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PAVER - Contextualizing laser sintering within a lunar technology roadmap

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Abstract

The Global Exploration Strategy of the International Space Exploration Coordination Group (ISECG) describes a timeframe of 2020 and beyond with the ultimate aim to establish a human presence on Mars towards the 2040ies. The next steps lie on the Moon with a focus on the coming 10 years. Early lunar surface missions will establish a capability in support of lunar science and prepare and test mission operations for subsequent human exploration of Mars and long-duration human activities on the Moon.

Given the extreme costs involved in the shipping of material from Earth, a prerequisite for future human exploration is the manufacturing of elements directly on the Moon's surface. Unlike the equipment, which at the beginning will have to be brought from Earth, raw materials and energy could be available following the concept of In-Situ Resource Utilization. The ESA OSIP PAVING THE ROAD (PAVER) study investigates the use of a laser to sinter regolith into paving elements for use as roadways and launch pads thus mitigating dust issues for transport and exploration vehicles. The ESA-funded study examines the potential of using a laser (12 kW CO2 laser with spot beam up to 100 mm) for layer sintering of lunar and martian regolith powders to manufacture larger 3D elements and provide know-how for the automatic manufacture of paving elements in the lunar environment. The project contributes to the first step toward the establishment of a lunar base and will lead to the construction of equipment capable of paving areas and manufacturing 3D structures.

PAVER project sets the starting point for an examination of the larger context of lunar exploration. Mission scenarios will look at different phases of lunar exploration: Robotic Lunar Exploration, Survivability, Sustainability, and Operational Phase. A proposed Technology Roadmap investigates the mission scenario and analyses how, and to which extent, laser melting/sintering will play a role in the various phases of exploration. The paper contextualizes laser sintering within selected mission scenarios and discusses the different kinds of infrastructure that can be produced at each phase of the mission. The outcome of the study includes the detailing of the TRL steps in the project and an outline of a timeline for the different elements. Covered aspects include terrain modelling such as operation pads, roadways, or towers, non-pressurized building structures to protect machinery, and habitat envelopes, to protect and shield humans against dust, micrometeoroids, and radiation.

Keywords: additive manufacturing, solar sintering, ISRU, infrastructure, lunar habitat, paving

Acronyms/Abbreviations

TRL – Technology Readiness Level
ISRU – In-Situ Resource Utilization

1. Introduction

A requisite for future, human exploration will be the manufacturing of objects directly *in situ* - on the surface of the Moon or Mars - given the extreme costs involved in the shipping of materials from Earth. For that, as for any form of manufacturing, the availability of three resources needs to be evaluated: equipment, raw materials, and energy sources. Equipment will certainly have to be brought from Earth at the beginning. Raw materials and energy, on the other hand, could be available following the concept of ISRU. Therefore, ISRU-based additive manufacturing - which allows for *in situ* creation of needed objects and components - will play a crucial role in significantly reducing the (re)supply needs. It will be a fundamental key player in the maintenance and operational phase of the lunar base.

This particular project is set in row of different technology developments which were undergone by international partners. One technology development project was RegoLight [1] which aimed at advancing automation in solar sintering of interlocking building elements for habitats and non-pressurized shelters from a TRL 3/4 to a near TRL 6. The ESA contracted project URBAN – Developing a Lunar base using 3D-printing technologies [2] looked at how a lunar base in its final operational status could become nearly independent from terrestrial resources using ISRU and 3D-printing technologies. SMARTIE [3] another ESA OSIP study contextualized URBAN with an internet of manufacturing thigs. All the mentioned projects are examples of creating the bigger picture and evaluating the feasibility of the ideas, addressing technology gaps, and proposing solution approaches to challenges.

Before building habitats and bigger structures, the creation of essential infrastructure, including roads and landing pads needs to be considered. The presented project PAVER is a study on the selective sintering/melting of lunar regolith for large paving areas, to create needed road infrastructure for future lunar operations. The process is fully automated and enables direct use of regolith in its powder form for Additive Manufacturing with no need for binder and additives. This dramatically reduces the urgency for additional material transportation from Earth [4,5].

