

The Lunar Simulation and Mission Control Center: the Italian integrated ground facility to support lunar operations preparations, validation and execution in a representative lunar environment

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Abstract

Italy is paving the way for the exploration and operations at the Lunar South Pole: with the signature of the “Artemis accords”, many countries are providing contributions in term of infrastructures and services, with the goal to bring back humans and cutting-edge technologies in lunar orbit and on the surface of the Moon. The “Back to the Moon” tactic is considered a fundamental step of the Mars colonisation strategy; humanity still needs to conquer knowledge and methodologies to safely send humans on the red planet: Moon is the place to gain what is still missing, also in preparation of the long and hard journey to Mars.

Within this scenario, the Italian Space Agency (ASI) decided to fund the Lunar Simulation and Mission Control Center (LS&MCC), an integrated ground infrastructure to support development, testing, validation, training, operations and simulation of a wide spectrum of activities and equipment in view of their utilisation on the Moon.

The LS&MCC will be built at the Aerospace Logistics Technology Engineering Center (ALTEC) headquarters in Turin, Italy. This Italian integrated ground facility will join other similar facilities already available at ALTEC for supporting robotic surface operations on the Martian soil, e.g. the Mars Terrain Simulator (MTS) embedded into the Rover Operations Control Center supporting the operations of the ESA ExoMars Rosalind Franklin Rover.

The LS&MCC facility is conceived around three main components: (1) Lunar Terrain Simulator (LTS): a lunar analogue indoor terrain filled with representative regolith simulants, designed to reproduce the morphology of the lunar surface with high fidelity; (2) Lunar Environment Simulator (LES): a controlled dirty thermo-vacuum chamber able to reproduce temperature, pressure, regolith contamination, environmental and illumination conditions characterizing the Lunar South Pole region; (3) Lunar Mission Control Center (LMCC): a center capable to interface with LTS and LES directly, to be used to provide operations planning, monitoring & control and data analysis capabilities for real lunar mission operations.

This paper presents the current status of the LS&MCC, focusing on the distinguishing functionalities with respect to other similar facilities available all over the world, supporting lunar operations with indoors or outdoors equipment. The LS&MCC will take into account both the exploitation of MTS experiences and the new challenges to face with the Lunar environment, e.g. the identification of the regolith simulants, the implementation of a smart gravity reduction device, the replica of the lighting conditions at the Lunar South Pole and the simulation of specific operative conditions like plasma, charging environment, ionizing radiation.

Keywords: Lunar morphology, Exploration Technologies Testbed, indoor analogue facility, Lunar South Pole, surface mission operations.

Acronyms/Abbreviations

ALTEC:	Aerospace Logistic Technology Engineering Company
ASI:	Agenzia Spaziale Italiana (Italian Space Agency)
COTS:	Commercial Off-The-Shelf
DEM:	Digital Elevation Model/Map
DTVC:	Dirty Thermo-Vacuum Chamber

DUT:	Device Under Test
EGSE:	Electrical Ground Support Equipment
ESA:	European Space Agency
GTM:	Ground Test Model
HW:	HardWare
ICD:	Interface Control Document
ISRU:	In Situ Resource Utilization
ISS:	International Space Station
JAXA:	Japan Aerospace Exploration Agency
LES:	Lunar Environment Simulator
LMCC:	Lunar Mission Control Center
LS&MCC:	Lunar Simulations and Mission Control Center
LTS:	Lunar Terrain Simulator
MCS:	Mission Control System
MGSE:	Mechanical Ground Support Equipment
MTS:	Mars Terrain Simulator
NASA:	National Aeronautics and Space Administration
PPE:	Personal Protection Equipment
ROCC:	Rover Operations Control Center
SW:	SoftWare
TC:	TeleCommand
TM:	TeleMetry
TVAC:	Thermo-Vacuum Chamber

1. Introduction

Fifty years after the first moon landing, global interest in Moon exploration and colonization has reached a new peak, largely driven by NASA's Artemis program [1,2] and the ESA's Terrae Novae roadmap [3].

Additionally, with the signature of the "Artemis accords", many countries, including Italy with the Italian Space Agency, are contributing infrastructure and services, aiming to return humans and advanced technologies to lunar orbit and the surface of the Moon. The "Back to the Moon" and "Moon to Mars" initiatives are considered a crucial step in the strategy for Mars colonization. Humanity still needs to acquire the knowledge and methodologies necessary to safely send humans to the Red Planet, and the Moon offers the ideal environment to gain the insights required for this next leap.

As part of this roadmap, in December 2023, ALTEC began developing the Lunar Simulation and Mission Control Center (LS&MCC) under a contract with the Italian Space Agency (ASI Contract N. 2023-38-I.0). Building on initiatives in Human Space Flight and Space Exploration, ALTEC will support future lunar activities, with the goal of establishing a permanent human presence on the Moon and ensuring sustainable access to and utilization of its resources.

The LS&MCC aims to support:

- technology demonstration of modules, systems/subsystems and payloads designed to operate on the lunar surface within an environment which can reproduce specific Lunar features and conditions;
- the preparation and validation of the operations to be performed;
- the execution of the lunar mission operations.

The LS&MCC facility design is under finalization, and its construction and testing are expected to be completed by the end of 2026. It will be located at ALTEC's headquarters in Turin, Italy, alongside other similar facilities that support robotic surface operations on Mars, such as the Mars Terrain Simulator (MTS) within the Rover Operations Control Center (ROCC), which aids in the operation of the ESA ExoMars Rosalind Franklin Mission.

2. LS&MCC Facility Requirements and Components

The LS&MCC requirements benefited from a preliminary comparative survey, including both existing facilities and those under construction (see Fig. 1), considering the following:

- indoor or outdoor artificial lunar analogue facilities;
- thermo-vacuum chambers that handle regolith simulants, commonly referred to in literature as Dirty or Dusty TVACs.

