PILOT STUDY ON THE IMPACT ASSESSMENT OF ESA EARLY R&D ACTIVITIES

Development of New 3D Printed Magnetic Materials for Space Applications

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Long-term space exploration missions will require hardware manufacturing beyond Earth …

The sustainability of future space exploration and long-term habitation depends heavily on the ability to manufacture spacecraft components in space, particularly as missions venture further afield from Earth (e.g. Moon, Mars).

Currently, all spacecraft components are manufactured, assembled and integrated on Earth before being launched into space to commence any designated mission. Though manufacturing methods are becoming more efficient – with automation and 3D-printing beginning to feature – all space hardware is constrained by the physical restrictions of launch payload capacity (volume, form, and mass) and strains (vibration, G-forces).

Even on Earth, magnetic materials – essential for systems like propulsion, energy storage, and communication – are particularly challenging to produce. Manufacturing methods used to achieve the highest magnetic performance are energy-intensive and require custom moulds, making them impractical for long-term missions where flexibility, adaptability, and efficiency are key to success.

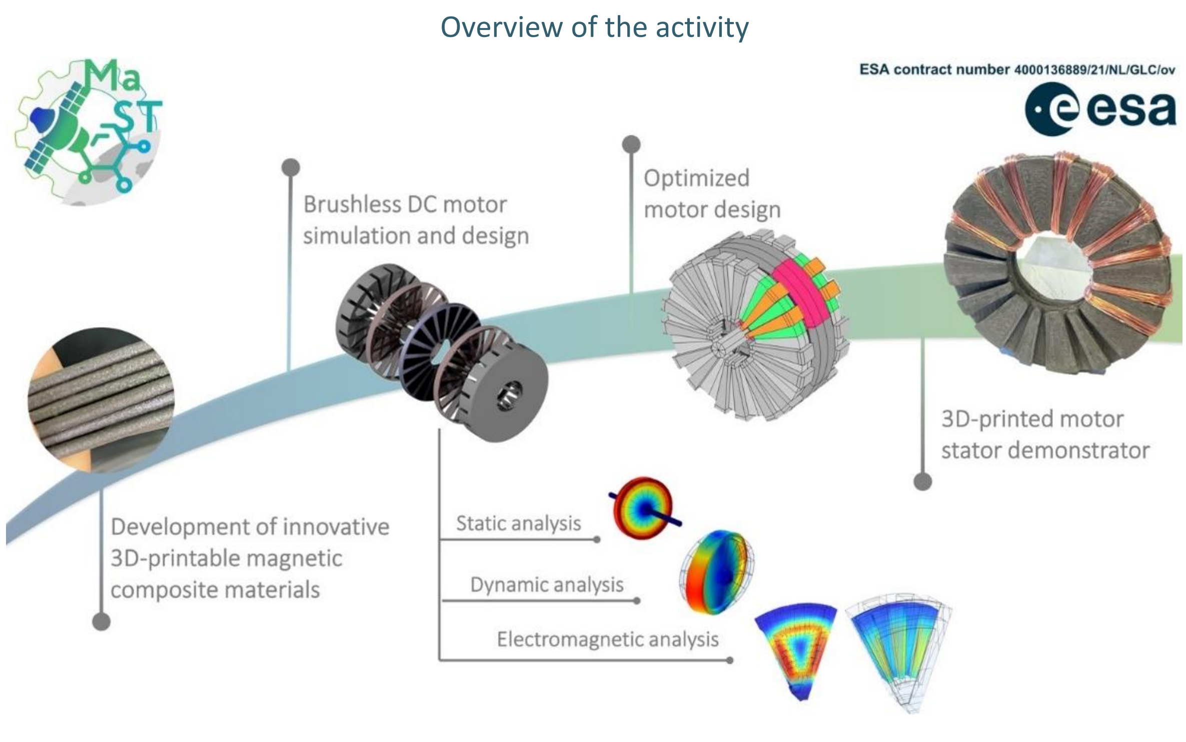
The ’Made on Earth’ model is particularly consequential for space exploration, constraining all missions to an origin point of Earth. Without the capacity to manufacture these components in space, future missions will remain constrained by the need to transport large quantities of materials from Earth. In-situ manufacturing, using raw materials sourced in space, offers a solution. By developing technologies to produce these components on-site, missions could become self-sufficient, significantly reducing costs and enabling deeper and more efficient exploration.