The manufacturing technology developed would provide a starting point in examining the broader context of lunar exploration. It is envisioned to play a major role in the first phase (survivability) of lunar infrastructure and base development, and over time to contribute to all phases of lunar exploration: robotic lunar exploration, survival, sustainability, and operational phase. The long-term goals of the project also involve layer-by-layer sintering for the manufacture of 3-dimensional elements for the construction of protective structures such as shelters for habitation units, storage, and hangars.

2. Technology development

2.1 Paving strategies

There are two main strategies taken into consideration in this project, for paving the infrastructure.

1. Static infrastructure: this involves the creation of separate elements (tiles), in one place – a stationery sintering setup (e.g., on a lunar lander) The tiles, after the sintering/melting and cooling process would have to be assembled to create a paving surface. For the assembly process, a mobile rover would be needed.
2. Mobile infrastructure: this involves a mobile sintering setup. The elements would be sintered/melted directly in place, without or with minimum movement of material, creating continuous paving for the needed infrastructure.

At this stage of the project, no definitive decision which of the strategies is more effective can be taken. Further, this also depends on the overall mission scenario, budgets, and other factors. The final choice of paving strategy would also depend on the outcomes from the experiments and availability of lunar landers, rovers, etc, which are already planned in the lunar missions. Options for lunar landers choices are further described in section 4. Currently, the experiments and technology development of PAVER are focusing on both strategies simultaneously.

2.2 Experimental setup

The current experimental setup consists of 12kW CO2 Laser of 100mm Laser spot, (A) KUKA robotic arm KC 350 with a testing bed (B), and a possibility of testing the sintering / melting in a vacuum chamber (1m^3) Additionally, there is an X-Y setup for larger area sintering / melting (C) with the possibility to achieve more precise geometries. An ABB (IRB 2400) robotic arm (D) with a customized recoater, enables the deposition of the regolith simulant in single or multiple layers, at the given area [see Fig. 1].

2.3 Creation of the elements

A couple of approaches to the production of the sintered/melted elements are being developed simultaneously and are divided into 1) Crucible. and 2) X-Y Unit [see Fig. 2].

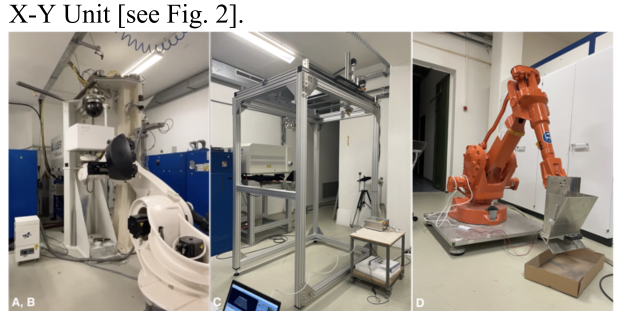

Fig. 1. Laser and Robotic arm with a test bed, X-Y unit, and ABB robotic arm with deposition recoater.

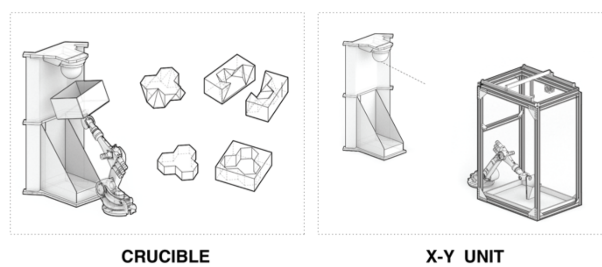

Fig. 2. Diagrams presenting crucible and X-Y Unit approaches for the creation of elements.

The crucible approach allows for the creation of more precise elements, which could be 2.5 or even 3-dimenstional. However, this approach requires the presence of a crucible, which would have to be either brought from Earth, or somehow produced at the destination. That raises an issue of reusability and a life-space of a crucible – how many bricks could be produced out of one crucible? It also potentially slows down the production process, where each element needs to be produced separately and demolded, before the next one can be produced. Filling the crucible with the regolith, and then demolding bricks are also additional steps in the manufacturing process, which decrease the ease and potential full automation of the manufacturing process.