Several comparative analyses have been conducted for each artificial lunar analogue facility and Dirty/Dusty Thermo-Vacuum Chamber, taking into account the following information, when available [4]:

- Name, Country/Location, Institution/Company;
- Indoor/Outdoor;
- Facility purposes and capabilities;
- Technical requirements and aspects;
- Support equipment;
- Websites or other bibliography references.

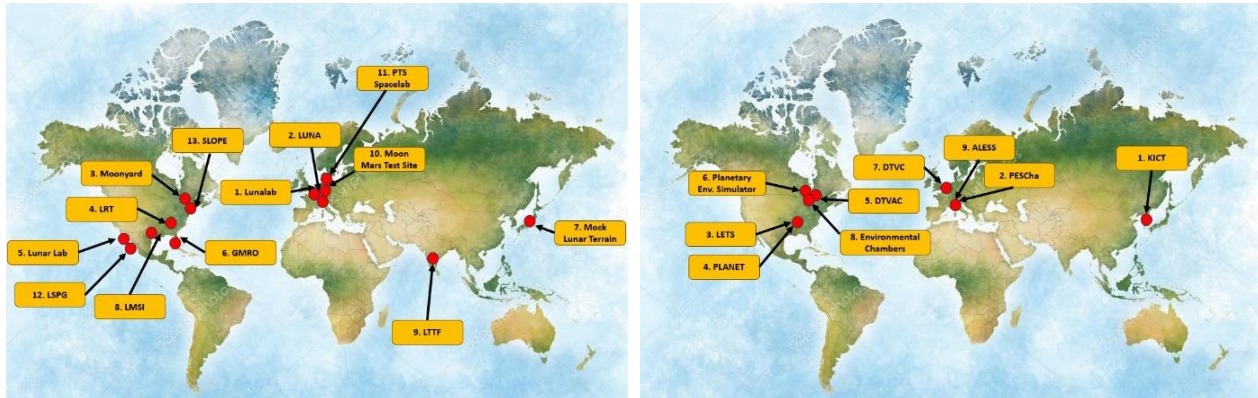


Fig. 1. Lunar analogue terrain and Dirty/Dusty TVAC locations

Based on the requirements defined during the LS&MCC design phase and considering the heritage and lessons learned from the construction, validation, and use of similar 'Martian' infrastructures, as detailed in [5], the LS&MCC has been conceived around three main components or subsystems:

- **Lunar Terrain Simulator (LTS):** an indoor lunar analogue terrain covered with representative lunar regolith simulants.
- **Lunar Environment Simulator (LES):** a controlled, dirty thermo-vacuum chamber capable of replicating the temperature, pressure, and regolith contamination conditions found on the lunar surface.
- **Lunar Mission Control Center (LMCC):** a center that interfaces directly with both the LTS and LES, allowing for local or remote monitoring of testing activities. The LMCC also provides capabilities for operations planning, monitoring, control, and data analysis for actual lunar missions operating in orbit and on the surface.

3. Lunar Terrain Simulator (LTS)

The LTS is an indoor analogue facility designed to reproduce, with high fidelity, the terrain characteristics at the landing site in the Lunar South Pole region.

The main purpose of the LTS is to accommodate rovers, ground infrastructures, scientific instruments, and payloads. This facilitates the development, demonstration and validation of innovative technologies and operational concepts, as well as training, alongside robotic exploration activities, concepts, and procedures. Furthermore, the LTS supports the daily ground operations through rehearsal and troubleshooting on representative hardware and instrumentation.

The following use cases are the drivers for the LTS current design and future developments:

- execution of locomotion tests including climbing performances and new mobility solutions (e.g. legged robots);
- execution of drilling tests;
- execution of navigation tests and acquisition of lunar datasets (e.g. images) with different light conditions to feed onboard navigation algorithms;
- support of landing functional tests (currently optional);
- support of test for harsh environment exploration (currently optional).

The LTS Arena concept is based on the Mars Terrain Simulator (MTS), presented at SpaceOps-2021 [6]. The experience matured over the years in the MTS has provided ALTEC a strong knowledge regarding the approach to follow for the design and development of the LTS.

3.1 Exploitation of MTS experiences

The Mars Terrain Simulator (MTS) [6] is an indoor analogue facility, located inside the ROCC [7], designed to represent, from a morphological, some possible terrains on Mars landing sites and to support the daily ground operations through rehearsal and troubleshooting on representative hardware and instrumentation.

The MTS facility has been specially tailored to perform ExoMars Rover Ground Test Model (GTM) [8] test and to give the adequate support to the Rover surface mission in case of contingency. The MTS Arena is shown in Fig. 2.



Fig. 2. Mars Terrain Simulator overview

The MTS was completed at the end of 2019 and it has become fully operational since May 2021 for the execution of the GTM functional test campaigns, covering all the ExoMars mission phases and operational scenarios.

The following main strategies have been considered to design the LTS and to simulate the lunar surface operations starting from the MTS [5,7]:

- The LTS Arena can be adapted to recreate the main Lunar topographic features with the approaches already validated in the MTS facility.
- The reconfiguration in terms of slopes, crevasses and soil/rock distribution can be executed by means of dedicated support equipment and mechanical tools already used in the MTS Arena. This includes the applicability of the reconfiguration procedures and operations already validated during the MTS Acceptance Test campaigns.
- The LTS Arena Systems can be also based on the MTS approach: a set of digital cameras will be used to track the motion of specific items inside the terrain, to generate the 3D Digital Elevation Map of the Arena, to acquire images and to record videos.