… and new processes, developed with ESA funding, demonstrate the potential of additive manufacturing …

The ‘*development of new 3D printed magnetic materials for space applications*’ project is designed to develop innovative 3D-printable composite materials[1] with soft-magnetic properties for use in space applications, focusing on the utilisation of in-situ resources on

[1] Composites are combinations of two or more materials, where each retains its own properties, but together they produce a material with enhanced or unique characteristics.

the lunar surface,[2] and recycled materials from end-of-life components to produce the required materials. The project exploited existing additive manufacturing technologies, seeking to harness them for space-specific uses. This could lead to unique and cost-effective capabilities in mission and spacecraft design and capabilities, utilising magnetic composites to print bespoke components on-site, rather than relying on the costly resupply missions or transport costs. The project aimed to create these materials using a high-performance polymer matrix, such as polyether-ether-ketone (PEEK), a high-performance composite which complies with the European Space Agency's (ESA) *European Cooperation for Space Standardization* standard for space utilisation and deployment.[3] The goal of the project was to produce materials and filaments that could be 3D-printed into brushless motor components for the space environment, optimising their mechanical, thermal, and magnetic properties. Components produced utilising these materials will also be more cost effective, more durable and perform to a higher standard due to the ability to manufacture more intricate and bespoke components that might otherwise be possible with traditional metals.



Source: University of Rome Tor Vergata

[2] Lunar soil contains materials with magnetic properties which can be leveraged, in combination with other materials, to create composite materials which can be used to print bespoke components in-situ.

[3] PEEK is one of the materials approved under *ECSS-Q-ST-70C Rev.2 – Materials, mechanical parts and processes (15 October 2019).* Standard specification available at https://ecss.nl/standard/ecss-q-st-70c-rev-2-materials-mechanical-parts-and-processes-15-october-2019/, accessed 1 October 2024.

The project received €175,000 through the ESA Discovery programme[4] and successfully produced a brushless DC motor using finite element analysis and 3D-printed a motor stator demonstrator. This was achieved utilising PEEK, showcasing the proof of concept for the application of these materials in space exploration. In practical terms, the project sought to harness resources which are expected to be available in-situ as part of future space missions and to demonstrate the initial technical viability of the technology.

This success demonstrated the feasibility of manufacturing a fully printed electric motor in low or zero-gravity environments. It also represented a significant advancement in technological readiness level (TRL) from 2-3 at the beginning of the project (early stages of development, where ideas start transitioning into practical applications) to TRL 5 at the end (validating the technology in a relevant environment through prototype testing, which is closer to the final design).

The project was undertaken by the University of Rome Tor Vergata, an Italian public research university which specialises in, amongst other fields, engineering, mathematics, and physics. The University boasts a rich history of collaboration with ESA, including as part of *LISA Gravitational Observatory Pathfinder* and its successor *Laser Interferometer Space Antenna (LISA)* mission (planned for launch in 2035), and ESA's *Jupiter Icy Moons Explorer (JUICE)* mission (launched 2023). It also has experience as a partner organisation or subcontractor on other technology development projects, including through ESA's *Advanced Research in Telecommunications* (ARTES) programme.

