Universal parts Fabricator-Replicator for Space Applications

EXECUTIVE SUMMARY REPORT

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1. SCOPE

The Executive Summary Report concisely summarises the result of the activity performed under the contract "Universal parts Fabricator-Replicator for Space Applications".

2. INTRODUCTION TO ADDITIVE MANUFACTURING

The main feature of Additive Manufacturing (AM) processes is the ability to produce parts of whatever shape is desired without the need for any traditional tooling.
The elimination of tooling and the subsequent removal of many DFMA (Design for Manufacture and Assembly) criteria will realize significant benefits in the design, manufacture and distribution of a part or components, including:

- economic low-volume production;
- increased flexibility and productivity;
- design freedom.

The ground based applications are at the moment the first feasible ones, even if the on-board utilization of Additive Manufacturing Techniques (AM) machines might become the logistic basis on which rely in case of further and long-lasting space mission, such as Mars exploration.
The adoption of AM for space missions will bring about a significant reduction of cargo volume and mass required for shipment (i.e. raw material instead of finished product), thus allowing the clearing of some volume on board, and an improved reliability and flexibility too.
The raw materials used in support to these AM systems are usually delivered as:

- metallic or plastic powders contained in sealed cartridges;
- metallic or plastic wire spools and metal foil coils.

To enable a full utilization of AM processes, the re-design of the ORU (Orbital Replacement Unit) concept will become necessary: the parts that can be manufactured will be limited to single items of an ORU instead of the whole assembly.

3. SELECTION OF ITEMS TO BE REPLICATED

Scope of the ESA study "Universal parts Fabricator-Replicator for Space Applications" lead by TAS-I with the participarion of TWI (Cambridge, UK) was the production of two sets of eight pieces each, the first to be replicated with polymeric materials, the second with metallic ones.
The search for valuable and interesting items to be proposed for replication has been carried out limited to the framework of the ESA Columbus programme. The ESA Columbus program was selected as reference since it represents an accessible, consolidated and validated data-source based on a multi-year experience in orbital operations.
A review of the logistics associated with program has been then carried out to compile a comprehensive list of potentially relevant items and a very long catalog of items was obtained by removing from the actual launch manifests (which enlist all items required over the years to support the orbital operations of the European facility) all those elements which are not replicable or not relevant for in-situ manufacturing application (e.g. food, clothes, paper, …).
Then, the entries of such catalog underwent a manufacturability assessment. All the items considered not satisfactorily manufacturable due to current AM processes limitation was removed from the list of the candidate parts. The outcome was a reduced set of candidate items to be further assessed through a dedicated engineering trade-off.
The results of this trade-off activity informed the final selection of the parts to be manufactured, which by the way took into account additional considerations developed internally and coming from ESA.
The final step was merging the list of items resulting from the trade off with the selected AM technologies in order to identify the most promising parts to demonstrate the capabilities of the AM processes.
The following table summarizes the final selection of parts have been manufactured and tested:

Category	Item	AM process	Material	Rationale for part selection
S1m	Smoke detector clamp	Electron beam melting (EBM)	Titanium Ti6Al4V	Challenging (small features), demonstration of potentially useful in-situ AM capability.
S2m	Bolts and Nut	Selective laser melting (SLM)	Stainless steel 316L	Re-designed for lower loads/mass savings (eg hollow parts, functional graded materials).
S3m	DPSB manifold	Direct metal laser sintering (DMLS)	Stainless steel 316L	Demonstration of innovative capability: no sealing, monolithic part.
WC	One shot tool	Direct metal laser sintering (DMLS)	Cobalt-chrome-molybdenum-based superalloy	Demonstration of potentially useful in-situ MFG capability (see below for candidates).
S1p	Biolab glove	Transmission laser welding (TLW)	Thermoplastic polyurethane	Demonstration of innovative capability: body-fitting item.
S2p	Smoke detector clamp	Stereolithography (SLA)	Thermoset UV cured epoxy resin	Re-designed for lower loads/mass savings (eg hollow parts, plastic instead of metal).
S3p	Plastic sealed container	Three dimensional printing (3DP)	Acrylic based thermoset polymer	Demonstration of innovative capability: fluid-tight container.
S3p	CO_2 scrub filter duct	Fused deposition modelling (FDM)	ABS	Case-study for in-situ maintenance (Apollo 13).

