Centre for EO Instrumentation
& Space Technology

Advanced Manufacturing for EO
&
Space Technology
Challenge Workshop

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1 Introduction

An enduring requirement of space technology R&D, in all its forms, is to find ways of reducing mass, volume, power consumption, and in particular, cost, whilst maintaining appropriately high performance.

This is particularly true if the UK is to be successful in creating self-sustaining and/or profitable services based upon in-space assets. The cost of payload, platform and access to space for satellites has tended to overwhelm the likely return on investment in all but the lucrative telecommunications market.

Recently SSTL has made inroads into reducing the cost of the space segment by re-examining and redefining the methodologies and timescales for the build and test of spacecraft. Airbus and others are able to build a telecommunications satellite within a couple of years. However many are repeat or near repeat builds, and so a degree of production-line engineering can be deployed.

For the institutional science missions, where groundbreaking instrumentation payloads are being flown, perhaps in challenging environments outside of LEO, the time from concept to launch can still be very long, i.e. 5, 10, or even 15-20 years in some cases.

We have recently seen a growth in 'advanced manufacturing' techniques, most obviously additive layer manufacturing, but other non-traditional engineering approaches are also allowing shapes, structures and subsystems to be fabricated that would not be possible, or would be prohibitively expensive, if addressed with conventional engineering approaches.

These approaches are very promising, but are in their infancy. Considering additive manufacturing with metals as an important example, there remain problems such as:

- Poor surface finish;
- Loose powder contamination;
- Resolution;
- Build orientation and other practicalities;
- Inadequate software;
- Process and materials repeatability and reliability;
- Qualification and characterization for space;
- Materials availability.

The use of robotic assembly techniques can be used to increase speed, accuracy and repeatability, and can take the human error factor out of a manufacturing process, but deployment of robotics is also not entirely compatible with our national aspiration to create more jobs in the space industry.

In this workshop, we began a dialogue between UKSA, CEOI-ST, the Satellite Applications Catapult, the High Value Manufacturing Catapult, and the users and practitioners (both current and aspirant). During the discussion, we began to capture some emerging needs that could be addressed by CEOI-ST, UKSA and the Catapults, to support the UK commercial and institutional space industry in realising the commercial potential in space.

1.1 Objectives

The workshop began with speakers representing CEOI-ST, the Space Applications Catapult, the High Value Manufacturing Catapult, and the European Space Agency

1.2 Attendance

Around 75 delegates and speakers, representing: industry; academia; national and international agencies, registered for the conference. We were particularly pleased to see Lee Boland from the UK Space Agency,Andy Barnes from ECSAT, and Mikko Nikulainen and Bernd Sierk from ESA ESTEC.

2 Sessions

2.1 Opportunities & Challenges with Advanced Manufacturing

Prof Mick Johnson, the CEOI-ST Director welcomed the delegates to RAL, and described the purpose of the day.

2.1.1 Advanced Manufacturing Context

Rob Scott provided an overview of the challenges arising from current needs in institutional and commercial spacecraft engineering, and gave a brief survey of available AM techniques with the potential to address these challenges. He also outlined some of the drawbacks of the new techniques and how the advantages need to be traded off against the need for radical changes in design approach, and the need for post–processing etc. Rob did not attempt to provide a comprehensive treatise on the use of advanced manufacturing (AM) in space engineering.

Rob Scott, CEOI-ST

http://www.ceoi.ac.uk/images/docs/advanced_manufacturing_cw/01-scott-brunskill_v1.0.pdf

2.1.2 Introducing the High Value Manufacturing Catapult

Daniel Thompson gave an overview of the High Value Manufacturing Catapult, against a background of the global and national manufacturing marketplace. Like all Catapults, the HVMC aspires to assist organisations to bridge the 'Valleys of Death' to bring new innovations to the marketplace. The aim is to take the risks out of establishing manufacturing systems. The HVM has 7 centres around the UK with very up to date manufacturing equipment:

- Advance Forming Research Centre – Strathclyde
- Centre for Process Innovation – Wilton & Sedgefield
- National Composites Centre – Bristol
- Nuclear Advanced Manufacturing Centre - Rotherham
- Advanced Manufacturing Research Centre - Rotherham
- Manufacturing Technology Centre - Coventry
- Warwick Manufacturing Group - Coventry

Daniel gave a number of cases studies of how the HVM Catapult has assisted various organisation since the inception.