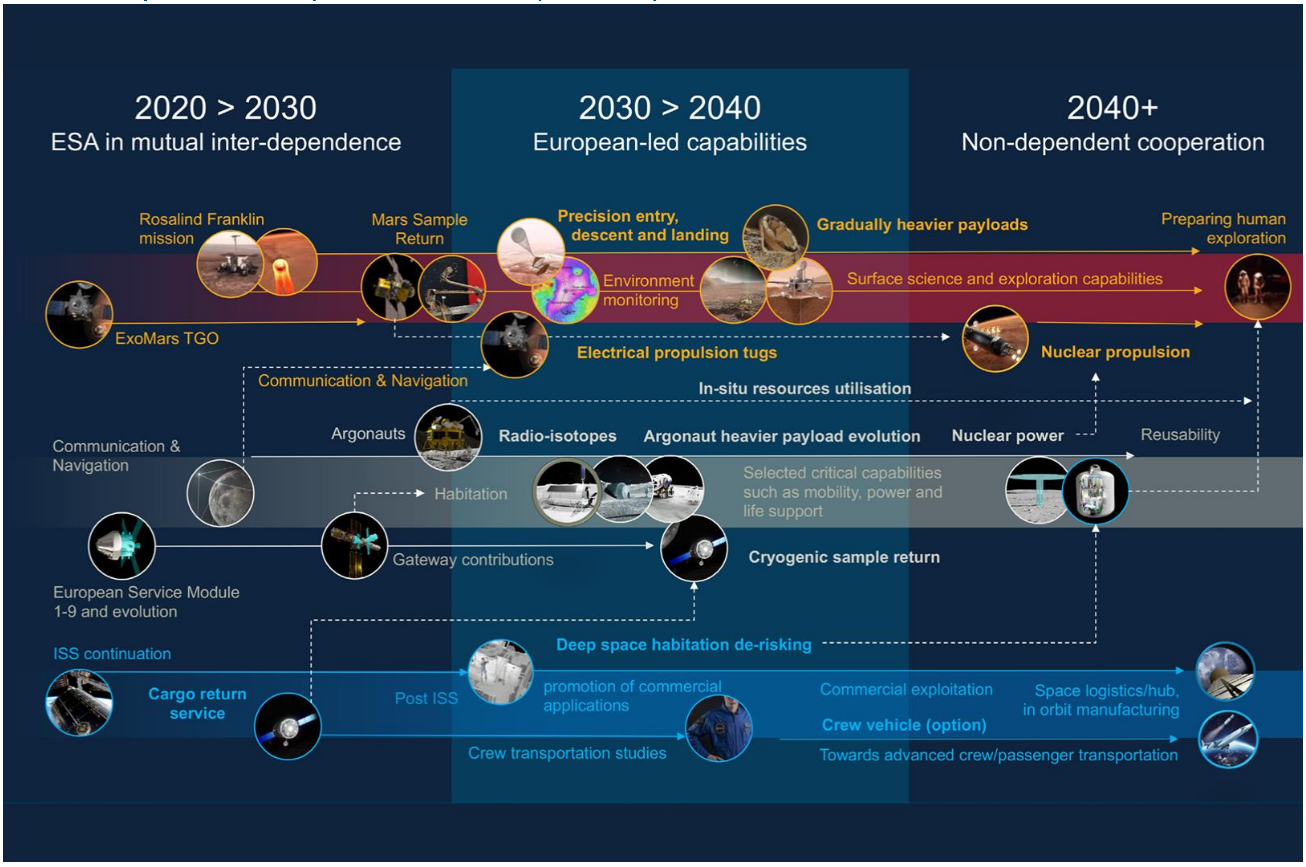
… and the potential for in-situ composite and materials production …

In-situ composite and materials production are seen as key enablers for future space exploration, enabling missions to use locally sourced resources, rather than relying on resupplies from Earth. This approach, referred to as in-situ resource utilisation (ISRU), enables raw materials (such as lunar regolith) to be manufactured into items such as

[4] The Discovery programme is part of ESA's innovation pipeline and is designed to explore new ideas and disruptive technologies by funding early-stage research and development in space technology. Through an open and competitive approach, it encourages risk-taking and collaboration with academia, industry, and innovative SMEs, aiming to identify game-changing concepts for future space missions.

building materials, tools, and spacecraft components. By leveraging local resources rather than relying on Earth-bound facilities, ISRU can ultimately reduce mission costs and alleviate logistical challenges, making long-duration space missions more feasible and affordable in the long-term. Early and successful development of this technology aligns with ESA's long-term plans for space exploration and habitation, and acts as an enabler for the successful deployment of long-term, sustainable space missions. In this respect ISRU creates opportunities to increase mission resilience, such as through the ability to replace critical components while the mission is ongoing, allowing the mission to continue in the event of technical challenges. This technology also introduces a degree of flexibility and autonomy that has otherwise been absent from current space missions.