Furthermore, some peculiarities coming from the Lunar simulated environment need more detailed analyses and trade-off with respect to the Mars analogue terrain. In particular, the following technical topics must be examined during the LTS design and development phases:

- Morphology: based on the MTS experience, a breakdown of the LTS Arena (e.g. flat area, drilling area and/or tilting area) has been considered.
- Lunar terrain simulants: the surface of the Moon, known as the regolith, is primarily shaped by impact processes, and is composed of silicate minerals resulting from the mechanical disintegration of basaltic and anorthositic rocks. The adhesive and cohesive properties of lunar dust, identified to be more dangerous from a safety point of view than Mars simulants (Pozzolana Volcanic Tuff or Rhein quartz Phyllosilicates), pose a

challenge to engineering systems for human health during long-term exploration of the Moon, and this aspect shall be considered in the LTS design.

- **Illumination System:** the main reference scenario, as identified by the ARTEMIS program, is the Lunar South Pole. In this area there are permanently shaded regions surrounded by regions hit by the direct sunlight for most of the year. Such characteristics impose a design of the Illumination System ad-hoc for the LTS, more refined than the MTS Illumination Facility.
- **Gravity Compensation System:** to simulate the Lunar gravity (equal to 0.166 g) in the Earth's environment, the gravity compensation system can be based on the MTS one, which employs a fluidic system comprising nitrogen bottles (a recurrent element). Improvements about the Bridge Crane, that includes the gravity compensation system, are currently under assessment with potential bridge crane supplier(s), as part of the LTS design and its future developments.
- **Bridge Crane design:** some crane automatisms (e.g. execution of a pre-defined trajectory and "follow-me" functionality) are under assessment, as well as the possibility to integrate and manage the Gravity Compensation System and/or Illumination System, representing an upgrade with respect to the "basic" MTS Bridge Crane.

The above strategies, considerations, trade-offs and technical topics act as engineering inputs for the definition and finalization of the LTS design, described in detail in the next subsections.

3.2 LTS Areas

The LTS will be composed by the following areas, depicted in Fig. 3:

- **LTS Lunar Arena,** where it will be possible to simulate physical, and morphological characteristics of the lunar terrain. The Arena will be embedded into a segregated area, completely separated from the other facility areas, in order to mitigate the risks, mainly safety risks, due to the nature of the regolith simulant (ref. to section 3.2.2).
- **LTS Arena Support Area,** an area outside the Arena segregated perimeter to be used as Preparatory Area, Storage Area(s), Laboratory Area, EGSE/MGSE Area.
- **LTS Airlock Area,** an area connecting the LTS to the external world, providing an access for the material and equipment to be brought inside/outside the facility.
- **LTS Operators Entrance Area,** for accessing the LTS in two ways: either by using a dedicated changing room (for the people allowed to enter the LTS Arena segregated perimeter, where to wear the needed PPE) or by using a normal corridor to access the LTS Arena Support Area, separated from the Lunar Arena, when there is no need to wear the necessary PPE.
- **LTS Control Rooms Area,** an area that allows visual inspection of the Arena through windowed walls. The Control Rooms are configured with dedicated workstations to support the operations inside the LTS Arena, and with systems monitoring, acquisition and data processing.
- **LTS Visitor Area,** a place where visitors of the LTS Facility can observe the activities on the Arena.

It has been determined that the LTS Control Rooms Area and the Visitor Area will be equipped with windows that can be darkened as required. This measure is intended to avoid light reflections in the LTS Lunar Arena during test executions.

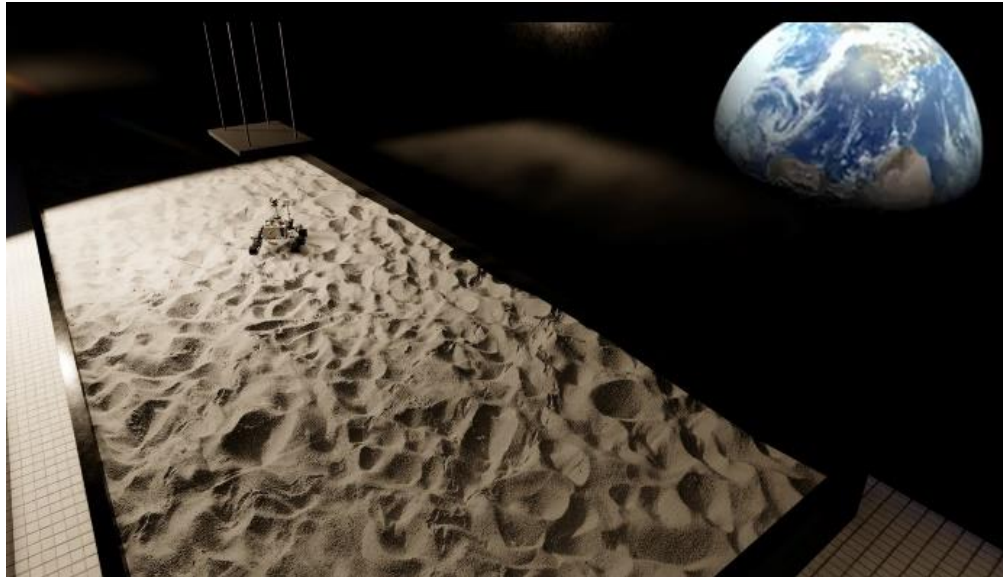


Fig. 5. LTS Arena terrain

3.2.2 Lunar regolith

The surface of the Moon is strongly brecciated and fragmented: this mantle of weakly coherent debris is called regolith.

Lunar soils consist of five particle types: mineral fragments, pristine crystalline rock fragments, breccia fragments, volcanic and impact-generated glasses, and agglutinates (lunar particles consisting of soil grains bonded together by impact-melted glass).

In general, the lunar soil is composed of sharp and abrasive particles. Grain shapes are highly variable, ranging from spherical to extremely angular. The average regolith grain size is 70 μm , with 20% having dimensions less than 20 μm .

The low electrical conductivity of regolith allows individual dust grains to retain electrostatic charge and become highly adhesive. Lunar soil particles can be levitated up to 10 m above the surface due to charging. Once disturbed, the lunar dust takes a long time to settle.

