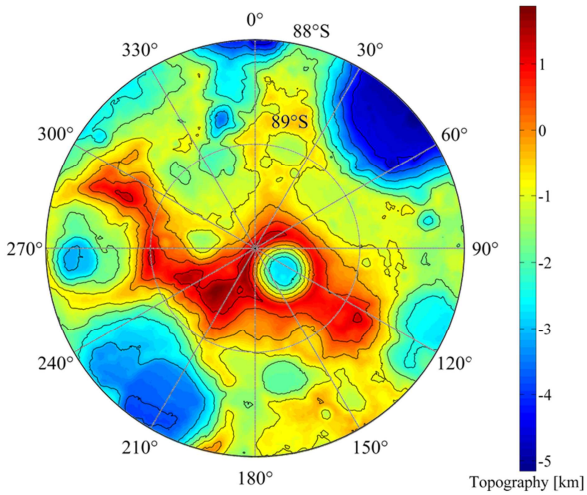


Fig. 4. Kaguya/SELENE lunar south pole topography

Native data were transformed into a Cartesian coordinate system: the point cloud obtained (i.e. x, y, z) was interpolated for creating a quadrangular mesh. The final grid resolution obtained was 430 m/pixel. For comparison purpose, a Delaunay triangular mesh was generated. Since no rendering and computational cost improvements were noticed, this mesh was not further used for the analysis.

Since the rims of the Shackleton crater (89.9°S, 0°E) are particularly interesting for high illumination rates, the DEM of the NASA LRO mission, retrieved from [50] ‡ and measured by the Lunar Orbiter Laser Altimeter (LOLA), has been also used for comparison. The area covered ranges from 89°S to 90° in latitude (see Fig. 5). Longitude values are defined east-wise.

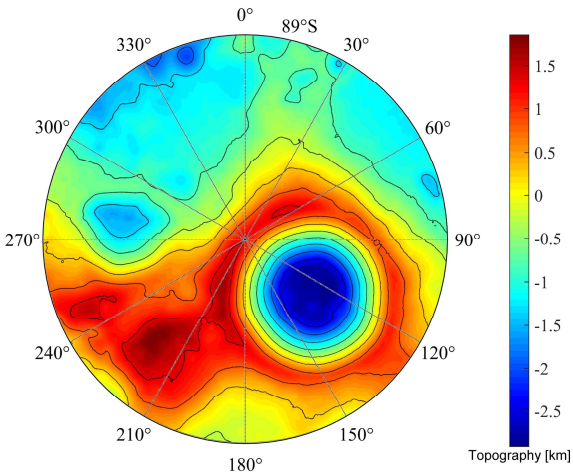


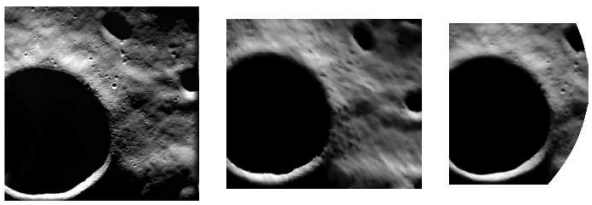
Fig. 5. LOLA lunar south pole topography

‡ We used the file LDEM_128: This data product is a shape map of the Moon, based on altimetry data acquired through mission phase LRO_ES_09 by the LOLA instrument. LOLA data used are geolocated using precision orbits based on a revised lunar gravity field.

Also for LOLA native data, the same previous transformation into a Cartesian coordinate system has been applied: the point cloud obtained (i.e. x, y, z) was interpolated for creating a quadrangular mesh. The final grid resolution obtained was 230 m/pixel. For comparison purpose, a Delaunay triangular mesh was generated. Since no rendering and computational cost improvements were noticed, this mesh was not further used for the analysis.

The illumination analysis has been done using VERITAS and its graphic engine, which is able to calculate and generate real-time shadows. The Sun (light source of the VR scene) angles were specified by an elevation angle and azimuth. The azimuth angles were referenced from the zero meridian, and elevation was set to 1.54°.

For a more realistic rendering, the graphic properties of the lunar terrain have been scaled using a real picture (see Fig. 6 a).