With the X-Y unit approach, the freedom of geometries that can be produced is diminished compared to the crucible approach. Especially when it comes to 3-dimensional shapes, where the geometry of the element differs along the vertical axes, the crucible approach is more suitable. However, the advantages of the X-Y Unit approach abandon the need for any additional equipment (crucible) to produce elements. Assuming the sintering/melting recoater is mounted on a mobile platform, the whole paving could be done directly in place without additional assembly. At the same time, this approach is suitable in the stationary set-up scenario.

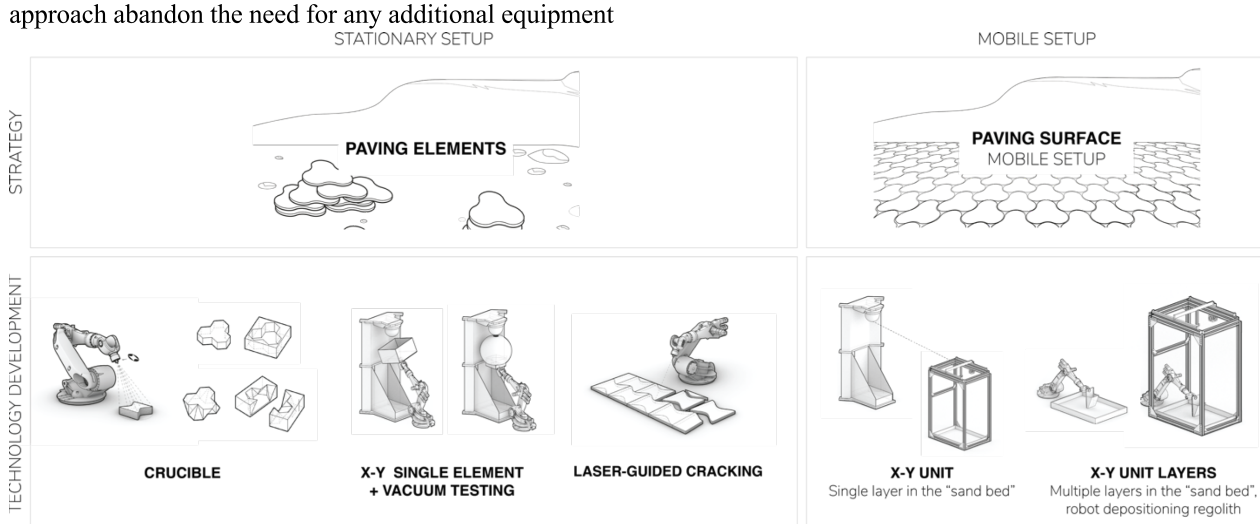

Fig. 3. Diagram showing the potential strategies for PAVING and experimental setup allowing for technology development.

Table 1. Comparison of the Crucible and X-Y Unit sintering/melting for manufacturing of the elements.

Casting	3D printing
Precise elements, freedom of geometry.	The elements are restricted to the potential movement of the x-y unit
Creation of 3-dimensional elements where the geometry varies along the vertical axis.	Creation of 2D and 2.5D elements only.
Need for the crucible. Issues of reusability and lifespan of the crucible.	No need for the crucible – elements manufactured directly at the powder bed, in the regolith at the lunar surface.
An additional process needed to assemble elements.	Suitable for both, mobile and stationary sintering set-up.
An additional process to sintering/melting – filling the crucible and demoulding elements.	Additional process to sintering/melting – site preparation
Slower process – one element produced at the time	More automated fabrication process – potential for the creation of the "whole paving area" at once.

2.4 Geometries of the elements

A principle that was selected for the design of geometries for paving elements is topological interlocking. It is a design principle, according to which elements of specific shapes are arranged in such a way that the whole structure can be held together by a global circumferential constraint. Locally the elements are held in place by kinematic constraints imposed by their shapes and mutual arrangement [6]. Originating from the principles behind topological interlocking, there are certain aspects that could impact the design decisions:

- **Self-adjustment.** Self-adjustments of elements - smooth, curved shapes will be easier to self-adjust than polygonal elements with straight edges and corners. High-fidelity geometries, where the interlocking capabilities are dependent on the precision of connection, would have lower self-adjustment potential than low-fidelity geometries, where the detailing of the connection does not affect the interlocking capabilities that much.
- **Compression/constraint.** With the topological interlocking of elements, peripheral compression/constraint of the system should be provided, in order to hold it in place. How to provide this compression is being considered in the further progress of the project. For example, the peripheral constraint could be catered by elements of planetary topography.