Table 1. Summary of the final selection of parts to be manufactured

4. MANUFACTURING AND TESTING OF THE PARTS

4.1 Part S1m – Smoke Detector Clamp

It is used to clamp the Columbus smoke detector device to the duct.

Part:	Smoke detector clamp
AM process:	Electron beam melting (EBM)
Material:	Titanium Ti6Al4V

Mechanical Integration Procedures specifies to install Duct Smoke Detector by means nr 1 DSD clamp and torque alternatively the screws at the nominal torque of 1,4 N.
DSD clamp failed on Columbus because astronauts, during DSD clamp installation, over tightened screws.

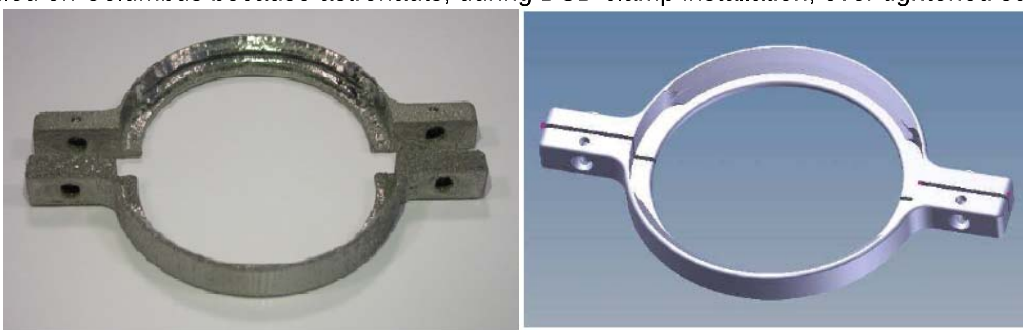

Figure 1. Clamp ring: CAD model and manufactured part

The parts did not include any fittings such as nuts or screws, these were from commercial supply.
Form, fit and function (i.e. it shall have the same dimensions and work as the original) plus torque test for screws, tightening the clamp screws with the torque values of 1.4Nm were carried out. The ring was clamped to an aluminum bar. The parts were measured before and after testing and compared to the expected dimensions of the CAD model.

Test results

- The parts A and B were essentially dimensionally unchanged after their attachment process (tightened to a torque of 1.4Nm). Dimension "D" has the largest change as it would be most likely to change with flexing of the assembly. All other measurements would tend suggest there is either not much change or the differences in measurements are so slight as not to be considered relevant
- The diameter of the bar which had been cut to fit the oversized clamp ring was 60.2mm outside diameter.
- The smoke detector clamp ring satisfactorily clamped to the metal bar, and was able to lift the bar and clamp weighing 5.7kg without detaching from the bar.
- The capability of the electron beam process to resolve these small tread is unlikely to be successful.
- The parts manufactured by the electron beam process were not as accurately made as expected. The surface roughness was also high, and using magnified viewing spatter could been seen.

4.2 Part S2m - Bolt and nut

This bolt is used for Feed Trough Installation, Rear Access Closure (RAC) Integration, Russian Docking System (RDS) FM Installation. In these cases the torque applied to the M10 bolts correspond to 80 Nm.

Part:	Bolt
AM process:	Selective Laser Melting (SLM).
Material:	Stainless Steel 316

One part of the replicated 10M bolt (of solid construction) has been used to determine the max applicable torque by destructive testing, the others was used in form, fit and function testing.
Three bolts were produced from the same material.

