Development of a Proof-of-Concept Space Propulsion System for Nano-satellite applications using Additive Manufacturing

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Abstract

In this project, Additive Manufacturing techniques was used to develop a proof-of-concept space propulsion system for nanosatellite applications. The main propulsion unit is made up of a metallic structural housing that is additively manufactured using aluminium powder (AlSi10Mg) on the EOS M290 machine. This housing serves as the reservoir that stores nitrogen gas as the propellant, and other components of the propellant system are assembled into it. The novel feature of the housing is that the propellant feed lines are integrated into the structure. This eliminated welds and joints typically found in conventional propellant storage tank, thereby minimizing leakage whilst simplifying assembly and integration. At the same time, the housing was designed using Design for AM techniques, and this made it possible to increase propellant storage capacity by minimizing support structures. The miniature propulsion nozzle, a key component of the propulsion system, was produced using micro-milling techniques to produce a full 3D converging-diverging profile.

A secondary objective of the project was to validate this unique approach by conducting in-space validation experiments to determine the viability of AM in the development of space propulsion applications. Work is currently on-going in the assembly and integration of the proof-of-concept propulsion payload into a 1U Cubesat, where it will serve as the primary payload. This Cubesat mission features a secondary payload which is a commercial off-the-shelf imaging sensor with M12 ruggedized lens that will be tasked with space imaging applications. The current plan is to launch the Cubesat from the International Space Station using the J-SSOD module.

The project was carried out by a multi-disciplinary staff/student team comprising faculty members with domain expertise in aerospace, additive manufacturing, avionics/electronics, advanced machining, quality assurance and mechanical testing. The faculty members were responsible for the design, development, and integration of the proof-of-concept propulsion and imaging payloads. The project also provided valuable opportunities for our students to gain hands-on experience in space and satellite engineering. The students hail from the diplomas in aerospace, aviation systems and advanced & digital manufacturing. They were co-located within the Assembly, Integration and Testing lab which features a class 10,000 clean booth. The students supported Cubesat and payload development and integration as well as mechanical testing.

Keywords
AlSi10Mg, Additive Manufacturing, Design for AM (DfAM), Direct Metal Laser Sintering (DMLS), Space Propulsion

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Acronyms/Abbreviations

AM	*Additive Manufacturing*
AIT	*Assembly, Integration & Testing*
CAD	*Computer-Aided Design*
COTS	*Commercial of the Shelf*
DEIC	*Digital Engineering Innovation Centre*
DfAM	*Design for Additive Manufacturing*
DMLS	*Direct Metal Laser Sintering*
EASA	*European Aviation Safety Agency*
EOS	*Electro-Optical Systems GmbH*
FEA	*Finite Element Analysis*
ISS	*International Space Station*
JEM	*Japanese Experimental Module*
J-SSOD	*JEM-Small Satellite Orbital Deployer*
POC	*Proof of Concept*
QA	*Quality Assurance*
NYP	*Nanyang Polytechnic*
SEG	*School of Engineering*
SSA	*Space situational awareness*
TPL	*Third party liability*

1. Introduction

In recent years, there has been a surge in interest in nanosatellites within the space community. In a report prepared by the global space consultancy company Spaceworks [1], it was shown that the nano/microsatellite segment has grown 10x over the last 10 years from 2010 to 2019, and it is projected that as many as 2,400 nano/microsatellites will require launch over the next 5 years. This is driven in part by the rapid evolution of miniaturized devices, which has redefined space technology, making possible the most ambitious interplanetary missions and near-Earth space exploration. Small, unmanned satellites are now being launched in hundreds at a time [2], forming constellations of powerful small satellites capable of providing platforms that serves as enabling technologies for global communication [3], navigation, ubiquitous data mining, Earth observation, and many other functions.

For smallsats to take advantage of these new opportunities, the presence of an onboard propulsion capability is necessary. The propulsion functions that are required on these smallsat missions include attitude control, orbit maintenance and manoeuvring [4]. However, by definition, nanosatellites are mass and volume constrained [5]. Therefore, it can be challenging for smallsat propulsion systems to fulfil these requirements adequately.

Additive manufacturing is an emerging manufacturing technology, that in the context of spacecraft propulsion, can potentially enable the designer to utilize space more effectively within the spacecraft structure. In addition, rather than just using AM to print specific components, this project also looked at using AM to fabricate an integrated system in which other functions of the propulsion sub-systems are integrated into the main structure.

This project also has important educational objectives on top of its technology demonstration objectives. Final year students are engaged in the project to provide them with valuable on-the-job training, and they work together with their supervising lecturers in a multi-disciplinary setting to support the assembly, integration and testing at system and sub-system levels. The students were also introduced to the rigorous procedures of screening and selection of materials for space applications.

