Advenit Makaya
Digitally signed by Advenit Makaya
Date: 2022.12.20 15:43:07 +01'00'

Document description:	**Executive summary**
Deliverable:	WP4-D02
Title of the project:	Off-Earth manufacturing through self-growing 3D printer
ESA reference:	ITT 1749-2
UNITS reference:	OMG3D
Version	1.1
Document date	02/10/2022

1 STATEMENT OF THE PROBLEM

The activity is labeled ESA AO/2-1749/20/NL/GLC, Activity No. 1000029261 in the “esa-star” system. The budget line is E/0600-06-B-01-09 (Discovery, 20-D-S-TEC-03 OSIP), in category ESA EXPRESS PROCUREMENT PLUS (EXPRO+). The invitation to tender is of the type “restricted competitive”.

The University of Trieste proposed the project “Off-world manufacturing via self-growing 3D printer” (OMG3D) to study the implementation of 3D printing of organic matter-derived polymers, originated from cultivation in lunar surface base building.

2 CONTEXT

During the project activities, we proposed a conceptual framework, which utilizes resources available *in situ* through the chemical and physical processes associated with agriculture; the soil and CO_2 (if present) are transformed into fibrous plant matter, harvested and finally converted into mechanical and structural components.

In order to provide a comparison, we investigated the use of regolith and wood as fillers in the matrix of 3D printable polymers. We tested these materials printability both at atmospheric pressure and in vacuum. According to both these scenarios, in a hypothetical settlement mission the bare minimum material and equipment is shipped from Earth to some suitable, i.e. material rich, location on the proto-planet of choice. This constitutes the basic building block to erect a precursor base.

Furthermore, we have studied the process of assembling modular 3D printable components with the aid of a robotic manipulator. This is another building block that enables the construction of complex structures on the surface of the Moon or on any other planetary surface.

3 RESEARCH

Within project scope, we have worked towards the conceptualization and development of technologies to implement 3D printing of polymers on the surface of the Moon and to service the fabrication via robotic means, thus enabling two major aspects of remote base building.

The study comprises:

- A state of the art survey about possible cultivation in a lunar environment and production of 3D printable materials from the fibres and cellulose.
- An economic analysis of the framework, highlighting the return of investment in relation to the use of *in situ* materials compared to traditional Earth launches.
- A study of vacuum 3D printing to enable fabrication directly in the lunar environment, complete with a full mechanical, chemical and material analysis on the printed samples.
- A preliminary study on Cellulose Acetate 3D printing via solvent evaporation, together with a mechanical analysis of the samples.
- A technology demonstrator of robotized assembly of 3D printable components.

3.1 Vacuum 3D printing

The first and most intense task of the research project has been the investigation of 3D printing in a vacuum of highly filled polymers. This topic is relevant in the context of space settlements in that it tries to fill the gap between the availability of *in situ* resources and the use of those resources for meaningful activity in the settlement construction and maintenance.

Printing directly in the lunar environment has several advantages, most of which are due to the absence of a pressurized vessel for the printing equipment:

- **Streamlined infrastructure**; the manufacturing can happen in a comparatively simple shielding infrastructure,
- **Lower infrastructure maintenance**; a pressurized environment requires gas reservoirs, regulation and control equipment, refilling capabilities which could possibly be required to be automated,
- **Lower manufacturing and setup costs** and **lower failure risks**,
- **In place manufacturing**: fabrication of structural components directly in place,
- **Fabrication of large objects**, due to the absence of geometrical limitation of a pressurized environment.

The setup (see Fig. 1) consists in a 40 mm cylindrical AISI304 stainless steel vacuum chamber with thermal IR camera, a combined vacuum gauge, and a large glass panel. The chamber is capable of reaching 10^{-4} bar during printing.

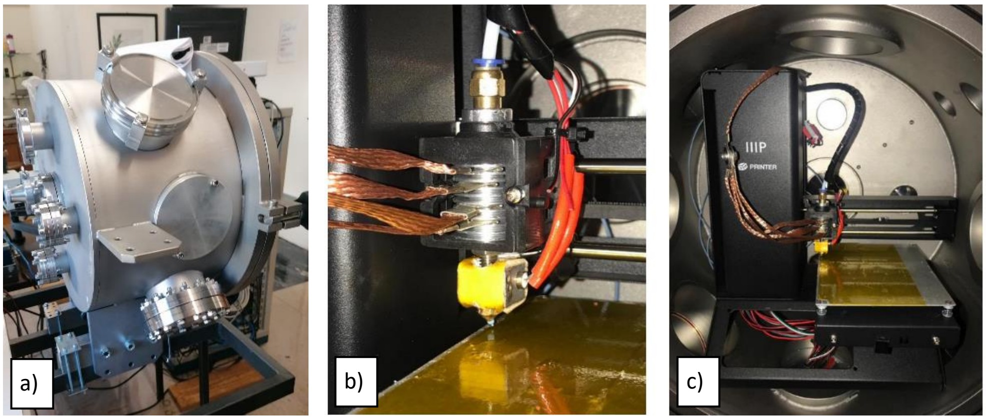

Fig. 1. Vacuum 3D printing experimental setup.