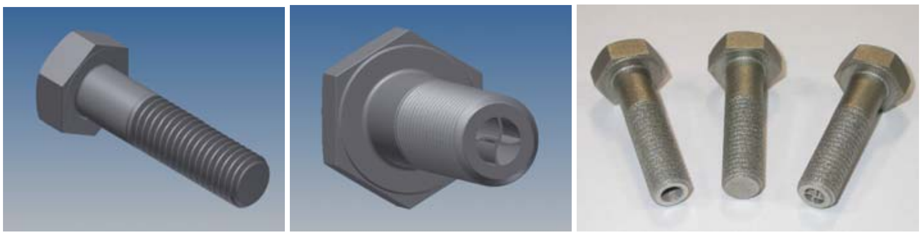

Figure 2. Hexalobular bolts: CAD models and manufactured parts

The surface finish of the material was in general very good, however the tread formation has revealed the weakness of the laser process to fully sinter at the surface of the thread. The tread surface comprises a large amount of lightly sintered material. During testing the open structure the surface is deformed and gives a change in appearance.

Test results

- The solid core bolt passed the 80Nm test criterion.
- The bolt with the hollow core passed 55Nm but failed before 60Nm.
- The hexalobular head was a very good fit with the drive tool
- The material performed well
- The size of manufacture parts was a close match to the model file
- There was less than 2% variation in expected weight compare to the ideal weight from CAD model
- The solid version of bolt passed the expected torque of 80Nm
- The hollow version of the bolt failed at between 55 to 60 Nm

4.3 Part S3m - DPSB Manifold

Water coolant equipment; Delta Pressure Sensor Block for measurement of different pressure.

Part:	DPSB (Delta Pressure Sensor Block) Manifold
AM process:	DMLS
Material:	Cobalt-chrome-molybdenum-based

The design and geometry of the DMLS has been changed in order to take as much advantage as possible of selected rapid manufacturing technology.

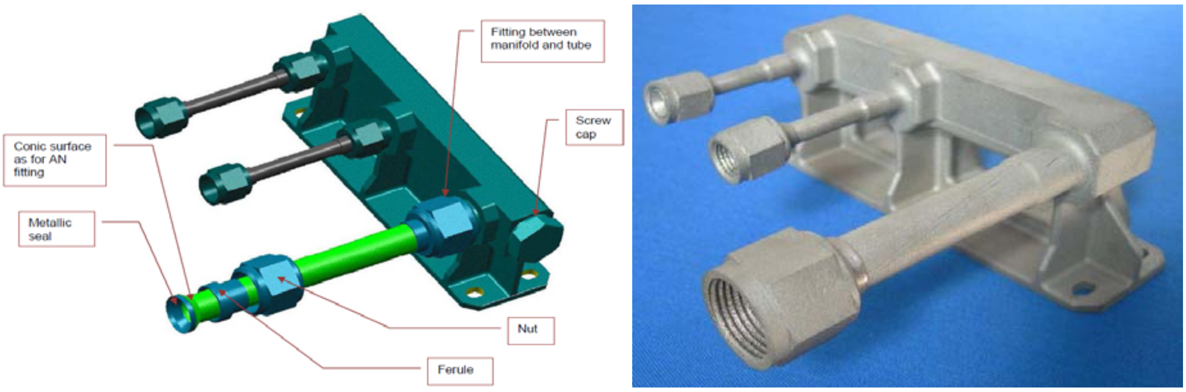

Figure 3. DPSB manifold: CAD model and manufactured part

The conic surface connection did not have a surface finish appropriate to guarantee a high sealing level. The conic surface (sealing surface) was manually polished in order to reduce the leak rate, and soft metal seals were used at the joint, but a seal could not be achieved.

<u>Test results</u>

- Leak rates from the conic seals were too high, before and after manual polishing.
- Ignoring the leaks, the laser sintered part supported 12.6 bar proof pressure without deformation.
- Based on the results, DMLS is unsuitable for making sealing surfaces of this form for space applications.
- Nevertheless, it could be possible to design a new concept of mechanical coupling using rubber or adhesive sealing in order to achieve the required leak rate, potentially using DMLS as a manufacturing procedure.
- In addition, cracks and other defects were visible in one sample that compromised the sealing performance. Further investigation may identify the cause and offer advice on designs to avoid the problem.