Daniel Thompson , Senior Technology Officer, National Composites Centre

http://www.ceoi.ac.uk/images/docs/advanced_manufacturing_cw/02-hvmc-introduction.pdf

2.1.3 ESA Perspective on Advanced Manufacturing

Mikko Nikulainen began by noting a general decline in manufacturing in Europe, due to a number of factors, including outsourcing. Thus there has been a loss of capability across the board, not just in space. He outlined the advantages of additive manufacturing, and the potential benefits for space and for the European economy in general. He outlined the range of AM activities under investigation in ESA projects. While potentially extremely enabling, there are also issues to be tackled such as:

- Inadequate design tools;
- Materials availability and quality control;
- Process stability;
- Space qualification challenges;
- Standardisation challenges.

He continued to explain that these issues are being tackled in ESA's R&D programmes and under the ECSS standardisation banner. He presented the ESA Cross-Cutting Initiative on AM and the programmes structure.

Mikko Nikulainen, Head of the Components Technology and Space Materials Division, ESA ESTEC

http://www.ceoi.ac.uk/images/docs/advanced_manufacturing_cw/03-esa_adv_man.pdf

An Introduction to Adapting Advanced Manufacturing Techniques to the Space Launch Market

Raymond Davies examined institutional versus commercial space engineering from a USA perspective. Machinists Inc supports many US Space Companies including Boeing, Lockheed Martin, NASA contractors and new entrants such as SpaceX and Blue Horizon. The company examines spin in of aeronautical and marine engineering techniques to the space sector. The company specialises in high dimensional tolerance and distortion control in large structures. Also experience is imported to the space sector from large scale vacuum systems engineering such as those used in particle physics, for example with respect to leak testing.

Raymond Davies, Machinists Inc

Company permission to publish the slides on the CEOI website was not available.

2.2 User Experiences and Issues with Advanced Manufacturing

2.2.1 Additive Layer Manufacturing Facilities & experiences at RAL

Mike Curtis-Rouse: At RAL the AM activities are focussed on experimental manufacturing. The main experience is with making stainless steel ALM, but RAL are moving to titanium and aluminium. There is interest in free-form mirror design in plastic. They have established an Advanced and Additive Manufacturing facility (AAMF), which is co-located with its Metrology facility. The AAMF focuses primarily upon laser powder bed processes, primarily to support spacecraft, cryogenics and embedded systems. Much work goes into process repeatability research and evaluation of component quality. There is a desire to integrate NDT testing (such as neutron diffraction) into the manufacturing process, in order to understand more fully residual stress and the key elements of build quality. To avoid component self-destruction due to residual stress build up, the work is supported by simulation activities. Stress build up is modelled, and this helps to suggest design strategies and support structures that would avoid dangerous stress build up. Integration of multiple components into monolithic structures is an active research area.

Mike Curtis-Rouse, STFC AM & Autonomy Lead.

http://www.ceoi.ac.uk/images/docs/advanced_manufacturing_cw/05-%20curtis-rouse_am_mcr.pdf

2.2.2 Additive Manufacturing Applied to Cryocoolers for Space Applications

Martin Crook: The RAL Cryocooler Unit make a variety of Stirling-cycle coolers for use in space, reaching the 50-80k level, with very long lifetime (10+ years) owing to the no-wear flexure suspension and non-contacting piston combination. The 50-80K cooler requires 40W electrical power for 1W heat lift at 80K. The limits of conventional engineering are being reached and AM techniques are being investigated e.g. for the regenerator heat exchanger component. Additionally, micro-coolers weighing 600g are under development, and the size reduction is giving rise to complex shapes, with awkward duct and channel runs. The new Small Scale Cooler requires 20W for 1W heat lift

Martin summarised progress in using AM techniques to address these manufacturing problems.

Martin Crook, RAL Cryocooler Unit.

http://www.ceoi.ac.uk/images/docs/advanced_manufacturing_cw/06-crook-cryocoolers.pdf

2.2.3 Achieving the Unachievable – Vibration Measurement & Correlation on Lightweight Space Structures

Martin Cockrill: ASDEC is a consultancy formed by University of Leicester. Martin gave an overview of how manufactured items, including very lightweight items, can be tested and assessed using a non-contact portable laser vibrometry system, i.e. without disturbing the structure response with attached sensors. The structural dynamics of the system can be assessed. The laser vibrometer looks for the Doppler shift of the scattered return.

Martin Cockrill, Technical specialist, ASDEC

http://www.ceoi.ac.uk/images/docs/advanced_manufacturing_cw/07-asdec_manufacture_for_space_2016.pdf

2.2.4 AM for the Manufacture of Lightweight Optics

David Walker: David presented the talk, as Berend Winter was unwell and unable to attend.