We considered three materials based on PLA (polylactic acid), a widely available biomass-derived bioplastic:

1. **Pure thermoplastic filament**; Formfutura EasyFil™ PLA Sapphire Grey 1,75 mm, 0.75 Kg
2. **Thermoplastic filament filled with vegetable fibres**; Formfutura EasyWood™ Pine 1,75 mm, 0.5 kg
3. **Thermoplastic filament filled with a regolith analogue**; Formfutura StoneFil™ Granite 1.75mm, 0.5 kg

All materials came in spools of ready-to-print filament, with a nominal diameter of 1.85 mm.

Mechanical testing, along with thermogravimetric, accelerated aging and chemical composition testing were performed on the 3D printed samples. The major results can be seen in Fig. 2, where the mechanical parameters are shown to be comparable between the samples printed in vacuum and those printed in normal atmospherical pressure.

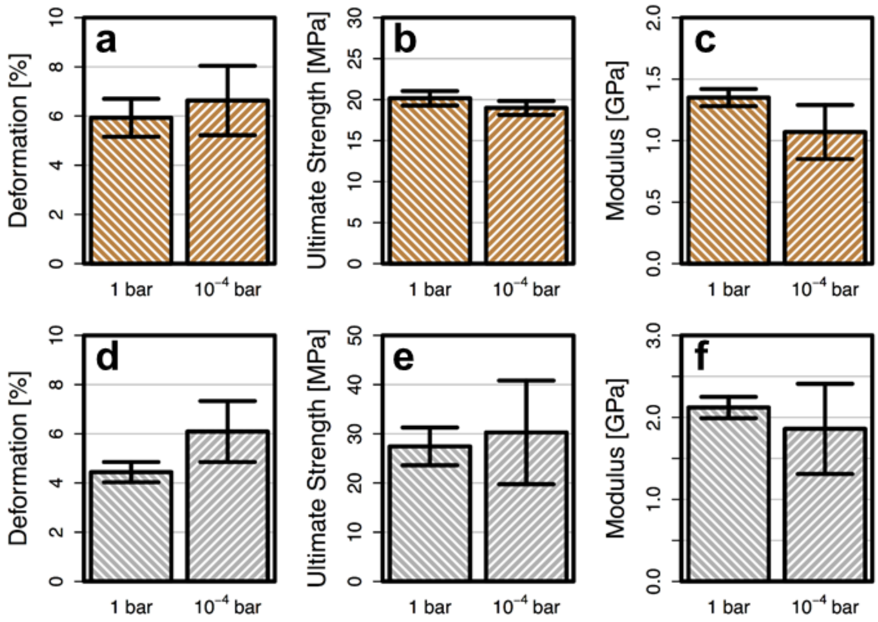

Fig. 2. Mechanical testing results of vacuum 3D printed samples.

3.2 Cellulose acetate 3D printing

Cellulose Acetate (CA) solvent-evaporation based 3D Printing was performed using the technique called Direct Inkjet Writing (DIW). Cellulose was indeed found to be the easiest bio-polymer to obtain in dedicated greenhouses on lunar soil. This technique required the following modifications to the Creality Ender 3 printer:

- Removal of the extruder and nozzle assembly, and of the heating system,
- Design and implementation of a peristaltic pump to extrude the CA-acetone solution,
- Fabrication of a nozzle compatible with the solution,

Following an extensive testing campaign, the best printing parameters were selected, and three concentrations of the polymer-solvent solution were chosen: 20, 25, 27 and 30%.

The most significant measurement we obtained was that for ultimate tensile strength ($\sigma_u = 34.4 \pm 2.2$ MPa), which displayed good reliability with a low standard deviation, especially when compared to the high variance-data obtained for elongation at break ($\varepsilon_u = 11.7 \pm 2.0\%$) and Young's modulus ($E = 604.7 \pm 225.4$ MPa). At this level of accuracy, the variation in concentration seems to only affect processability of the material rather than its mechanical characteristics.