Table 1 summarizes the various properties of the main three types of soil identified in the lunar regolith composition, along with the recommended values considered in the selection of a soil simulant [9,10]. Real values can vary significantly with temperature and depth. The adhesive and cohesive properties of lunar dust pose a challenge to engineering systems such as Extravehicular Activity suits, seals, and bearings, as well as to human health during long-term exploration of the Moon. The abrasive, glass-like material sticks to suits, irritates the throat and lungs, impairs vision, and can damage mechanical systems by increasing friction and accelerating wear of mechanical joints.

Table 1. Lunar Soils General Properties

Soil properties	Fined grained igneous rocks	Breccia	Fines	Recommended values
Bulk density [$\text{g}\cdot\text{cm}^{-3}$]	2.95	2.29	1.26	1.3
Thermal inertia [$\text{cm}^2\text{s}^{1/2}\text{K cal}^{-1}$]	23.3	38.9	1000	800
Thermal Conductivity [$\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$]	0.002	0.002	0.002	0.002

NASA's Apollo mission astronauts reported major problems regarding the lunar regolith: lunar dust can contaminate optical observations by scattering light from the dust; electrostatic adhesion of dust to optical surfaces and solar arrays leads to degradation of optical measurements, reduced solar power generation and reduced effectiveness of thermal radiators.

Due to the above considerations, the selection of a representative lunar regolith simulant and its future management inside the LTS have impacted the design of the facility, and an ad-hoc "segregated area" will be created around the Arena for safety reasons.

3.2.3 LTS morphologies

The LTS Arena is designed to be filled with up to 60 cm of regolith simulant, obtained by crushing larger basalt or basanite rocks from an Italian quarry and then transported into bags to the facility. The regolith will be procured as a loose material of representative granulometry and set in the Arena to better represent different terrain morphologies inside the LTS. Rocks of different size, shape and, more than anything, mineralogical composition will be used to increase the representativeness of the lunar terrain, in particular during specific type of tests and simulations.

The terrain on the LTS Arena will be physically adapted and configured as necessary to simulate some Lunar soil features: craters, dunes/hills, sand fields, flat terrain, sand trap, ramp, rock field, rock steps or crevasses.

The morphology of the terrain will be variable, thus the following areas are currently foreseen:

- a relatively flat area with representative rocks and craters distribution;
- a climbing area where to support climbing tests through the use of a mechanically ramp, tiltable up to 25 deg with respect to the horizontal flat surface (similarly to the MTS Tilting Platform);
- a connection area, connecting the flat area with the climbing area with a fixed slope of 10 deg, to be also used in stand-alone configuration (i.e. without the tiltable ramp, near the Arena boundary).

This approach, different from the MTS concept, allows the coexistence of different areas altogether inside the Arena to facilitate the operations on the Devices Under Test (DUTs) in the same zone and to allow integrated test campaigns with multiple purposes.

The baseline of the LTS Arena morphology is shown in Fig. 6 and Fig. 7.

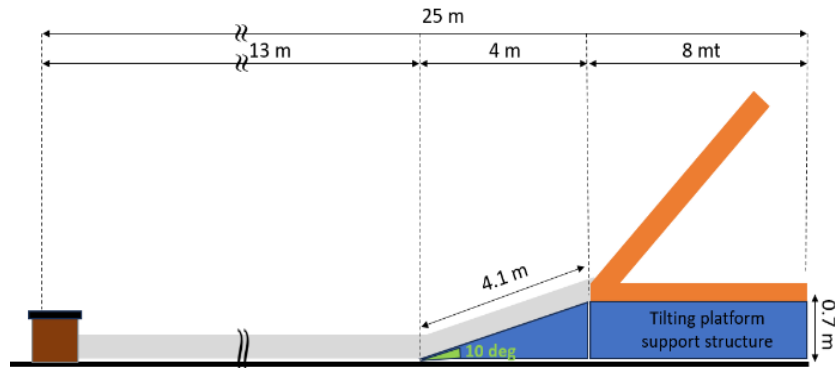


Fig. 6. LTS Arena morphology (lateral view)

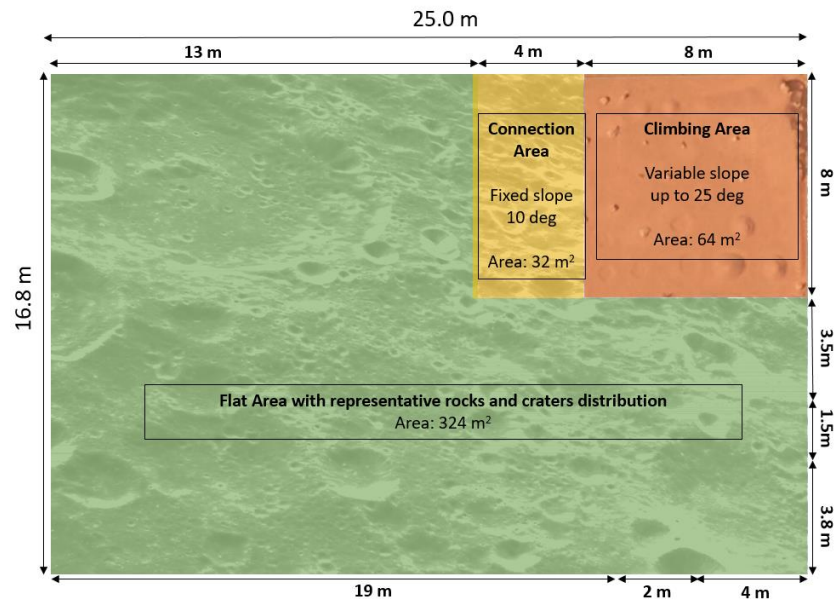


Fig. 7. LTS Arena morphology (top view)

3.3 Bridge Crane and Gravity Compensation

A Bridge Crane with a maximum capacity of 10 tons will support the operations inside the LTS Arena. The LTS Bridge Crane can be commanded by the operators directly in the LTS Arena or remotely from the LTS Control Room (ref. to section 3.6). In particular, the Bridge Crane remote control avoids the presence of the LTS operator inside the segregated area and allows a better visibility over the entire LTS Arena.