One of the secondary objectives of the project was to establish a ground-station for mission control of the Cubesat during the space segment. This will be integrated with data analytics capability of the Digital Engineering Innovation Centre (DEIC) to explore the possibility of deriving deeper insights using some of the analytics tools. However, this portion of the project was not carried out as there were some issues faced which led to the Cubesat not being launched. The issues and follow-up actions are addressed in Sections 8 (Discussion) and 9 (Conclusion).

2. AM for Space Applications

Additive Manufacturing is a process of joining materials to make objects from 3D model data, usually layer upon layer. The AM process traditionally begins with the creation of a three-dimensional (3D) model using computer-aided design (CAD) software. The CAD model is then sliced into individual layers, which are collectively sent as instructions to the AM machine, which then re-creates the object by adding layers of material, one on top of the other, until the physical object is created.

2.1. Applications of AM for Space Propulsion

Some advantages of the AM process compared to conventional manufacturing processes in the context of space propulsion system are:

- Part consolidation
- Design flexibility
- Design freedom

2.1.1. Part consolidation

Using AM techniques, conventional assemblies can be redesigned and consolidated into a single complex structure encompassing the functions of the propulsion sub-components: propellant storage, manifold, piping. This greatly simplifies the assembly process and reduces errors due to tolerance stack-ups.

2.1.2. Maximizing design flexibility

AM enables the manufacture of complex and intricate geometries without many of the constraints imposed by traditional manufacturing techniques. This is beneficial as the propulsion system can be designed to conform to the internal space of the Cubesat without comprising on structural requirements. This maximises the propellant storage capacity and improves the Cubesat's lifetime in orbit.

2.1.3. Design freedom

Another important benefit of using AM to build the propellant tank is that it can be built in one piece, without the need for welding two shells together as in the case of a conventional tank. This eliminates the joining/welding process that can be costly to inspect and qualify, as well as eliminating the possibility of leaks. With careful design and planning, the internal propellant storage spaces can be maximised without the need for support structures that is typical of the AM process.

3. Design Approach

A novel gas propulsion system for Cubesat application is proposed based on AM techniques. The concept of operation for this system is illustrated in Figure 1.

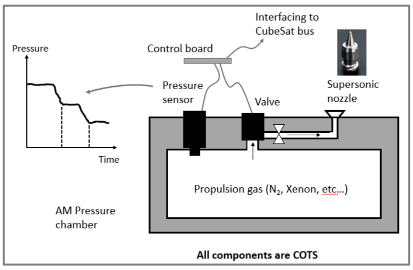

Figure 1. Schematic of gas propulsion system with integral propellant flow channels

The main housing for the propulsion is designed to store the propellant under pressure as well as to serve as a manifold structure with integrated ports and flow channels. This concept is illustrated in Figure 2, which shows the CT-Scan model of an earlier design. The internal flow channels and ports can be seen are integrated within the main structure. The structure also had to match the footprint of the Cubesat standard PC-104 board. This included mounting support for four threaded rods that spanned the full length of the spacecraft. The material chosen for the main structure is AlSi10Mg. This material was chosen as it is strong and yet lightweight, and it is a widely used and well-understood material for AM machine.

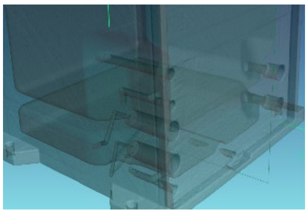

Figure 2. CT-scan of an earlier prototype showing internal flow channels and ports integrated into the main structure

Ports for sensors, solenoid valve, check valve and gas screens are also printed into the main structure together with the flow channels. The result is a very compact and integrated propulsion main structure, which conforms almost perfectly to the internal outline of the Cubesat structure. This maximises the available volume for storing the propellant gas, thereby improving the propulsion capacity.

The pressure sensor, solenoid valve and micro-nozzle will be mounted to the main structure using O-ring seals. To ensure leak-free connections, and to ensure proper operation in the harsh space environment, the seals will have to be carefully selected and evaluated for operation in the harsh space environment that is characterized by a wide operating temperature range, ultra-high vacuum, and radiation.

3.1. CAD modeling design

The 3D CAD software Creo was used in the modelling of the structure. A top-down design approach was taken whereby the propulsion structure was modelled in the context of the Cubesat assembly (Figure 3). This ensures that the propulsion structure maximises the available space within the strict confines of the Cubesat assembly, whilst also ensuring all the components can be assembled without any interferences.