4.4 Part WC - One Shot Tool

Part:	One Shot Tool
AM process:	DMLS
Material:	Cobalt-chrome-molybdenum-based

The tool, originally composed by three parts (one 6” extension, 1/4” drive; one 1/4” bit holder, 1/4” drive and one Bit M5 XZN for 1/4” bit holder) was designed and manufactured in 2 parts: the bit and bit holder were combined into one piece.

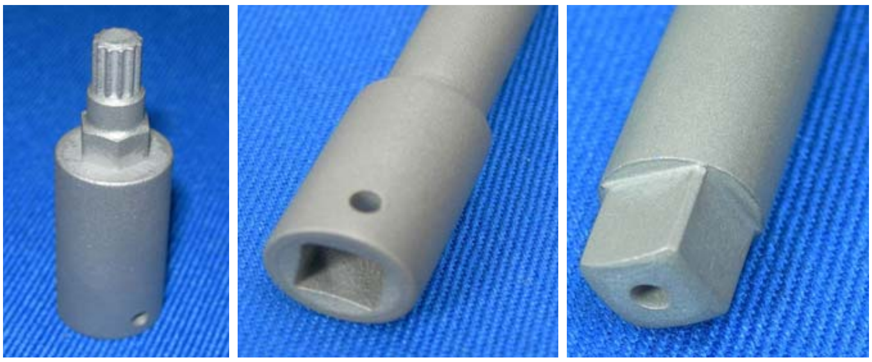

Figure 4. BIT M5 XZN and 1/4” BIT Holder in 1 piece (left); Tool extension details (center & right)

Test results

A torque was applied progressively and around 10 Nm a minor plastic deformation occurred while at 16Nm a large deformation limited further increase in torque. From part inspection it was observed that:

- relative large plastic deformation on teeth of BIT M5 XZN top
- small plastic deformation of elongation.

According to tests results on the first sample, a second sample has been implemented with the following modifications:

- external diameter of elongation has been increased to maximum diameter
- gap between elongation and Bit has been reduced in order to have a more accurate engagement
- internal diameter of elongation has been increased in order to avoid mass increase
- teeth to be engaged with screws have been shorted to minimize the part subject to deformation;

The torque has been applied progressively also to the second sample. Around 10 Nm a minus plastic deformation occurred but we had the possibility to increase the torque up to the required torque 17 Nm. From part inspection at the end of test it resulted:

- small plastic deformation on teeth of BIT M5 XZN top
- no plastic deformation of elongation
- the tool can be reused for additional screw tightening

4.5 Part S1p - Biolab Glove

Part:	Biolab Glove
AM process:	Transmission Laser Welding (TLW)
Material:	Thermoplastic polyurethane (TPU)

Four gloves were made from two flat sheets of polyurethane using transmission laser welding. The flat form profile was designed to provide a 3D form on completion to closely fit the glove form and size selected. A sliding ring clamp with a diameter of 20mm, was used to apply a load of 400N throughout the welding cycle.

Figure 5. Biolab glove

Test results

There was no discernible leak. The pressure did not drop over 3 tests carried out over a period of 30 mins. The sensitivity of the gauge is 5Pa. The tests were carried out at 500Pa and the leak pass level was 25Pa.

4.6 Part S2P - Smoke Detector Clamp

Part:	Smoke Detector Clamp
AM process:	(SLA)
Material:	Thermosetting UV cured polymer

This part is identical to the Part S1m already described but this time it was manufactured from UV cured liquid polymer using the SLA process rather than the EBM.

The design has been adapted for manufacture of the part in polymer, and is thicker to provide increased rigidity and strength. The clamping screws have been commercially procured.