ESA Explore2040 capabilities roadmap and beyond for Terrae Novae with notional timelines



Source: ESA 2024[i]

Composite materials are important due to their strength and adaptability to harsh environments. Innovations in material sciences and characterisation, including 3D printing and additive manufacturing, have enabled the production of the high-performance composites required to operate within the space environment. These materials offer structural advantages for habitats, spacecraft, and other mission-critical functions, while reducing dependence on Earth-produced and launched components. In-situ composites produced using a combination of local resources (e.g. regolith, water ice, and carbon dioxide) and advanced materials (e.g. volcanic basalt), can provide strong, resilient structures and components crucial for sustaining human activities in space. Though research and development efforts remain ongoing in developing this field, it is envisaged that a wide range of composites could be developed in-situ. Composites include regolith-polymer (for cabinet construction, tools, and spare parts); basalt fibre (suitable for high-strength structure construction); metal and ceramic matrix composites (for spacecraft components, tools and mechanical parts); and carbon and hydrocarbon-based composites (with applications for shielding, and electronics and sensor components).

While the benefits of in-situ production are significant - offering cost savings, mission autonomy, the ability to sustain longer missions over greater distances, and greater overall sustainability - there are technical challenges. The harsh environment of space places increased stress on both materials and processes, creating the requirement to develop manufacturing and production techniques which are able to function reliably and consistently in low-gravity and high-radiation environments.

… with potential, specialist contributions to existing terrestrial applications …

The ability to 3D-print magnetic materials and components, such as those demonstrated as part of this project, has significant potential within terrestrial applications driven by the requirement for customised magnetic components with specific properties. Though current limitations of additive manufacturing mean that mass production applications are presently out of reach, there is a significant demand for the production of complex and bespoke components. The technology demonstrated in this project could feasibly contribute to meeting this demand as it matures.

In the automotive and aerospace sectors for example, materials produced using this technology could enhance the design and production of electric motors and generators. Unlike traditional manufacturing, where individual components are manufactured and assembled, additive manufacturing processes could integrate complex components into a single print. In practical terms, the approach demonstrated through this project could lead to improvements and efficiencies in magnetic flux pathways (such as those used in magnetic resonance imaging, MRI, machines), enhance cooling efficiency of components, and the optimisation of vehicle performance (potentially extending the range of electric vehicles, or increasing aircraft efficiency). The ability to produce custom-shaped magnetic components also creates opportunities for future innovations in sensors, actuators, and other components that benefit from tailored magnetic field configurations.

There are also potential applications within the energy generation and storage sector. Wind turbines, for example, could see the efficiency of energy conversion within their generators increased through the development of custom-shaped magnets, leading to more sustainable power production. More broadly, magnetic materials are key components of batteries and energy storage systems, where they are used in inductive charging and magnetic refrigeration. The ability to print magnetic components with optimised heat dissipation or magnetic field distribution could improve the overall efficiency of these systems.

… which deliver potentially valuable socio-economic benefits

This technology is at an early stage of R&D and needs to be further developed to be commercially deployed and to unlock the most significant benefits. However, **some important human capital and knowledge benefits, as well as potential future collaborations and partnerships, have already been realised at this early stage** through the feasibility study.

Continued development of knowledge, bolstering Italian national expertise and competitiveness

Italy's rich legacy in materials characterisation has fostered a strong research ecosystem, advanced expertise, and enabled projects such as this one to expand knowledge for future space applications.

Italy has built upon a legacy of materials characterisation (dating back to the Renaissance with advancements in metallurgy and glassmaking), fostering a robust research ecosystem that includes universities (such as the University of Rome Tor Vergata); laboratories (including the Institute of Intelligence Industrial Technologies and Systems for Advanced Manufacturing’s Physical Characterisation Laboratory); and specialised research centres such as the Materials Characterisation Facility operated by the Istituto Italiano di Tecnologia. Italian researchers have made significant contributions to the development of advanced materials, including high-performance ceramics, composite materials, and nanomaterials, which are essential for a wide range of industrial applications. Participation in the ESA Discovery programme provided the university with an opportunity to add to this heritage and, reflecting the perishable nature of these specialist skills (the need to continually undertake research and keep skills and knowledge current), the opportunity to stay at the forefront of this field.