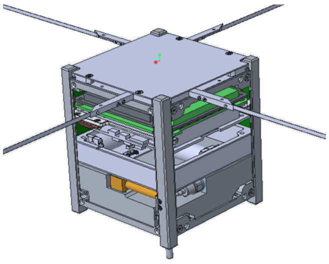

Figure 3. CAD modeling of propulsion structure within the context of the Cubesat assembly

Two variants of the propulsion structure were designed: (1) AM-ready variant, and (2) as-designed variant (Figure 4). The AM-ready variant includes the part geometry that will be produced by the AM process, and includes excess materials distributed strategically over the model which will be subsequently removed by machining and threading operations. The as-designed variant represents the final desired part that will be derived after all the post-build machining processes have been completed.

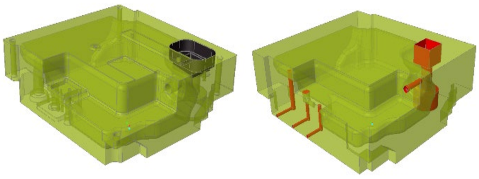

Figure 4. Simplified representations of the CAD model showing the two variants

The Simplified Representation functionality was employed to enable the programmatic regeneration of features based on a single master model to generate two variants This ensures that both the as-designed and AM-ready models share the same baseline features, whilst at the same time, are properly pre-processed for the AM operations downstream. This improves modelling efficiency and reduces errors, thereby ensuring the high quality of the final part.

3.2. *AM Build Simulation*

The AM build simulation software Magics from Materialise was used to prepare the CAD model for AM operations. The necessary features were designed into the model to ensure that the part can be built properly and efficiently. In summary, Magics allows for:

- Optimization of AM build to reduce unnecessary support structures
- Reduction of warpage by the strategic placement of support structures, ensuring build success

4. Fabrication of Propulsion Structure

4.1. *AM Build Process*

The part was printed using the M290 direct metal laser sintering (DMLS) machine from Electro-Optical Systems GmbH (EOS). This machine was previously qualified for aerospace applications by the European Aviation Safety Agency (EASA). The AM powder used in the project was AlSi10Mg, which has comparable mechanical properties to AL2024.

The novelty of the project is that the part was strategically oriented within the build platform such that the propellant cavity can be built without any support structures, as can be seen in the CT-scan (Figure 6).

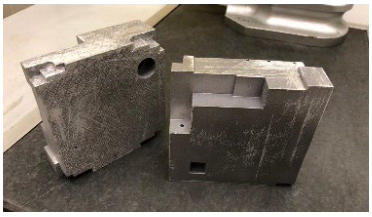

Figure 5. Printed parts, with support structures removed

4.2. *Post-AM Build Inspection*

The AM parts were then inspected using non-destructive CT technology. The results of the scan (Figure 6) revealed that all the designed features were successfully built. The internal chamber for propellant gas storage was built successfully without any support structures. The air flow channels were also successfully built without any closures or blockages.

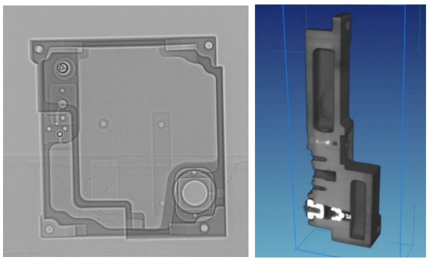

Figure 6: CT-Scan post-processing showing internal features of housing (left) and valves and fittings (right)

4.3. *Quality assurance of AM-built propulsion housing*

The quality and accuracy of the parts produced by the additive manufacturing process is dependent upon many parameters (AM process, powder, post-processing, environment, etc.), which must be carefully monitored and controlled to achieve consistency and repeatability. In this project, the

EOS M290 DMLS machine has previously undergone successful quality control audit by a major Singapore-based aerospace company. This shows that the processes and workflow of the M290 AM machine is highly reliable and can therefore be relied upon to print the propulsion structure with the desired level of quality and accuracy.

4.4. Post-Processing

Although AM technology has improved tremendously, it has not reached the level of accuracy and dimensional tolerances required for high-precision work. The propulsion structure will be required to interface with valves, fittings, sensors, etc. and it is necessary to produce a high-quality surface finish to prevent leakages. Therefore, the R_a for these mating surfaces were specified at 3.2 μm or better. In addition, the machining datums were chosen using the appropriate part features to correspond to the AM-ready variant so that the final part can be produced. Ports were also reamed into the part so that check valves and plug fittings can be assembled. Threads also were machined into the part for accepting the M12 lens, pressure sensor (M5), and plug fitting. Finally, the post-build machined part was then sent for chromate conversion for anti-corrosion protection. The final completed part is shown in Figure 7.