The LTS Bridge Crane will be mainly used for standard operations:

- support the configuration/reconfiguration activities inside the LTS Arena;
- move the DUT in specific location inside the LTS segregated area;
- transfer heavy loads (e.g. Storage Units filled with regolith simulants).

The LTS Bridge Crane will be designed in a modular way to include the following use cases and “advanced” functionalities:

- mapping/scanning of the terrain with a camera system installed on the crane, to support the Lunar terrain DEM generation/reconstruction;
- automatic crane “follow me” function, to avoid the presence of an operator in the loop following the locomotion activities of the DUT and commanding the crane with a remote control;
- Dynamic Illumination System (ref. to section 3.4);
- gravity compensation (when needed), for small weights and (possibly) up to 10 ton for larger and heavier surface assets.

According to this last use case, the LTS Bridge Crane control system can interface with the LTS software to retrieve the needed pieces of information for the commanding inputs: start movement, stop movement, velocity to be provided. A preliminary simplified design diagram is shown in Fig. 8.

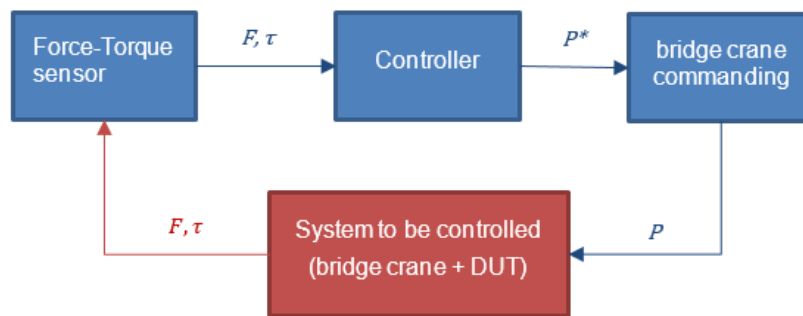


Fig. 8. Simplified scheme for the LTS gravity compensation device

3.4 Illumination System

The LTS Illumination System will simulate the typical lighting conditions observed at the Lunar South Pole. This environmental aspect will be extremely critical for the operations during the actual missions (and so the test too), since it affects several activities like optical navigation and motion control in general, power generation etc.

The baseline consists of tripods with spotlights positioned along the horizon line, with the aim of creating a sun apparent inclination of approximately 8 deg or less to recreate the long lunar shadows that are characteristic of the polar area.

The light source spotlights will be two dimmable Fresnel LEDs with the following characteristics:

- color temperature: ranging from 2.800 K to 10.000 K;
- capability to focus the light beam power in a range from 15 deg to 50 deg;
- light equipped with 8-leaf barndoors allowing for control of light spill and beam.

A possible additional system named “Dynamic Illumination System” is under evaluation to be included in the facility. For this functionality, a light package is installed on the LTS Bridge Crane and is commanded to simulate the azimuth and elevation profile of the Sun. The LTS Bridge Crane will be moved to follow a pre-established profile, simulating the Sun’s movements (azimuth and elevation at different latitudes) along the lunar day or according to an accelerated timeline profile. This will remove the need of having an operator moving the tripods with the spotlight.

3.5 LTS Arena Systems

Based on the Arena Systems developed for the MTS and described in section 3.1, also the LTS will be equipped with dedicated Arena Systems, composed of HW components that are located all around the Arena and SW components installed inside the LTS Control Room.

3.5.1 LTS Measurement System

The LTS Measurement System will track the motion of specific items in all or parts of the LTS Arena, depending on the operations. This tracking will be done in real time and will provide the position and orientation of the tracked items. After an extensive comparison of various systems and considering the MTS heritage, a system utilizing reflective markers will be adopted for the LTS. This system will be based on COTS (Commercial Off-The-Shelf) options that will be procured and customized as needed. Specifically, the OptiTrack™ system, which uses infrared cameras, meets the following accuracy requirements: 5 cm in position and 1 degree in orientation. The OptiTrack Motive:Tracker interface is shown in Fig. 9.

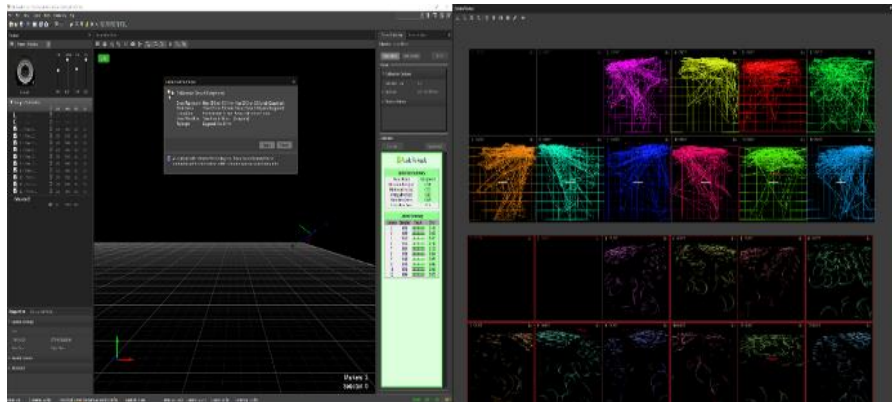


Fig. 9. OptiTrack Motive:Tracker interface

3.5.2 LTS Modelling System

The LTS Modelling System main goal is to generate a 3D maps or Digital Elevation Model (DEM) of the LTS Arena configuration. Such system will be composed by the elements reported in Fig. 10. As part of the LS&MCC project, a new system for the DEM generation has been proposed with respect to the MTS Modelling System. This technology will rely on a single stereo camera to be mounted on the LTS Bridge Crane, collecting stereo images of the full Arena area. Dedicated pieces of SW hosted in the LTS Control Room will be in charge to merge the point clouds and generate the Arena DEM.