- **Size.** The size of the element impacts the detailing. The ideal size of the elements, to ensure efficient production and assembly process and to avoid, this needs to be answered through experimental work and testing of produced elements.
- **Z-axis interlocking.** The interlocking elements have the tolerance to missing pieces, which means even if some pieces will be missing or will become damaged, the whole structure will still hold its interlocking capabilities. However, in case of any necessary replacements, it may not be possible to easily replace elements that are interlocking on the z-axis. Therefore, probably only 2.5-dimensional elements will be considered for the further development of the project.

3. TRL development roadmap

At the start of the project, the developed technology was on TRL 3 - proof of concept. Currently, through the conducted experiments and tests, it has reached TRL 4 - functional verification. The outcome of project will be TRL 5 - the critical function verification of a laser sintered element in a relevant environment. To advance the technology to a flight proven system, approximately 9.5 years are foreseen. That would still comply with the scenario envisioned by the International Space Exploration Coordination Group (ISECG) roadmap with ISRU missions starting from the early 2020ies and envisioning a human lander in the late 2020ies [7]. It can be feasible to give the advancements from TRL 6 to TRL 7 more time and accelerate the final development steps until TRL 9 within three years. The viability will be proven with TRL 7. If the technology is chosen as mission critical and its development lies within the ISEGC timeline the final development steps for this proposed technology can be secured.

To develop the technology to move from TRL 4 to TRL 9 there are certain steps necessary, listed below. The main description of each TRL is following ESA TRL [8].

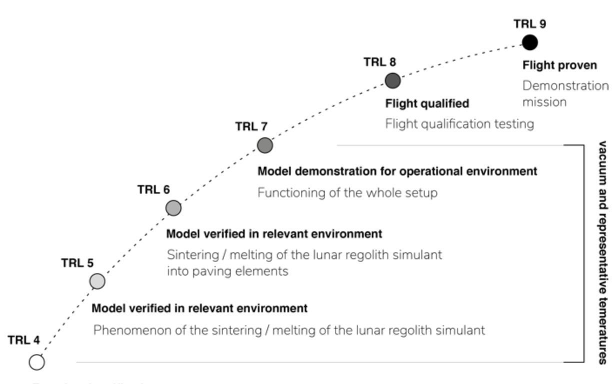

Fig. 4. TRL development roadmap

TRL5 – Breadboard verified in relevant environment. To achieve TRL5, the technology should be verified in a relevant environment. It could be a reduced-scale setup, proving just the phenomenon (sintering/melting of the lunar regolith), not the whole system (precise geometries, assembly process, etc). In this case, the target environment is a lunar environment. Therefore, the phenomenon of sintering/melting of lunar regolith (simulant) should be verified in a vacuum and at representative temperatures. The goal is to check if the sintering/melting process that the project team has investigated in ambient pressure would behave similarly in a vacuum. The other aspect is to check the behaviour of the whole process in temperatures close to the temperature on the lunar poles, in the sunlight, ranging from around 190K (-83.15°C) to 380K (106.85°C) [9].

TRL6 – Model verified in relevant environment. To achieve TRL6, demonstration in relevant environment (vacuum and representative temperatures) should be moved from a breadboard to a setup closer to the final one, demonstrating a critical function - sintering / melting of the lunar regolith simulant into paving elements. The aim would be to successfully create a brick, which would survive the vacuum and later the cooling process, which could be quite rapid taking into consideration lunar temperatures. At this stage the system does not have to be autonomous; the process could be run and operated by humans, to test its functionality and outcomes from the sintering/melting process.

TRL7 – Model demonstration for operational environment. TRL 7 requires the demonstration of a function of the whole setup (not only the sintering / melting process). The outcome should be a good quality product. At this stage, the whole setup should be tested. The process should be more autonomous, showing the capacity for the site preparation (smoothing the surface, getting rid of bigger rocks, etc.), and successfully sintering/melting the brick in the prepared bed. The test should be conducted in the operational environment, which means vacuum and respective temperatures, but also simulated lunar surface (regolith simulant, rocks, etc). However, there is no need to test the functionality of the system in the lower, lunar gravity environment (1.62 m/s^2) due to technical constraints.