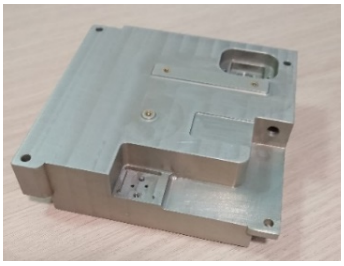

Figure 7. Post-machined propulsion housing with surface treatment for corrosion protection

4.5. Micro-machining of de Laval nozzle

The role of the converging-diverging nozzle (or a de Laval nozzle) is to produce thrust by efficiently converting the pressure/internal energy of inlet gases into kinetic energy. The profile of the nozzle adopted the 80% bell contour as proposed by Rao [6]. The nozzle throat diameter was minimised as much as possible to achieve the lowest “minimum impulse bit”. In this project, it was possible to achieve a throat diameter 0.4 mm for the full 3D converging-diverging nozzle profile. The micro-nozzle was fabricated using high speed ultra-precision micro-milling technique on the multi-axis Mikron HSU 00U.

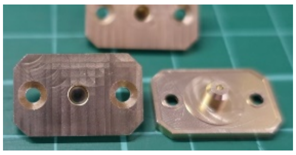

Figure 8. Machined propulsion nozzles

5. Assembly and integration of sub-systems

The assembly and integration of the propulsion payload sub-system was carried out within the clean booth that was setup for this project within the DEIC lab. In addition to the propulsion function, the structure also accepts a COTS imaging sensor with a ruggedized M12 lens for space imaging application.

5.1. COTS imaging system

The imaging sensor system used in this project is the OpenMV H7. This sensor board was chosen for its simplicity and ease of integration. The team has implemented the multiple functions for the OpenMV camera including photo shooting, video shooting and resetting.

The assembled sub-system is shown in Figure 9, where the solenoid valve, pressure sensor and imaging sensor are shown assembled.

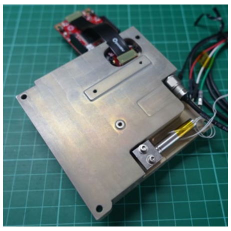

Figure 9. Assembled payload sub-system

6. Testing

The assembled propulsion sub-system was then subjected to leak testing. Nitrogen gas (99.99% purity) was pumped into structure and the internal chamber pressure was monitored using the pressure sensor connected to PicoTech ADC-24. The monitoring was conducted over a period of more than 24 hours, and the results show that the pressure remains virtually unchanged.

The sub-system also underwent thermal-cycling testing with a temperature range between -15 degrees Celsius to +35 degrees Celsius over several hours. The result of the thermal cycling test proved that the COTS sensors and camera were able to function as per normal during and after the test. Additionally, there was no leak from the sub-system.

7. Involvement of students

An important aspect of this project was the involvement of the final year project students. The multi-disciplinary team comprises students from the aerospace, aviation systems and advanced & digital manufacturing diplomas. They were co-located within the DEIC lab, and they supported the assembly, integration and testing of the payload sub-system (Figure 10). For example, they helped to produce mock-ups of the 1U Cubesat using plastic 3D printing for fit checking the payload sub-system. They also helped to screen and select suitable adhesive systems for the staking of the fasteners. There was also industry exposure via visits to local space companies and thermal cycling testing at external test house.

Figure 10: Students supporting cleanroom AIT (left) and component testing (right)

8. Discussion

In exploring launch options for the deployment of the Cubesat for the space segment, there were some issues uncovered. One of these issues relates to the launch and post-launch in-space operations of the Cubesat.

A key requirement of the project is to reduce our overall risk exposure, and to procure insurance where risk exposure cannot be avoided. However, in-orbit TPL insurance products for Cubesats are not readily available. In addition, to minimize risk exposure, it is imperative that in-space operations be conducted in a safe and sustainable manner. However, these guidelines are not yet well-defined. As a result, the launch procurement was suspended pending the outcome of the review.

After consultations with industry experts, the recommended approach for risk minimization was to:

1. Adopt the launch option provided by ISS (J-SSOD)
2. Establish space traffic conjunction warning and alert capability, possibly with Space Situational Awareness (SSA) capabilities, to support in-space operations.

Both approaches are currently undergoing review for implementation feasibility.

9. Conclusions

In this project, a propulsion sub-system with integrated COTS imaging was successfully designed and developed using metallic AM techniques. The sub-system has been successfully tested in the labs and the next steps involve integration with the Cubesat flight model. The project was led by faculty staff members and supported by a multi-disciplinary team of final year project students.

Some issues were encountered which led to a review of the launch options and post-launch Cubesat operations to minimize risk exposure. Although the review has not been completed, initial findings suggest that the next steps of the project involve the establishment of a SSA platform to support the Cubesat operations, and to deploy the Cubesat using the J-SSOD option from the ISS. This will enable the operations to be conducted in a safe and sustainable manner, thereby reducing the risk exposure.

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