3D printing supports free-form surfaces, the next revolution in optical design. In a project with partners OSL and Glyndwr University, MSSL have been investigating under CEOI-ST funding, AM for the production of lightweight mirror blanks. Materials used were titanium and aluminium. Lighter structures and freeform shapes can be achieved with e.g. laser sintering but there are potential issues to solved. There are often high levels of internal stress after sintering, and size is limited to around 400 x 400 mm at present. Also current CAD software is unable to cope with complex lattice structures, and similarly FEA software struggles to model the resulting structures accurately. A prototype mirror with a nickel-coated surface has been produced and the evaluation was presented. Further samples are in preparation with gold finish. Uncoated mirrors in aluminium may not achieve optical levels of surface finish, but this correctable by overcoating. It seems possible to achieve optical quality with titanium however. The progress is held back as much by CAD capability issues as by the printing technology. Next step could be the construction of an ellipsoidal mirror, which could be optically tested with a null interferometer.

Talk by Berend Winter, UCL MSSL

http://www.ceoi.ac.uk/images/docs/advanced_manufacturing_cw/08-berend-am-optics.pdf

2.2.5 *Advanced Instrumentation for Micro-Vibration Characterisation of Satellite Components*

Dan Veal: NPL perform vibration measurement on space related devices and subsystems. They have a sophisticated vibration-isolated platform on which tests can be conducted. The vibration isolation techniques can be applied to improve performance of advance manufacturing systems using active isolation retrofits. The facilities can be used to evaluate the performance of AM produced components. The difference in surface finish arising from AM vibration signature as opposed to contact vibration from traditional machining can be explored.

The testing of the micro vibration environment in e. g. solar array drive mechanisms with measurement to µN level to very low frequency/acceleration level was described. X-ray computer tomography can be used to examine printed components.

Dan Veal, NPL

http://www.ceoi.ac.uk/images/docs/advanced_manufacturing_cw/09-veal-microvibration.pdf

2.2.6 *Benefiting from LISA Pathfinder Technology: Precision Glue-Less Adhesion & Novel Position Sensor Architectures*

Christian Killow was speaking on the afternoon of the announcement of the first unambiguous detection of gravitational waves by LIGO, which added some excitement to his talk. Christian related the technical challenges in the manufacture of the optical bench, which the group built for the Lisa Pathfinder (LisaPF) payload. Their adhesive-free silicate bonding technique is now at TRL 9 after the successful launch of the Lisa Pathfinder spacecraft. Under CEOI-ST funding they have been investigating the possibility of using robotic techniques to reduce error and speed up the delicate process of aligning and placing the components for the assembly of such a very precise optical interferometer. They have also been investigating the precision position and angle measurement of the gold test masses used in LisaPF and the future eLisa gravitational observatory. Using a fibre head, they have shown that position and angle measurement can be made up to 4 times more accurately than the current capacitive readout, using their new technique. It is hoped that both the robotic assembly and high precision sensor head can also be used in terrestrial industry, and this is under investigation.

Christian Killow, Institute for Gravitational Research, University of Glasgow

http://www.ceoi.ac.uk/images/docs/advanced_manufacturing_cw/10-killow.pdf

2.2.7 *Additive Manufacturing for Propulsion Components*

Ray Thompson: Airbus Defence and Space is exploring how AM techniques can improve hardware systems throughout its product line. The current programme (funded by CEOI-ST) is examining how AM can be deployed in thruster subsystems to reduce weight and complexity, and improve reliability. Specifically AM fabrication of pipework is being investigated to see if complex 3D pipe runs can be produced with few joins and acceptable surface finish, using laser sintering. In an earlier NSTP project, simple pipe test pieces were produced. The current work explores more complex geometries such as elbows, tees, and 3-way elbows. Firstly using the same drawings as conventionally produced elements, a set of test pieces was printed to give a one-to-one comparison. These were subjected to hot isostatic pressing (HIP) to remove voids and improve structure. The external surfaces were treated using various mechanical and chemical processes to remove loose powder and improve smoothness. Internal surfaces were treated using various abrasive techniques and conventional honing. The presentation evaluates the degree of success, and outlines plans for further development

Also a set of more organic and long manifolds was produced, acknowledging that finishing the bores could not be accomplished at present.