TRL8 – Flight qualified. To get to the level where technology is accepted for flight, the setup (similar form the TRL7) must undergo flight qualification testing (e.g. payload vibration testing, lunar surface thermal cycling, etc.).

TRL9 – Flight proven. The last step, bringing the technology to the TRL9, is a demonstration mission on the Moon. The main challenge in realizing such a demonstrator will be down-scaling the PAVER hardware for accommodation on a prospective lunar lander. Assuming the PAVER TRL development will lead to a demonstrator available in the next decade, then several lander vehicles may provide sufficient payload capacity to support such a mission. This is under the assumption that the setup can be miniaturized. The main driver behind the setup requirements for the demonstration mission will be constraints given by the chosen lander.

4. Demonstration mission

The main objective of a PAVER demonstration mission will be to show that PAVER can operate in the lunar environment and melt/sinter regolith to produce elements with mechanical properties required for paving large areas such as roadways and landing pads. The PAVER payload will be transported to the lunar surface using government agencies or commercial landers (see section 4.1). The deployment of PAVER can either be supported by a robotic arm on the lander vehicle or by means of a rover. Both approaches require the preparation of a suitable test site (racking/grading the surface to remove larger rocks), and the set-up of a solar concentrator to provide the energy needed for melting/sintering regolith. The use of a rover to support the PAVER demonstration mission adds significant mass to the allocated mass budget. This can be offset by using a rover from a previous mission such as the proposed ESA ISRU Pilot Plant for O_2 [10] extraction to prepare the test site and a robotic arm on the lander for PAVER deployment.

4.1 Lunar landers

The interest in lunar science and exploration has seen a strong revival in the last years by many countries and even commercial and private entities. Many new lunar lander vehicles are planned or in development that could potentially support a PAVER demonstration mission (Table 2.) The ESA European Large Logistics Lander (EL3) has a payload capacity of up to 1500 kg [11] that can support both a dedicated rover and a reduced-scale version of PAVER. NASA as part of its ARTEMIS human lunar program preparation has contracted several commercial organizations to land science and technology payloads on the moon as part of its Commercial Lunar Payload Services (CLPS) [12]. The first mission is scheduled for December 2022 with the Peregrine lander developed by Astrobotic Technology. The payload capability is 100 kg, but this will increase significantly with the later Griffin lander that can deliver up to 625 kg to a high latitude site [13]. This commercial approach may prove attractive to ESA for the near-term realization of PAVER-type payloads while concurrently developing its own lander capabilities with, for example, EL3.

Table 2. Lunar lander missions for PAVER demonstrator

Planned lunar landers	**Overview**
USA Commercial Lunar Payload Services (CLPS)	• Joint NASA/industry commercial development of robot lunar landers/rovers. • Precursor robot missions to support landing of Artemis 3 manned mission. • Example mission performance 100 – 625kg payload. Astrobotic Peregrine/Griffin. Landing in lunar South Pole Region • Investigation of lunar resources, ISRU utilization investigation, and lunar science • First Mission December 2022 – Astrobotic Peregrine
USA Human Landing System (HLS) – Artemis3/Space X Starship	• First astronaut landing system in Artemis program. Envisaged 2025 tbd. • SpaceX Starship • Payload capability to the lunar surface from lunar orbit 100-200 tons
Europe European Large Logistics Lander (EL3) - ESA	• Payload download to lunar surface 1500 kg • Designed to support scientific and technology investigations • First mission late 2020s • Launch frequency every 2-3 years
China Chang'e	• Chang'e 6 Robotic lunar landing system • Payload download to lunar surface 1500 kg • Up to 10 kg payload for international partners • Chang'e 7 und 8 planned for 2023/2027 • Human lander in the next decade. Details unknown.
Russia (Roscosmos) Luna	• Luna 27 is a joint Roscosmos and ESA mission to send a lander in 2025 to the lunar south pole Aitken crater to investigate volatiles. Now on hold. • Luna 28 is a sample return from the lunar South Pole planned for 2027. 400 kg payload. Comprises 2 landers one with a rover to collect samples and a second with a sample return capsule
India Chandrayan	• Chandrayan-3 lander mission planned 2023? No plans for international partners because of limited payload mass. • Long-term goal to land astronauts on Moon in the next decade?
Japan (ispace) Hakuto-R	• Commercial lunar lander • First lander mission planned for 2024 carrying UAE Rashid rover
Israel (SpaceIL) Beresheet	• Israel private initiative, Cooperation agreement UAE • Beresheet 2 as follow up to Beresheet 1(2019), Landing planned for 2024