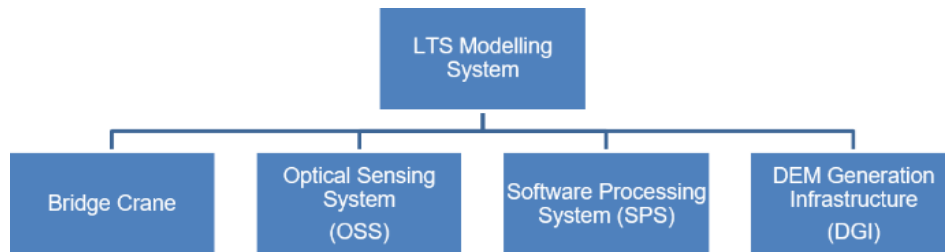


Fig. 10. LTS Modelling system components

3.5.3 LTS Ambient Cameras System

The entire LTS Arena will be monitored by a dedicated Ambient Cameras System. It will consist of video surveillance cameras, equipped with Pan/Tilt/Zoom capabilities and placed all around the Arena, to monitor directly from the control room and record tests and operations under execution in the Arena. The cameras will be also equipped with night vision/infrared capabilities, to match the characteristics of the LTS Arena that is ranging from low illumination to high illumination areas.

The images and videos acquired by the LTS Ambient Cameras System will be used for public relations/media, post processing, training and education.

3.6 LTS Control Room and Support Area

The LTS Control Room will be equipped with a proper set of workstations, to be used for:

- Measurement System monitoring and control;
- DEM Generation System monitoring and control;
- Measurement System integration with the DEM Generation System for the motion tracking operations and for the DEM re-shaping;
- Ambient Cameras monitoring and control;
- Illumination System monitoring and control.

All the developed and procured SW related to the above LTS commanding are installed in the LTS Control Room and managed by dedicated IT infrastructure through the LMCC (ref. to section 5).

From the LTS Control Room, the operators will have a direct view to the LTS Arena using the windowed wall and the live video images provided by Ambient Cameras Systems.

4. Lunar Environment Simulator (LES)

The lunar surface presents a unique and challenging environment: with no significant atmosphere, the Moon experiences extreme temperature variations. Solar radiation is the primary source of illumination, with no atmospheric diffusion, leading to intense light exposure in sunlit areas and complete darkness in shadowed regions.

The vacuum conditions on the Moon are also extreme, with pressures as low as 10^{-12} mbar.

Additionally, the surface is covered with a fine, abrasive dust known as regolith, which poses significant challenges for both instrumentation and human operations.

For this reason, the LES Thermo-Vacuum Chamber (TVAC) facility is designed to conduct functional and qualification tests on components or equipment that are part of lunar projects, as well as scientific payloads that are meant to operate either on the Moon's surface or aboard the Lunar Gateway. Due to the inclusion of regolith simulants, the LES is referred to as a Dirty Thermo-Vacuum Chamber (DTVC).

In particular, the LES will support testing in a controlled environment, capable of:

- simulating thermo-vacuum conditions on the lunar surface;
- simulating illumination condition on the lunar surface;
- simulating the interaction between the Device Under Test (DUT) and the lunar regolith simulant(s).

4.1 LES main characteristics

The LES facility is a controlled dirty thermo-vacuum chamber, capable of supporting tests in a controlled environment. The formulation of the LES concept and design was based on:

- evaluation and study of the lunar environment [11];
- collection and analysis of information related to existing DTVC facilities [4];
- gathering and analysis of requirements for potential use cases that will utilize the LES.

The LES will be able to simulate:

- the operative temperature and pressure conditions of the Moon's surface;
- the interaction between the DUT and the regolith simulant;
- illuminations conditions with photon sources covering Vacuum-UV (VUV), Near-UV (NUV), Visible (VIS) and Infrared (IR) ranges.

Based on the potential Use Cases and comparison with other available DTVC [4], it has been decided to design the LES with internal dimensions of 2.5×2 m² for diameter and length respectively, to accommodate DUTs with maximum dimensions of $1.5 \times 1.5 \times 1.5$ m³. This capacity is intended to support the testing of small-to-medium payloads and systems, technologies and instruments within the chamber.

Furthermore, a specified number of ports will be available along the sides and on the door of the vessel for various purposes, such as viewports for inspection and potential camera installation, feedthroughs for power and data cables connecting the DUT to its EGSE, and spare ports reserved for future updates or upgrades.

The LES facility will comprise a thermoregulation system capable of maintaining the temperature within the range of -170°C to $+200^{\circ}\text{C}$, and a depressurisation system with the capacity to reach values of 1×10^{-5} mbar during a dusty test, and 1×10^{-6} mbar during a clean test.

A local monitoring and control system for the chamber thermo-vacuum conditions will be present, as the possibility to monitor and control the chamber thermo-vacuum from a remote location, without the necessity of being physically present in the close vicinity of the LES Chamber, will be available.

The LES tools and, potentially, the DUT will be monitored and will interface with LMCC, to allow end-to-end testing.

Based on the survey of the lunar environment, existing DTVCs, and potential use cases, Table 2 and Table 3 provide an overview of the general, thermo-vacuum, simulant, and illumination characteristics that the LES should guarantee.