(a) (b) (c)

Fig. 6. Real image [51] (a) and terrain rending comparison (Kaguya model, b, and LOLA model, c) of the Shackelton crater area

4. Analysis results

Simulations were run for a generic lunar day, extracting 36 images (one every 10° of Sun motion), starting with the Sun at 0° azimuth. They were then transformed into binary images to differentiate between sunlit and shadowed regions: if the ground was illuminated that pixel was set to one (white), or zero (balck) if shadowed. All the binary images were then merged to measure the average illumination rate of each pixel over a lunar day [48].

The averaged illumination maps for both Kaguya and LOLA DEMs are shown in Fig. 7. The results are coherent with [48], [52] except for the area of the Shoemaker crater (upper right part of Fig. 7 b). This mismatching is due to the absence of the surrounding lunar topography (to reduce the computational effort of the graphical engine), which causes a wrong illumination of the crater. Other sources of errors are due to erroneous images post-processing and binary mapping.

The red dots in the greyscale images (Fig. 7 c, d) represent the points with the highest illumination percentage over a lunar day. For Kaguya the value is 91.67% and the point is located at 89.76°S, 203.34°E. For LOLA, the value is 86.11% and the point is located at 89.69°S, 197.91°E. The positions and the values of the resulting points are similar to [48], [52]. From these analysis, it is confirmed that there are no peaks of eternal sunlight, while permanently shadowed craters are largely present.

Even though the two datasets have been taken from different instruments mounted on-board of two different spacecraft, the simulations have been run to compare how VERITAS can handle different models with respect to the grid resolution, rendering and computational effort. No major differences have been noticed while running the virtual scenes. Still, the LOLA data used in the simulations represent a smaller data subset of the Kaguya one, i.e. a smaller portion of the lunar south pole. Since the Shackleton crater is one of the major area of interest, via computing the same survey, it was possible to assess how the two missions mapped this area. The resolutions used, which is the result of a meshing operation, are somehow comparable: in fact, the best illumination points computed show consistency, even though the results are not the same. Nevertheless, an increase of the resolution is foreseen as a future work. A join co-registered dataset of LOLA and Kaguya [53] will be used to better predict illuminations peaks.

The areas with the highest illumination rate represent favourable possible locations for installing the lunar outpost. The solar panels positioning should follow the same criteria to provide electrical power for the longest practical period. Additionally, thanks to the steady light conditions in some areas, the temperature is almost constant during the lunar day. Specifically, if a horizontal surface is placed at 89°S, the model's calculations from [54] have shown 128 to 180 K temperature variation during the summer solstice (continuous illumination conditions) and almost constant 38 K during the winter solstice (un-illuminated polar night conditions) [55]. The south pole region has globally an average maximum temperature ~200 K with average minimum temperatures ~50 K [56]. Hence thermal control results easier.