Two different materials were selected and the 2 samples have been manufactured with:

- Nanotool (with higher structural performances)
- Protogen (more flexible material)

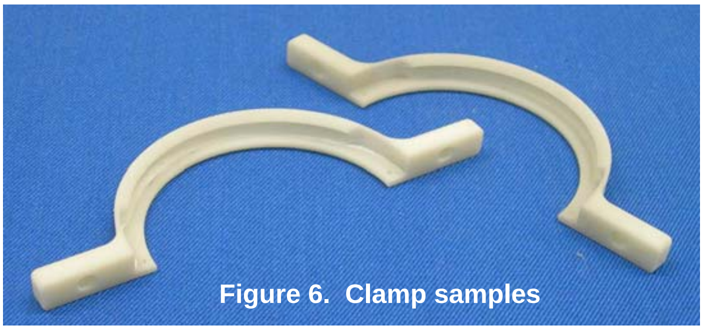
Figure 6. Clamp samples

Test results

The results of the size control were as follows:

- The sample manufactured with nanotool was in line with nominal geometry.
- The sample manufactured with protogen showed some deviations higher than 0.25 mm with respect to nominal (in the direction normal to stratification; as such deviations have no impact on functional performance, the sample was tested)
- The samples were dimensionally unchanged after attachment with screws tightened to a torque of 1.4Nm.

4.7 Part S3P - Plastic Sealed Container

Part:	Plastic Sealed Container
AM process:	(3DP)
Material:	PolyJet™ photopolymer (Acrylic based thermoset polymer)

The items consist of container and screw top lid for the container comprising a two millimetre thick wall and pitched thread. The design incorporated a double sealing knife edge to seal the lid.


Figure 7. Plastic container.

Test results

There was a very good match between CAD dimensions and dimensions of the manufactured items. The finish of the parts was good and as expected. There was a reasonably strong smell from the container, which lasted for many weeks; although bagged.
Two leak tests were undertaken: the container was pressurised to a differential pressure of +7kPa before and -7kPa after and held for 30 minutes for each test. Any pressure drop / increase were measured.

4.8 Part S3P - CO2 Scrub Filter Duct

Part:	CO2 Scrub Filter Duct
AM process:	(FDM)
Material:	ABS

The design of the CO2 Scrub filter duct consists of three parts: the filter box; the filter and the seal.
The box has been designed with an internal rib to assist with supporting the filter against the box wall, in addition to the supporting step at the bottom of the filter. The external envelope of the box is 200x200x200mm with an 8mm wide wall. The filter is simulated by a foam block with approximate dimensions of 180x180x130mm. Manual assembly was used to fabricate the item.

Figure 8. Filter housing manufactured parts

Test results

Measurements were made to assess whether the dimensions were as specified, that the pieces fitted together and could be taped to provide some air tightness.
There were no performance reference values for this part, simply this form, fit and function evaluation.

5. Conclusions

The utilization of the AM on ground for space parts have the potential to reduce the costs associated with the procurements of spares and tools on ground. Instead of buying required items from several market suppliers, selected parts required to support space infrastructure with a long life cycle could be produced by one versatile workshop.
Regarding conversely the application of AM for universal part manufacturing in space, there are some general aspects regarding part reproduction:
Positive

- Replicated parts have the expected structural performance in terms of strength
- Manufacturing time is relatively short
- Part functionality is in most cases adequate
- Parts can be reproduced already integrated or combined
- No limitation due to geometrical complexity

Negative

- Size limitation
- Surface finishing relatively poor (sealing surfaces cannot be manufactured in all cases)
- Geometrical accuracy (tight tolerances cannot be achieved)
- Sometimes a redesign is necessary

Among the above listed parts manufactured, the performed functional test revealed how some parts can be used on-orbit as they has been manufactured, replacing those initially provided, while some other parts need to be reviewed in terms of material and/or process for being able to functionally replace the original ones.
Considering the next steps can be carried out as a continuation of this study, the ISS is the natural place where to perform a test to qualify AM device for microgravity. The ISS could be utilized not only to asses the AM device performance and reliability, but also to evaluate the viability of the overall concept of enhanced on-orbit maintenance. All related uncertainties (e.g. impact on crew operations, process dependability) could be assessed with acceptable risks. Adequate experience could be gained on related hardware and processes before considering these capabilities in the design of new space systems.
Beyond the process validation path, the following objectives relevant to the technological development of the AM techniques can be addressed as additional objectives of the on orbit test:

- Acquire and increase knowledge and operational ability to optimize the AM process in microgravity;
- Increase knowledge relevant to the materials and the parts manufactured with AM technique in microgravity.

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