Lander vehicles are also being built by Russia, China, and India that could be used as PAVER lander vehicles in a cooperation agreement with ESA. The main problem here is either political (Russia, Luna 26, on-hold) or very limited payload capabilities for international participation (China, Chang'e 6, 10 kg) [14]. The Japan company ispace Inc. is developing the commercially funded Hakuto-R for a landing attempt in 2024 that will also carry the United Arab Emirates Rashid rover [15]. This initiative by ispace is part of long-term development of commercial landers with increasing frequency and payload mass. Also, the Israel Beresheet-2 is planned for lunar landing in 2024 and future Israel landers may be a potential for cooperation with ESA [16]. The lander vehicle with the least payload mass restriction is the ARTEMIS-3 STARSHIP human lunar lander in development by SpaceX, with a payload capability exceeding 100 tons [17].

5. Envisaged mission implementation

A first reference to develop a viable mission scenario is contextualizing it within a larger setting. The ISECG agencies have consolidated their views on international lunar surface exploration in a last update in January 2018 [7]. The ISECG plans look at a timeframe of 2020 and beyond with the aim to establish human presence on Mars towards the 2040ies. The next exploration steps lie on the Moon with a focus on the coming 10 years

The technology suggested in this project - Solar Sintering - is envisaged to play a major role in the first phase (Survivability) of lunar infrastructure and base development [4,5]. However, all three stages – Survivability, Sustainability, and Operational (ref to URBAN where we came up with these 3 phases) would benefit from the implementation of the PAVER to the technological solutions for the creation and development of the lunar base.

Fig. 5. Three phases of the creation of the lunar base – Survivability/foundation, Sustainability, and Operational

In the first stage "Survivability", the focus will be put on infrastructure preparation. Therefore, the envisioned outcomes would include mainly landing pads to enable safe landing and ascent of vehicles from the lunar surface. Together with landing pads, the creation of the first, main roads is envisioned. The process in this stage is envisioned to be fully automated. It would enable the direct use of regolith in its powder form for Additive Manufacturing with no need for binder and additives.

In the second stage "Sustainability", the road infrastructure would be further developed. Additionally, the operation pads and infrastructure for machinery, telescopes, etc. would be developed. Further developments of the project would result in the possibility to construct non-pressurized building structures such as shelters for rovers or launch aprons. These structures would protect the machinery from dust, micrometeoroids, and radiation.

In the last, fully operational phase of the development of the lunar base, the infrastructure is envisioned to be finalized. At the same time, PAVER offers the possibility to extend the infrastructure and any other structures, according to the mission needs and changes in the base plans. It is envisioned that at this stage, additionally to infrastructures and non-pressurized shelters for rovers and other machinery, PAVER would give the possibility to create building structures and habitat envelopes to protect and shield humans against dust, micrometeoroids, and radiation [see Figure 6.].

In Table 3. potential PAVER contributions at different stages of the development of a lunar base is mapped with International Space Exploration Coordination Group (ISECG) scenario objectives for the lunar surface exploration, presented as part of the Global Exploration Roadmap [7]. Figure 7 presents the roadmap of the implementation and contribution of PAVER mapped on the ISECGs Lunar Exploration Roadmap. It starts with a demonstration mission. After that, the next steps, within an actual mission, start with a selection of a specific site for the creation of the first landing pads, roads, etc, followed by site preparation and finally "paving the road". The later stages include moving from 2.5D to 3-Dimensional structures, enabling the construction of shelters and habitats shells. The whole process is envisioned to support a series of human-operated missions on the Moon, which will contribute to the overall technology development and creation of the lunar base.