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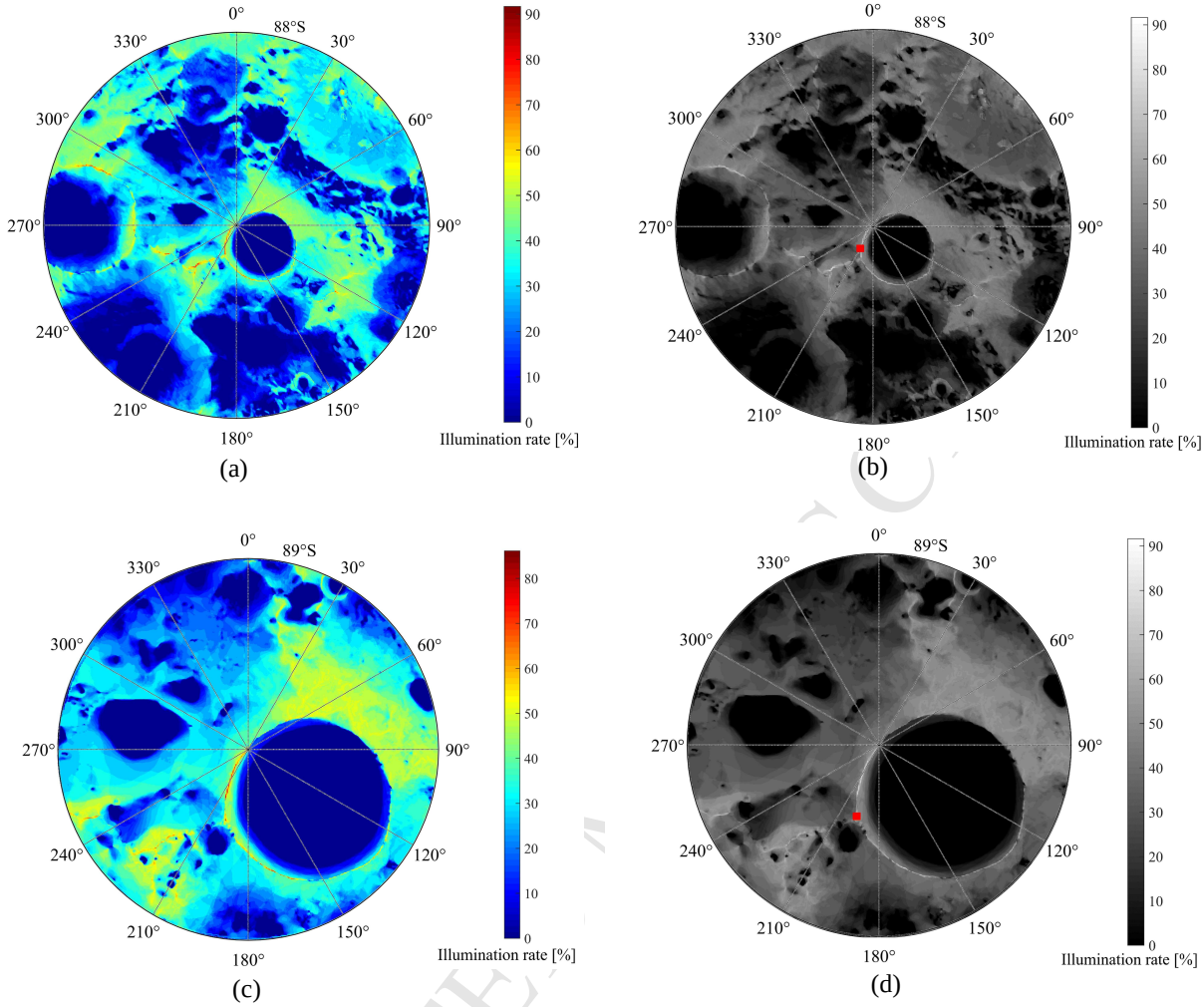

Fig. 7. Kaguya (a, b) and LOLA (c, d) illumination maps

The results obtained showed that Shackelton crater rim is the best solution for the site positioning. However, due to graphical rendering limitations, a first fictitious base near the Linné crater surroundings have been implemented to firstly test the aggregation of several virtual model into the same VR scene. The simulated crewed settlement is formed by the following 3D models: the NASA Apollo lander [57], the NASA Habitat Demonstration Unit (HDU) [57] and the TAS-I Pressurized Lunar Rover (PLR). The VR scene designed is show in Fig. 8.

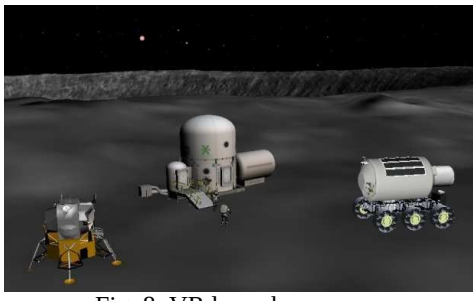

Fig. 8. VR lunar base scene

The same scene was also displayed using CAVE where a user can actively interact with the virtual environment (see Fig. 9).