Table 2. LES general characteristics overview

General DTVC Characteristics	Value
Internal LES volume (D x L)	2.5 x 2 m ²
Useful volume for DUT(s) (L x H x W)	up to 1.5×1.5×1.5 m ³
Number of viewports & feedthroughs	At least 12 (TBC)

Table 3. LES thermo-vacuum characteristics overview

General DTVC Characteristics	Value
Temperature Ranges	[-170; +200] °C
Vacuum Ranges (minimum pressure)	1*10 ⁻⁵ mbar with regolith 5*10 ⁻⁶ mbar without regolith
Temperature and vacuum condition maintenance	At least 30h
Performance for vacuum conditions achievement	5*10 ⁻⁶ mbar within 6 hours (starting from an ambient pressure of 1000 mbar)

4.2 LES regolith simulant distribution and management system

A DTVC containing a regolith simulant bed is essential for testing equipment and techniques related to lunar surface exploration. Based on what it was learned in literature [12,13] and reported in [4], there are several ways which can be employed to handle the regolith simulants in the DTVC:

- immersion (in which the DUT is immersed on a large bed of simulant);
- gravitational force (with the dust simulant is distributed from above by gravitational force);
- agitation of the bed simulant in the which the DUT is placed;
- placement the DUT on a large bed of simulant;
- a combination of the above.

In the LES facility, the regolith will be handled in two principal ways:

1. by distributing dust simulant from the top of the chamber on the DUT by gravitational force;
2. by placing the DUT on the surface of a sand box of still simulant or by immersing the DUT in a bed of simulant.

In order to implement these regolith distribution systems, the LES will be equipped with a regolith distribution system to be placed on the internal ceiling of the LES Chamber. This system is conceived to allow the deposition of the regolith simulant in a uniform and controlled way inside a “Regolith Sand Box”, i.e. a sand box containing the regolith simulant. The Regolith Sand Box will be hosted inside the LES Chamber and its dimensions are the following:

- Length x Width = 1.6 m x 1.6 m
- Depth = 20 cm

The Regolith Sand Box will be inserted/removed in/from the LES Chamber by means of a dedicated mechanical system. This system will be used also for the regolith loading/unloading from the Regolith Sand Box and for the placement of the DUT on the Regolith Sand Box.

A general overview about the regolith types to be used inside the LES chamber is reported in Table 4. It is important to note that a single lunar regolith simulant will not be sufficient to meet all the technological needs of a comprehensive lunar exploration program. An enhanced simulant, designed to achieve a high level of fidelity in specific properties, will be used for its particular attributes in each test. For example, a simulant for dust mitigation would not be the same as a simulant for excavation or chemical tests involving high temperatures.

Table 4. LES regolith types overview

Simulant Types	Properties
Engineering	Particle size range 10 – 2000 μm (*)
Dusty	Particle size range 10 – 35 μm (*)
Fidelity	high chemical and geotechnical fidelity

(*) The regolith used inside the LES can be substituted with another type of regolith by means of a system capable to insert/remove the sand box in/out the chamber easily.

4.3 LES allocated areas

Different areas inside ALTEC headquarters will be allocated for the LES facility:

- LES chamber indoor area, where the thermo-vacuum chamber will be hosted;
- LES chamber outdoor area, where the support equipment or consumables (e.g. bottles/tanks) are hosted;
- LES airlock area, an area connecting the LES Facility to the external environment, allowing the access for the material and equipment to be brought inside/outside of the facility;
- LES storage area, where equipment and regolith simulants will be stored;
- LES laboratory area, where the DUT can be stored and prepared for testing;
- LES EGSE/MGSE area, where the DUT EGSE/MGSE can be stored and placed during the testing sessions.

4.4 Monitoring & Control System of the DUT in the LES

The monitoring and control of the DUT activities performed inside of the LES, for example to execute functional testing under relevant and controlled environmental conditions, can be managed:

- directly by the external DUT's operators/owners with their own specific EGSEs. Such EGSEs can be hosted in the LES EGSE Area, in the close vicinity of the LES Chamber. The umbilical cable(s) will have dedicated feedthroughs allowing the connection between the EGSE and the DUT within the LES;
- by the Monitoring and Control capabilities offered by the LMCC, in case the DUT's TM/TC ICD is compatible with the LMCC MCS characteristics. In such a case, the LES operator will be capable to Command and monitor the activities of the DUT in the LES via the LMCC Mission Control System (MCS), connected to the DUT via dedicated EGSEs.

5. Lunar Mission Control Center (LMCC)

The LMCC will be a key element in support of the preparation and execution of future national missions: it will provide resources and services for the preparation and the execution of mission operations, related to the following type of lunar assets:

- surface fixed infrastructures (habitats, landers, robotic systems, etc) to be delivered on the lunar surface;
- surface mobile systems (like robots or other devices equipped with locomotion capabilities), released on the Moon surface with their associated robotic elements (e.g. arms, drills, manipulators, etc);
- orbiting infrastructures;
- payloads installed on board of surface or orbiting infrastructures, offering dedicated services to payloads PIs/PDs for the experiment execution and data exploitation.

The LMCC is not specific for a single lunar mission. Rather, it is conceived to be a control center with a platform, services and an operational area, all of which are configured to create mission-oriented or mission-specific settings, following also the concepts and experience matured by ALTEC and well described in [14]. On one hand, this approach demands designing and implementing the LMCC with general capabilities. On the other hand, these capabilities must be easily adaptable to tailor them for mission specific needs, if necessary. It implies that the LMCC will be designed and developed with the following key design goals:

- Multi-Mission: to accommodate the establishment of multiple control centers for various lunar missions, all falling within the LS&MCC perimeter;
- Modular: to construct control centers with a set of data systems that meet mission-specific requirements and allow for their evolution throughout the operational lifetime of the control center;
- State-of-the-Art: in selecting infrastructural architecture and technologies, including necessary software systems, to ensure the control center's medium to long-term operational viability;
- Reuse: where feasible, to leverage national assets available at ALTEC premises, maximizing past investments and reducing the time required for control center development.

5.1 LMCC Context

Figure 11 depicts the high-level LMCC context diagram, illustrating the external and internal entities with which LMCC will interface to perform and accomplish its tasks in mission preparation and execution.