The project harnesses the expertise of the Materials Science and Technology research group at the University and provides new opportunities to develop knowledge and experience in magnetic composites, integration, and techniques for working within the unique operating environment of space. In harnessing this expertise, and by collaborating with ESA, the project contributes to Italy's existing leadership, heritage and capabilities within the field, whilst opening up further opportunities for development (e.g. through future phases of this project, or through new projects by other organisations).

Supporting and developing early-career researchers

The project significantly supported the development of early-career researchers by providing hands-on experience, and career advancement opportunities through direct collaboration with ESA.

This ESA-funded project supported the professional development of early-career researchers at the University of Rome Tor Vergata, with three students - including two doctoral (PhD) candidates - gaining experience and exposure to cutting-edge space research and collaboration with ESA. The skills and experience acquired during the project opened diverse career pathways: one student progressed to PhD studies, another secured a position as a post-doctoral researcher, whilst the third secured a role in the Italian Space Agency (ASI).

The project supervisor at the university offered the research team a significant amount of autonomy in the development and delivery of the project. This autonomy enabled them to take key responsibilities, honing project management and problem-solving skills, as well as allowing them to develop their own professional networks and broader knowledge base through engagement with ESA and wider industry.

Enhanced credibility and reputation

The University benefitted from the 'ESA stamp of approval', which can help secure follow-on funding and innovative collaborations, and harnessed the project's success to bolster its own reputation and credibility through conference participation and academic publications.

Projects undertaken in partnership with ESA significantly enhance the credibility and visibility of contractors, in this case the university and its associated research group. The endorsement from ESA serves as a powerful stamp of approval, demonstrating that they can successfully fulfil the stringent technical and project delivery requirements that are recognised as hallmarks of ESA technology development programmes. This can help increase the existing credibility and trust that exists in the university's capabilities and reliability, attracting partners and collaborators in space and beyond, and can be particularly beneficial to secure further funding.

The project, in addition to being included in four conference presentations, has also generated two academic publications, which are currently in the process of being peer reviewed prior to publication. These papers, once published, will contribute to enhancing the project's visibility within the scientific community whilst showcasing the potential of 3D-printed materials in the space environment and the success of the university's efforts in collaboration with ESA.

Securing follow-on funding

The success of the project has enabled the project team to secure additional non-space funding and pursue further funding through ESA's General Support Technology Programme to advance the project towards operationalisation.

Building on the success of the project, the university has also applied for €1 million in ESA General Support Technology Programme (GSTP) funding and aims to develop a prototype within 18 months. GSTP is an optional ESA initiative aimed at developing and maturing technologies needed for future space missions and other commercial applications. GSTP's goal is to bridge the gap between early-stage technological concepts and their readiness for integration into operational space systems and is a significant step towards the continued development and operationalisation of the technologies demonstrated through this project. As the project progresses to higher TRLs (anticipated over a five-year timeframe), further technology development will be central to advancing the project to TRL 6 and beyond. As the technology level increases, so too will the likelihood of deployment on missions (e.g. onboard the ISS) and of broader terrestrial commercialisation.

The project also helped to secure €1 million in non-space supply chain construction funding from the European Commission - with a 30% co-funding commitment from the University - involving a consortium of 31 companies from ten different European regions to collaborate on developing innovative solutions. This application was bolstered by the university's experiences and successes as part of the Discovery-funded activity, with the high-technical requirements for space technologies being received well by non-space sector actors, demonstrating the university's ability to deliver complex projects in an efficient and effective manner.

Catalysing new discussions and collaborations

The project's next phase will foster new partnerships, with Thales Alenia Space Italy as the lead integrator and two SMEs collaborating on the prototype development and implementation.

