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Emerging Space Technologies: Macro-scale On-orbit Manufacturing

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ABSTRACT

Advanced additive manufacturing (AM) technologies have the potential to change the way in which satellites and spacecraft are deployed in orbit by removing traditional launch constraints, whether faring volume or launch loads, and allowing space structures to become larger, lighter and more capable with integrated features. These same approaches may also be exploited for on-orbit servicing, thereby potentially extending the operable lifetime of space infrastructure and increasing cost effectiveness.

This paper will provide an overview of the key issues associated with on-orbit manufacturing and discuss the use of AM technologies and investigate the next wave of emerging space technologies enabled by on-orbit manufacturing.

KEYWORDS: Additive Manufacturing, On-orbit Manufacturing, Fused-filament Deposition, New Space

INTRODUCTION

It could be said that the space industry has been built from the ground up because, until recently, most scientific and commercial achievements made in space have required hardware that has first been developed and manufactured on Earth prior to being launched into orbit.

However, not only does this drive the cost of missions, but it also limits the scale and application of traditional space systems, which must be constructed and stowed in a suitable manner to preserve their full operational function after being subjected to the extreme launch environment; including vibrations, acceleration and thermal loads [1]. To achieve this, the masses, stiffnesses and redundancies of space structures are usually extraneous to their normal operational requirements once deployed in-orbit, and furthermore these factors limit the available payload volume within the launch vehicle fairing.

To challenge these constraints, on-orbit manufacturing (OOM) and servicing has the potential to change the way in which spacecraft are designed, manufactured and deployed in orbit [2]. Whilst the ‘New Space’ movement is driving down the costs of accessing space, with the emergence of reusable launch systems [3] and dedicated launchers for low-cost standardised micro-satellite form factors such as

CubeSats [4], the available launch vehicle faring volume still represents a fundamental ceiling to the scale of objects that can be deployed in orbit. The objective of OOM is to create autonomous spacecraft that contain the necessary tools and materials to produce tailored architectures in space that need only meet the demands of their operational environment alone.

This concept is not new, and in fact NASA recognised in the 1970s that such approaches could not only enhance existing infrastructures such as the thermal regulation of orbiting space stations through the construction of thin-film solar shades or thermal coatings, but also new applications such as thermal barriers for orbiting cryogenic storage facilities [5].

However, today the advanced manufacturing industry is seeing a new revolution in additive manufacturing (AM) technologies that 'New Space' companies such as Made In Space are looking to exploit for space applications [6] [7]. In 2016, Made In Space were the first to successfully demonstrate 3D-printing technologies in orbit on-board the International Space Station (ISS) using their Additive Manufacturing Facility (AMF) [8]. Whilst this was only capable of producing simple small plastic tools, it set an important precedent that no longer is the production of tools and components restricted to earth.

Indeed, the Made In Space AMF was a precursor to the more ambitious Archinaut mission that is being considered for launch no sooner than 2022. Their goal is to 3D print in low-earth orbit (LEO) two 10-meter beams lined with solar cell arrays that will be capable of producing up to five times more power than similarly sized spacecraft [1]. This is seen as an enabling mission to later be able to produce telecommunication antennae, large scale space telescopes and other complex structures.

Similar systems are also under development by Tethers Unlimited [9], but it is clear that these new systems still require extensive in-situ testing before the technologies can be considered practical and economically viable, and there remain a number of challenges that must still be addressed.

EMERGING SPACE TECHNOLOGIES

Our programme of research is aimed at understanding the utilisation of AM in orbit for the construction of macro-scale space structures and identifying what their potential applications could be; to be discussed later.

When developing a technology for space applications, there are fundamental questions that must be addressed when it comes to the viability of deploying on-orbit manufacturing technologies in a mission; principally the question of how such hardware will operate in the space environment, and also what level of autonomy can be introduced must be explored.

To begin answering these questions, the most accessible 3D-printing technology was down-selected for initial trials; fused disposition method (FDM). This technology operates by feeding a filament feedstock material into a hot-end where it is heated to melting before being extruded in a controlled manner. By coupling this with traditional CNC technology, high quality three-dimensional objects can be produced on command.

The effects of the space environment

A simple experiment was conducted to obtain a coarse assessment of the effect gravity upon the printed object of an FDM printer. This simply involved reorienting the printer itself such that the gravity vector was directed along three mutually orthogonal axes. By only changing the gravity vector relative to the printer, and no other parameters, a visual assessment of each printed article could be made.

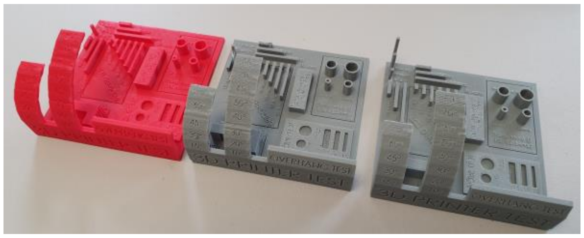

Figure 1. 3D printed test articles printed in three-mutually orthogonal orientations demonstrating gravity vector independence.

The results of this simple experiment were somewhat surprising. After tuning of the printer parameters to produce a high-quality printed specimen from PLA feedstock material, each other mutually orthogonal printed specimen produced visually similar results. This is an early indication that, given the correct conditions, FDM printing technologies may be compatible with microgravity environments.

However, with further consideration of the processes involved in FDM, one can recognise that convection plays a significant role in the solidifying process of the extruded feedstock material, and therefore, the absence of this form of heat transfer in a hard vacuum may yield very different results. Therefore, efforts are now been made to design a modified FDM printer to operate within a vacuum chamber in order to better simulate the space environment.