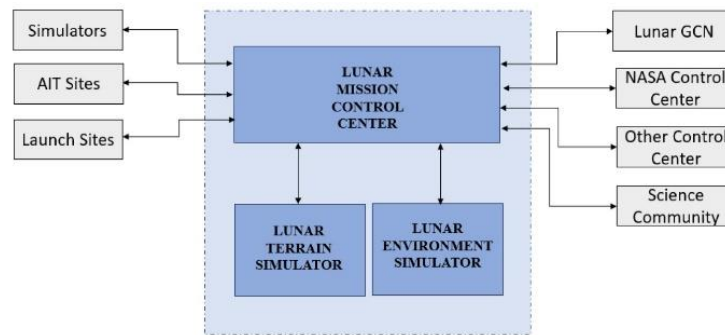


Figure 11. LMCC context

The LMCC will foresee the possibility to exchange data with the following external interfaces (according to the kind of mission):

- the AIT/AIV sites for ground testing of the system before launch;
- the launch site / transportation system Control Centers responsible for the transportation to the Moon of the foreseen elements or payloads, from all pre-launch activities up to the final placement on the Moon;
- the Control Centers for the Earth-Moon Communication Systems;
- the NASA Artemis / Gateway Control Center, for all the activities involving elements on the Gateway, as well as all the “joint operations” on the Moon (especially for those involving the presence of astronauts);
- the scientific and engineering community for the coordination and the execution of experiments to be carried out on the Moon;
- Control Centers of international partners for the joint execution of operations, on the basis of bi-multilateral agreements.

To interconnect external entities, the LMCC will use ASINET, the network of the Italian Space Agency, as main national communication infrastructure. ASINET will be used to interconnect the LMCC with the Earth/Moon communication systems and/or the NASA's and other international partners' (ESA, JAXA, CSA, etc.) Control Centers.

Furthermore, and this is for sure a key element of the LS&MCC Facility, the LMCC will not be working as a standalone subsystem, but it will be designed and developed to be interconnected with the LTS and LES facilities, by providing adequate interfaces with:

- the LTS facility, ensuring (locally and remotely) monitoring and control capabilities to its operators/users;
- the DUTs operating inside the LTS facility, ensuring (locally and remotely) monitoring and control capabilities to its operators/users;
- the LES facility, ensuring (locally and remotely) monitoring and control capabilities to its operators/users;
- the DUTs operating inside the LES facility, ensuring (locally and remotely) monitoring and control capabilities to its operators/users.

5.2 LMCC Architecture

The high-level scheme for the LMCC architecture is mainly composed of the following elements:

- IT Infrastructures & Services: they consider the low-level hardware and software elements necessary to the LMCC functioning (network, servers, storage, client computers, voice loop system, video management system, Internet connection, WIFI). In other terms, it is the infrastructure backbone for the creation of the private cloud platform, the networks to interconnect external and internal to L&SMCC interfaces, and all hardware and systems needed to setup the client area and services;
- Platform Services: they refer to these services needed to generate dedicated environments for each mission specific control center, and for the utilization of the data systems across all LMCC environments like security, logging, authentication and data archive functions;

- **Data Systems:** these encompass the software systems and tools required to operate the mission providing all the necessary capabilities for mission planning, manoeuvre calculation, simulations, commanding, data reception, flight infrastructure monitoring, data product generation and management, and service provision to end-users;
- **Client area:** it refers to the operational rooms properly equipped with hardware, internal connectivity to environment hosting data systems, external connectivity to external interfaces, mission support systems and tools supporting the LMCC operations.

The LMCC will be implemented by exploiting virtualization technologies on a private cloud infrastructure, as already put in place for the Multi-Mission Support Center (ISS Sustaining Engineering and Operations support) and for the Rover Operations Control Center (ROCC, ESA ExoMars Rosalind Franklin Mission [7]) hosted at ALTEC premises.

The availability of the cloud platform shall allow the creation of dedicated environments with specific data systems, corresponding to different control centers, each of them fulfilling the needs and requirements of a specific lunar mission falling under the LS&MCC perimeter.

5.3 LMCC Data Systems

The Data Systems are those software components offering the functionalities needed to build the mission control center environments, dedicated to each lunar mission. The list of the so-far identified set of data systems, for the realization of Lunar Mission Control Centers are listed here below, grouped based on mission dependencies:

- **Mission Dependant:**
 - Mission Control System (MCS);
 - Mission Planning System (MPS);
 - Flight Dynamics System (FDS);
 - Simulators (SIMS);
 - Data Product Management System (DPMS);
 - Data Processing System (DPS);
 - 2D Geographic Information System (GIS);
 - 3D/VR Visualization Tools (3DVT);
 - Lunar Localization Tools (LLT);
 - AI Model System (AIMS).
- **Mission Independent:**
 - LMCC Data Archive;
 - Lunar Terrain Simulator I/F (LTS I/F).

6. LS&MCC Design and Development Schedule

The LS&MCC development is following an incremental logic approach, subdivided into 3 phases spanning over 36 months, from December 2023 to end of 2026:

- **Phase 1** is almost completed and had the goal to complete the system definition and system design up to a maturity level necessary to start the implementation phase.
- **Phase 2**, the current phase, is related to the system implementation, including: adaptation of the ALTEC building to the LTS/LES/LMCC needs, configuration of the IT systems, development of SW components. Once the physical areas are available, it will be finally possible to start the configuration and set-up phase with the different subsystems components. This step will be completed by mid-2026.
- **Phase 3** is dedicated to system integration and tests. The final goal is to have the facility ready for usage by the end of 2026.

7. Conclusions

The paper describes the ASI project “Lunar Simulations and Mission Control Center”, an Italian integrated ground facility dedicated to support development, testing, validation, training, and operations simulation of a wide spectrum of activities and equipment (e.g. robotic assets, surface infrastructures, ISRU technologies, scientific experiments), in view of their operation and utilization on the Moon. The Project is currently under implementation by ALTEC, which will also host the facility at its main site, in Turin.

The established planning for its construction, testing and validation, foresees the completion of the Project and readiness for operations by the end of 2026.

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