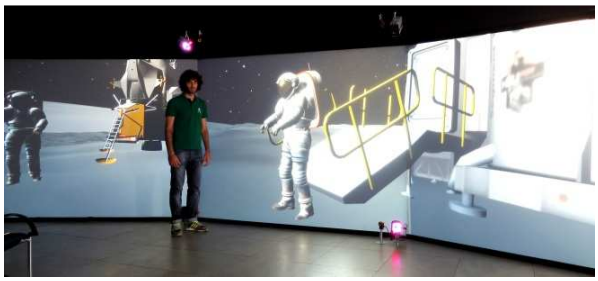

Fig. 9. VR lunar base displayed into the TAS-I CAVE

Since the human exploration of the Moon is considered preparatory towards potential Mars exploration, and thanks to the versatility of the virtual tool used, a similar fictitious base on Mars has been simulated. This scene was placed near the Victoria crater and included the 3D models of the NASA HDU [57] and of the NASA Curiosity rover [57] (see Fig. 10).

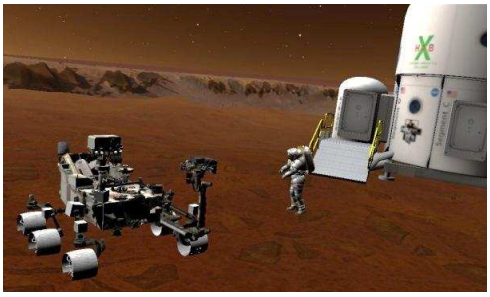

Fig. 10. VR Martian base scene

The same scene was also displayed using CAVE where a user can actively interact with the virtual environment (see Fig. 11).

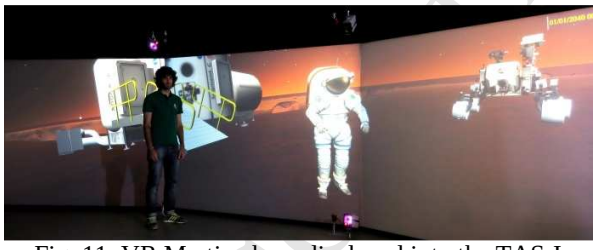

Fig. 11. VR Martian base displayed into the TAS-I CAVE

5. Conclusions and future works

An innovative approach for studying a future lunar outpost using VR technologies has been proposed in this paper. The use-case demonstration of this generic exploration scenario shows the potential of virtual tools to create a flexible environment to be used for future mission design. Via gathering different output solutions driven by trade-off studies among various disciplines, an optimized solution could be generated in a smarter and quicker way. A collaborative environment is mandatory to fully address the goal of this work. Models and data exchange between experts is the key element for rising reliability and dovetailing the virtual world with the real one. As a general comment, more development work is still necessary for VR to make them compliant to space industry standards.

The mission scenario selected was a preliminary analysis of an incremental architecture to support a permanent crewed outpost on the Moon. The technologies required for exploiting in-situ lunar resources are fundamental building block for the human exploration strategies, which have the journey to Mars as final goal. The resources of our natural satellite can also provide an actively support to Martian missions. Common mission elements can be tested achieving acceptable reliability metrics. The final goal of this research is to obtain a full functional virtual outpost which can be used for training and design evaluation purposes. All the elements will be able to reproduce both their physical and functional behaviours. The virtual output generated in this paper is just a proof-of-concept which highlighted some limitations of the instruments which were used in the VR loop. In this sense, VR could offer a powerful multidisciplinary platform where the modular hardware design process, the operations procedures optimization, low gravity environment familiarization, and EVAs training could be tested in an innovative and more effective way.

Concerning the illumination analysis, a possible improvement is to increase the DEM resolution. This fact will pose major challenges for manipulating big data and for the computational cost. However, if shadows calculation can be made more accurate, then the analysis of results will provide a more reliable tool for evaluating specific base element location and possible local obstacles. Sunlit areas near permanently shadow craters could offer a unique opportunity to study cold traps. Their physical exploration is critical in order to assess icy water deposits and to size a proper ISRU useage scenario.

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Highlights

- A lunar permanent outpost is analysed within an incremental exploration architecture
- ISRU techniques are included in the evolution scenario to support human presence
- The Moon environment is used to test enabling technologies for Martian sorties
- A proof-of-concepts with virtual simulations is proposed for space missions design
- Virtual reality is used to study the illumination condition at the lunar south pole