3.3 Robotic assembly of 3D printed modular components

The robot used to assemble the elements made by 3D printing process is a collaborative robot, model Universal Robot UR10. It is a 6-GdL robot that has full manipulability within a workspace volume of

0.5x0.7x0.7 m^3. The robot is equipped with a two-jaw gripper, model onRobot RG6 (6kg payload-150mm stroke). The system is shown in Fig. 3.

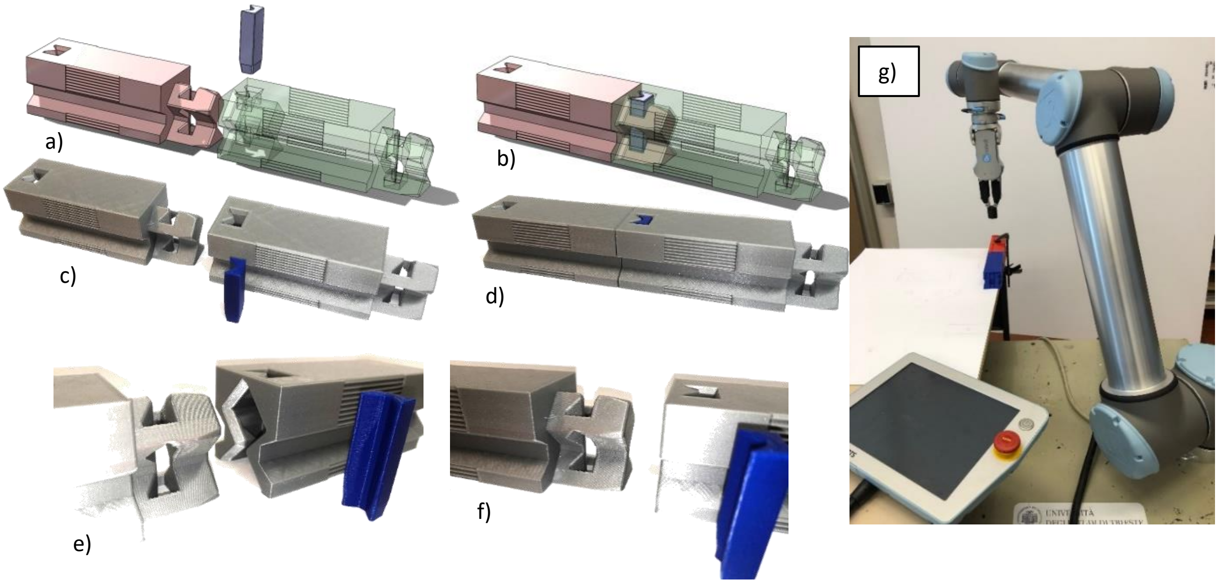

Fig. 3. The experimental setup for the robotic assembly tests.

The design requirements and objectives for the design of the 3D printable modular components are outlined in the following:

- **No supported overhangs**: to avoid post-processing supports are to be avoided.
- **Low required tolerances**: designed components should either compensate or minimize error due to 3D printing inaccuracies.
- **Good joint stiffness**
- **Low alignment tolerances during assembly**: designed components should provide margin for assemblability in terms of sufficiently high tolerances for the alignment and locking of the components.
- **Easy bed separation**: after print completion, a critical step is that of detachment from the printing bed. Designed components shall minimize problems related to this aspect.
- **Self-supported during assembly**

The assembly procedure was carried out on three conceptual prototypes, one of which is shown in Fig. 3a-f. We have seen reliability between 50 and 80% depending on the module geometry.

4 OUTCOME AND CONCLUSION

The OMG3D project successfully explored several novel aspects of the use of additive manufacturing as an enabler for the construction of precursor bases on off-Earth planetary surfaces. The experimental campaigns related to 3D printing provided valuable insight about the use of filled polymers printed in vacuum and of organic waste derived polymers. On the other hand, the robotized assembly study provided a foundational framework for the design of modular components that can be 3D printed and directly used as building blocks for complex structures like actuator guides.

The work carried out during the project provides a first step towards a real use-case for the application of polymer 3D printing on the lunar surfaces. As such, much research has yet to be done to reach operational capabilities. We believe that the current Technology Readiness Level is around 3-4 (Experimental proof of concept/Technology validated in lab) for most of the topics touched in the research.

We estimate to reach TRL 5 in the near future, with a fully integrated technology demonstrator comprising a vacuum environment with the 3D printer, the robotic arm and the object to assemble. Then, in order to reach TRL 6 we plan to extend the demonstrator to process raw materials, including regolith harvesting, multi-part mechanisms production and dust mitigation.

Signatures

Stefano Seriani
Project Manager
Department of Engineering and Architecture,
University of Trieste

____

Advenit Makaya
ESA

____