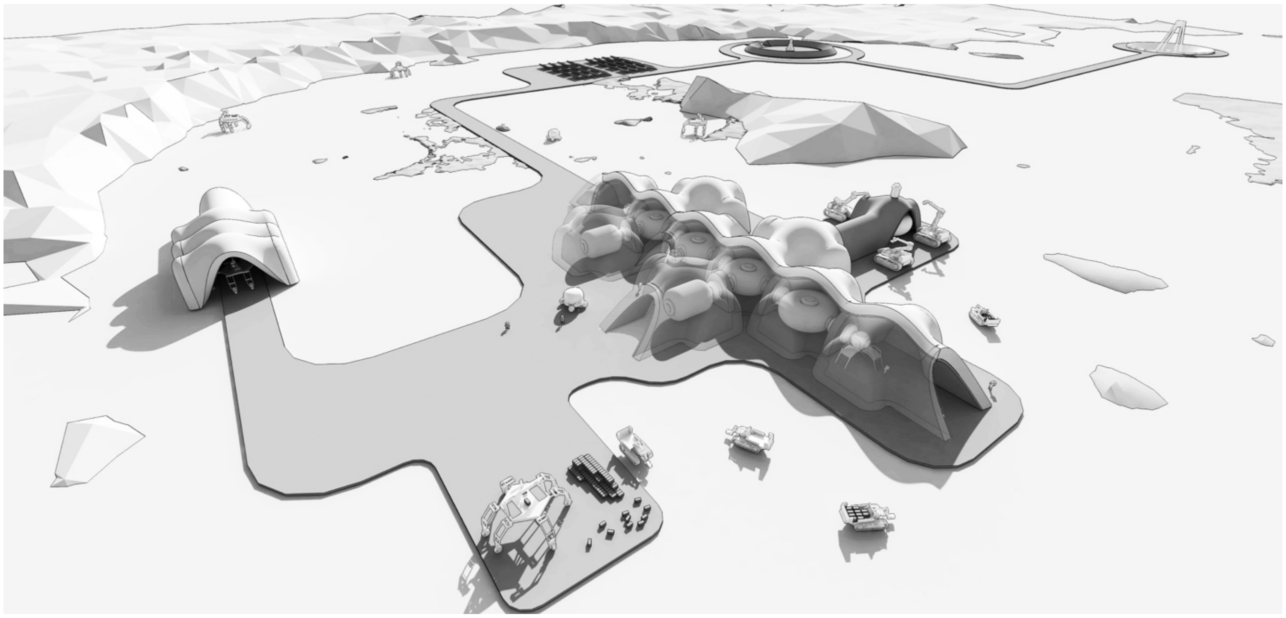

Fig. 6. Implementation of PAVER project for creation of lunar base together with its infrastructure.

Table 3. ISECG Lunar Surface Exploration Scenario Objectives [7] mapped with potential PAVER contribution

ISECG Objective	PAVER contribution
Demonstrate human landing/ascent capability to and from the lunar surface.	Robotic preparation of landing pads for dust-free landing and ascent from the lunar surface.
Demonstrate a range of cargo delivery capabilities on the lunar surface for large surface elements and logistics.	Landing pads for cargo vehicles landing.
	Resistant road infrastructure for cargo deliveries between the elements of the base.
Demonstrate Extra Vehicular Activity (EVA) capabilities on the lunar surface.	Robotic preparation of roads, to enhance transportation potential for lunar exploration and commercial activities on the lunar surface.
	Onsite dust management/mitigation.
	Minimization of road maintenance needs.
Demonstrate human long-range traversing capability on the lunar surface.	Enhances mobility capability by providing reliable, paved road infrastructure, which enables safer traversing on the lunar surface, and enhances the lifespan of vehicles.
Demonstrate reliability of human long-duration habitation capability and operational procedures on the lunar surface.	Providing resistant, replaceable elements for the construction of roads and landing pads.
	In later stages - providing resistant 3-dimensional building elements for the construction of protective structures for habitation modules, storages, hangars, etc, enhancing astronauts' safety and operational reliability.
Demonstrate crew health and performance sustainability to live and work on the lunar surface for a sufficient duration to validate Mars surface missions.	Mitigation of dust exposure, through paving the lunar surface.
Demonstrate in-situ resource production and utilization capability sufficient for crew transportation between lunar surface and Gateway and lunar surface utilization needs	Production of paving elements by sintering/melting regolith with concentrated solar light.
	Providing landing pads for landing and ascent from the lunar surface, and road infrastructure for mobility on the lunar surface.