The 3D printer design is based upon the "H" pattern layout [10] (similar to CoreXY) that accuates the print head across the XY plane via a single timing belt that is driven by two fixed position stepper motors. With this approach, any heat generated by power losses from the stepper motors can be more effectively thermally managed, whilst also increasing the positional accuracy of the print head through the reduced inertia of moving parts. The filament feedstock is fed to the print head hot-end using the Bowden extrusion approach, which again fixes the position of the extruder stepper motor to reduce the inertia of moving parts and improve thermal management.

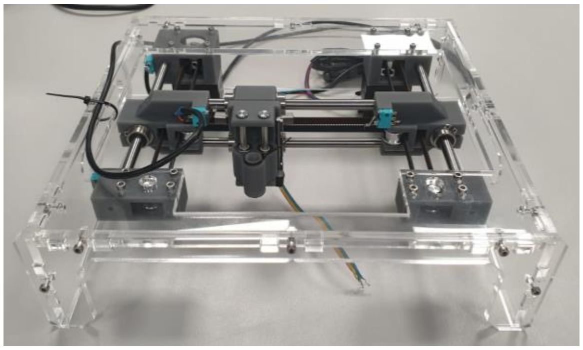

Figure 2. Partially assembled bespoke 3D printer for vacuum environment testing.

Once operable, the gravity vector experiment can then be repeated under vacuum and the results compared.

Of course, not all feedstock materials are suitable for the extreme environment of space. Challenges include selecting a material that demonstrates low-outgassing properties, a resistance to extreme thermal swings, resistance to UV radiation and atomic oxidation erosion. This coupled with an ability to be supplied in a suitable feedstock form and be 3D printable limits the availability of materials.

However, PEEK and Ultem are two types of materials that have flight heritage in space applications and are known to be resistant to the extreme environment. Further still, these materials are readily available in filament form for 3D printing applications.

It is for these reasons that carbon fibre reinforced PEEK will be selected for use during the next trial phases of experimentation through our programme of research.

Autonomous operation

Many terrestrial-based AM technologies can function semi-autonomously, in that a user uploads a model into slicing software so that it can be prepared into a G-code format that the printer can read. Once commanded, the printer will follow the instructions as defined by the G-code itself, only being interrupted in the event of limited feedback control from various on-board sensors if present (an example being a thermocouple/thermistor providing telemetry that indicates a thermal runaway scenario).

However, more comprehensive closed-loop control, whilst under development by various enterprises, is far from mainstream use. And yet, if we imagine a scenario where 3D printer might be operating in orbit about the earth, then failure detection, isolation and recovery techniques will absolutely be essential for mission viability.

To this end, efforts are also being made into introducing closed-loop control that can provide real-time feedback on the print article quality itself. This would have the effect of reducing down-time, material wastage and reduce the requirement for input commands from an earth-based operator.

Machine vision technologies is one such avenue that will be explored for this purpose, whereby visual indicators will be used to compare the programmed print geometry with the actual, and response decisions made autonomously to recover from any deviations encountered.

APPLICATIONS AND OPPORTUNITIES

Assuming confidence in the developing OMM technologies can be realised, there a numerous potential applications for which it could be exploited for. These might include large-scale antennae to support the fastest growing trend for the LEO telecoms market, where commercial entities are demanding ever greater data transfer rates to support the expanding data-downstream sector; or for building larger space telescopes for space-based astronomy.

One sector that has been highlighted by our initial work is the terrestrial energy sector. For example, integrating gossamer membranes with 3D printed structures directly on orbit could produce ultra-large orbiting structures from a relatively modest launch mass. For example, a 100m radius reflector potentially with a mass of less than 1 tonne, would be capable of intercepting approximately 40MW of solar power. Using larger kilometre-scale reflectors new energy services could then be envisioned, whereby orbiting solar reflectors could project sunlight onto terrestrial solar PV farms after local sunset when demand is highest and spot prices are greatest [11].

Further still, this same approach could be used to develop on-orbit solar arrays capable of delivering industrial-scale power to support other emerging applications such as processing near-Earth asteroid regolith [12], and perhaps other yet to be thought of serendipitous discoveries.

CONCLUSIONS

On-orbit manufacturing represents an exciting new emerging space technology. It has been discussed how OMM has potential to unlock the normal constraints of traditional launch systems from deployable space structures, and thus help to drive down costs and realise potential new applications.

It has also been discussed that initial efforts will study the viability and modification of terrestrial-based 3D printing technologies for use in the space environment to fabricate structures directly in orbit. This has already begun with the demonstration that under ambient atmospheric conditions, an off-the-shelf FDM 3D printer is capable of printing in any of the three mutually orthogonal orientations, thus indicating gravity has little effect under such conditions as applied during the experiment.

However, under hard vacuum conditions, the lack of convective heat transfer may yield different results, and therefore a bespoke 3D printer is under development that will be able to repeat this test within a vacuum chamber.

The importance the role of autonomous printing will have on such technologies was also discussed, with a proposal to incorporate machine vision technologies to ‘close-the-loop’ on the printing process. It was suggested that such approaches will be essential for any future missions and applications.

Finally, an application of on-orbit manufacturing was discussed to harness solar energy from the sun to be converted into electrical energy by terrestrial-based solar PV farms. To achieve this, it is suggested that macro-scale orbiting solar reflectors could be manufactured on-orbit and used to extend the normal sunlit period of the solar PV farms by reflecting sunlight after dusk when spot prices are at their highest. It was further posited that such an approach could also be used to produce on-orbit solar arrays capable of delivering industrial-scale power for other applications in space.

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