Collaboration with ESA provided the university with access to space-specific expertise and specialised facilities that were not available in-house. Working with an experienced ESA technical officer in particular allowed the university's researchers to gain insights and guidance that enhanced the quality and potential applications of their work. This close collaboration ensured that the project was directed towards the requirements and needs of potential end-users, and that the initial outputs demonstrated the project's feasibility as a deployable and useful space-system which could contribute to ESA's long term exploration goals. Additionally, access to the European Space Research and Technology Centre (ESTEC) provided access to state-of-the-art facilities for testing and validation which were otherwise unavailable to the university. Combining this expertise and access together with the project team's existing skills and heritage in the field helped to accelerate the development of this technology, resulting in a significant TRL level increase (from TRL 2-3 to TRL 5, evidenced through the production of a viable, working, component), and therefore making the technology more attractive to potential partner organisations and funding programmes.

Looking ahead to the next stages of the project, the university has received positive feedback on its recent GSTP application and is now awaiting official confirmation of the outcome. The consortium for this next phase will include Thales Alenia Space (TAS) Italy as the integrator and end user, alongside two SMEs that will take responsibility for the production and implementation of the prototype system.

Potential creation of spinouts

The specialised nature of this technology, and its continuing development will likely create opportunities for the university to create a spin-out to support the 3D-printed magnetic materials supply chain.

The university has indicated that it may seek to create a commercial spin-out focused on exploiting both terrestrial and space applications of the technology. This spin-out is not yet a materialised benefit, or expected to be realised in the immediate future, but is likely to focus on the commercial production of materials. It will seek to further capitalise on the partnerships and collaborations established during the technology development phases. The realisation of this spin-out is conditional on the continued development and maturation of the technology, which in turn is contingent on continued funding availability.

Specialist contribution to an expanding terrestrial market

The global 3D printing and additive manufacturing market continues to grow, with a market value of approximately €26 billion in 2024, with the potential to reach €118 billion by 2032.

The entry of a technology designed to manufacture 3D-printed magnetic materials into terrestrial markets has significant potential, particularly when 3D-printing is estimated to account for 27% of global advanced manufacturing activities.[ii] As previously highlighted, this technology represents a specialist application of an existing technology (additive manufacturing) to develop niche components.

At this early stage, there are still many steps required before any revenue benefits can be realised. Further development, knowledge transfer, testing, and funding is required to mature the technology to a commercially viable level.

Would these benefits have been realised without ESA?

The development of novel 3D-printed magnetic materials for space applications is not just about adapting existing technologies; it involves creating entirely new materials and processes that can withstand the unique challenges of the space environment. Although alternative funding routes were available, public funding was essential to provide support for the initial development and de-risking of new, novel, technologies.