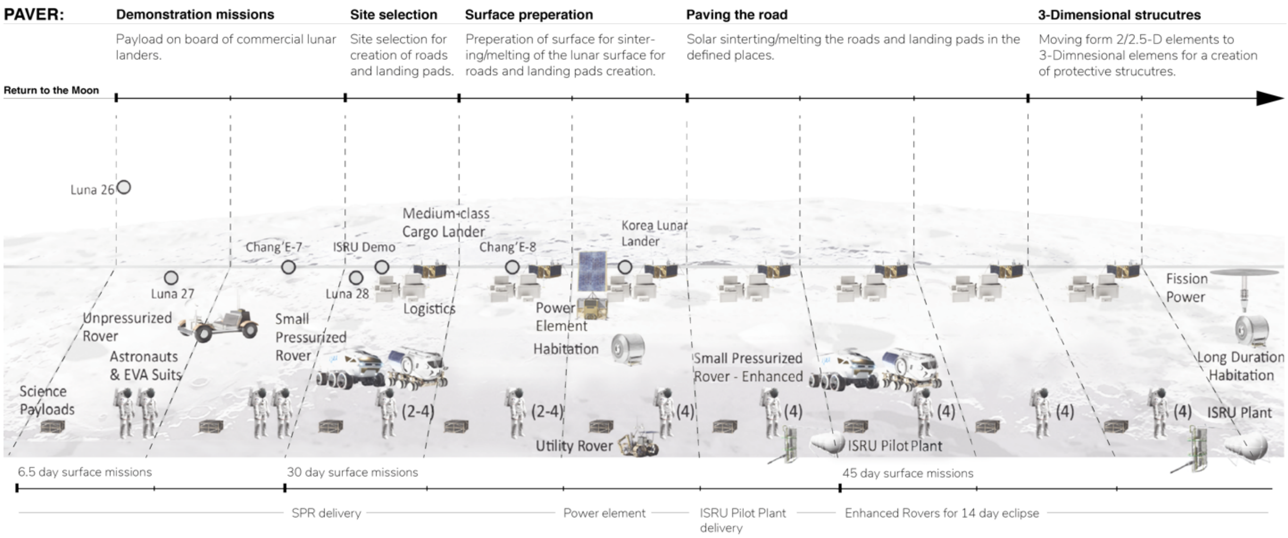

Fig. 7. PAVER project in the context of Lunar Exploration Roadmap, drawn after Global Exploration Roadmap – Expanding and Building [7].

6. Discussion

Together with the development of technologies for building in space and of lunar and Martian infrastructures and habitats, terrestrial applications can equally be considered. An example of terrestrial application of an additive manufacturing project initially developed for space is the project ACME – Additive Construction with Mobile Emplacement [18] developed by NASA and the U.S. Army. Similarly, the sintering / melting technology developed in this project could find a terrestrial application. PAVER could demonstrate the feasibility of constructing shelters for human crews and other surface infrastructure. It can be envisaged that this technology can also play a major role after natural disasters when infrastructure needs to be rebuilt locally and ideally in-situ by the people who live in the affected areas.

7. Conclusions

The ESA Strategy for Science at the Moon [19] clearly states that lunar surface missions can serve as steppingstones for Martian missions and offer great opportunities to build expertise and capabilities in ISRU. The robotic missions will be precursors of lunar exploration; they will demonstrate technologies for human missions and perform surveys or sample returns for science as well as conduct resource and environmental assessment [7].

The PAVER project would help to establish a lunar surface capability in support of lunar science and prepare and test mission operations for subsequent human exploration of Mars and/or long-duration human activities on the Moon. This will lead to a better understanding of the potential economic implications of lunar development and/or commerce.

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