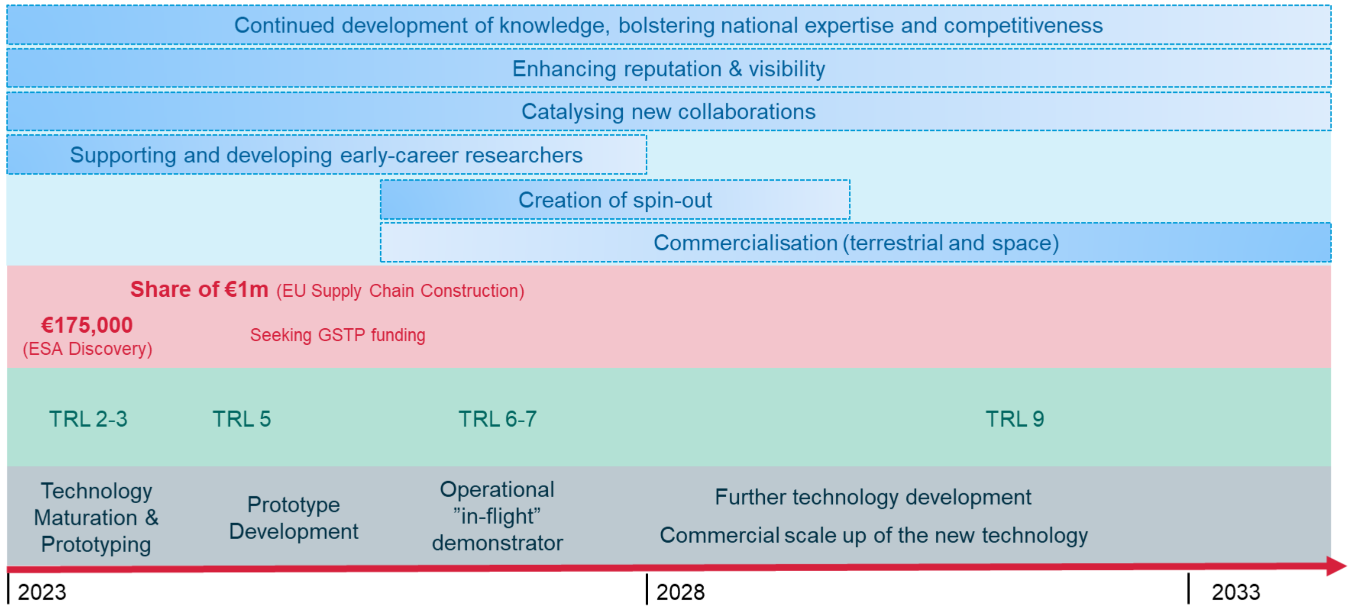
"We were able to have nice technical discussions with ESA […] and explore the feasibility of using lunar regolith to make magnetic materials" – Professor Francesca Nanni, University of Rome Tor Vergata

ESA's support supplied not only crucial financial support, but also provided access to technical expertise, facilities, and a broader network within the space industry. Without ESA's involvement, it is unlikely that the benefits of the project - particularly the development of unique space-ready composite materials, the demonstration of its feasibility, and the subsequent collaboration with TAS Italy - would have been realised to the same extent, or in the same time period. Partnership with ESA also enabled and facilitated discussions about the use of lunar regolith within the development of these materials to prove the feasibility of in-situ resource utilisation.

Next steps: Further development, further benefits

If awarded, GSTP funding is set to last for 18 months. There remains, however, a need to identify a company capable of producing material at a commercial scale as part of the follow-on GSTP project. The university is limited to producing only small quantities of the materials, and TAS Italy has expressed an interest in purchasing all of the currently available products. A key step, therefore, is to identify and engage with an appropriate company to meet this requirement: the subsequent collaboration between the university and this new partner could streamline the transition from prototype to market-ready solution, ensuring that developments and production capabilities, are both scalable and economically viable.

Overview of the timeline of the 3D Printed Magnetic Materials project, and the potential associated benefits



Source: know.space based on University of Rome Tor Vergata data

As the technology matures, future work will likely be needed to develop terrestrial applications such as in electric motors, power systems, and medical devices like MRI machines, benefiting sectors beyond space exploration. In developing these applications, it is important to recognise that 3D printing and additive manufacturing are established processes that already enjoy commercial success: this project seeks to address a capability gap in space applications, and any terrestrial application will naturally focus on niche, bespoke components and parts.

Key priority indicators

Programme	Discovery
Country	Italy
Activity cost	€175,000
Duration	18 months
Lead contractor	University of Rome Tor Vergata
Sub-contractors	-
TRL progression	Started at TRL 2-3, reached TRL 5 at project completion
Spin-in into the space sector	-
Jobs supported	3 students
New collaboration with ESA	Previously worked with ESA.
Partnerships created	Potential future partnerships with TAS Italy, as well as with two (unnamed) SMEs.
Follow-on funding applied/secured	• Secured non-space supply chain construction funding from the European Commission totalling €1 million, including 30% co-funding as part of a consortium of 31 companies from 10 different European regions. • Applying for €1 million in GSTP funding for prototype development.

[i] ESA (2024). Explore 2040: The European Exploration Strategy. Available from: https://esamultimedia.esa.int/docs/HRE/Explore_2040.pdf

[ii] European Commission (2024). Strategic Insights into the EU's Advanced Manufacturing Industry: Trends and Comparative Analysis. Available from: https://publications.jrc.ec.europa.eu/repository/handle/JRC139092