Ray Thompson, Airbus Defence and Space

http://www.ceoi.ac.uk/images/docs/advanced_manufacturing_cw/11-thompson.pdf

2.2.8 Selective Laser Sintering & Post-Manufacturing Analysis for Spacecraft Propulsion

Angelo Grubisic outlined Southampton's work in advanced propulsion techniques, in particular the work at the electric propulsion laboratory. Additive Manufacturing, and other engineering techniques are being used to fabricate ultra-compact but complex components for thrusters and their support systems. A suite of analysis tools is available to monitor and test the work-pieces, including X-Ray computed tomography, scanning electron microscopes, and profilometers for surface roughness characterisation.

A particularly challenging component is the development of a heat exchanger for a high performance resistojet (under CEOI-ST funding), which is being printed from refractory metals. Topological optimisation and multi-physics modelling assist the design process. Examples are shown, success is assessed, and lessons learned are expounded.

Angelo Grubisic, University of Southampton

Permission to publish the slides on the CEOI website was not available.

2.2.9 SHIPSHAPE Project funded by Innovate UK: Net Shape Hot Isostatic Pressing (HIP) of Advanced Materials & Structures

Robin Young related his experience on an Innovate UK project to investigate a new approach to producing moulded shapes via hot isostatic pressing of powdered alloys, using sacrificial shells. The technique is seen as complementary to ALM, when the work piece lends itself to a moulded approach. A mould is typically made by electroplating on a sacrificial mandrel which is removed by chemical means. The mould is then filled with powder, compacted and HIPped at high pressure and temperature. The mould can then be removed mechanically.

The talk examined the trade-offs against other approaches, the kind of component suited to the approach, and the advantages and drawbacks.

Robin Young, Applied Metal Technologies Limited

http://www.ceoi.ac.uk/images/docs/advanced_manufacturing_cw/13-young-shipshape.pdf

3 Discussion

The discussion was guided by the following 4 questions, and was led by Rob Scott.

Q1: What are the emerging manufacturing challenges for commercial and institutional space?
Q2: What are the burning issues arising from the use of Advanced Manufacturing (surface finish, process repeatability, space qualification)?
Q3: How can CEOI-ST/SAC/HVMC and UKSA help consortia both exploit new manufacturing techniques, whilst addressing repeatability, quality and space qualification challenges?
Q4: What are the next steps for all? – (e.g. visits to advanced manufacturing centres, future workshops, themed project calls, incorporation into national strategy)?

3.1.1 Q1: What are the emerging manufacturing challenges for commercial and institutional space?

Education: The first discussion centred on education for AM techniques:

- Southampton University has AM modules as part of their Engineering Degree, and students can have an MSc project in AM.
- Similarly Bristol University has its Innovation Works

What needs are there?

- Skills training for experienced CNC machinists
- A bottleneck in uptake of AM is finding experienced technician grade machine operators
- Catapults have training centre e.g. at the HVM Catapult
- Key requirement is designing for AM, rethinking approach to design
- Design skills are becoming less of an issue currently, but success in AM appears to depend strongly upon local technical expertise.

Manufacturing Process Efficiency: The discussion then switched to process efficiency

- AM is developing very fast, especially for metal printing
- AM machines currently still require a lot of manual setup and intervention, and attention to detail to get the quality required
- 'Composites' was in the same position 10-15 years ago - are there any lessons learned from that experience?

Software/CAD : CAD systems seem to be lagging behind the aspirations of the practitioners at present

- The market will drive future developments
- Transfers of large files of data should not be an issue in the future (although there have been some issues – very long transfer times, and limited data/command storage, implying the digital systems of the AM printing machines is under powered. This is easily corrected.)
- Need control over all machine operating parameters

3.1.2 Q2: What are the burning issues arising from the use of Advanced Manufacturing (surface finish, process repeatability, space qualification)?

The following comments were made on this topic:

- On-line inspection and diagnostics are needed to show what is being built is what you want. STFC RAL are investigating a portable inspection facility, and are examining ways of introducing NDT inside the machines to monitor the work-piece as it is built.
- Machine manufacturers typically are seen to be trying to limit operator options on setting up and adjusting parameters. This is seen as restrictive, especially during early development and in gaining manufacturing experience.
- National activity in ALM - Mike Curtis Rouse is member/chair of 2 national strategy working groups *(contact mike.curtis-rouse@stfc.ac.uk for more information).* Mike is willing to act as recipient of input from the community on these matters.
- Parameters for metal AM are reasonably well known, but not for machines
- Materials/process/machine are highly interactive
- Can satellite manufacture be symbiotic and/or parasitic on mainstream industry such as the aerospace or car industries
- Bespoke "mass" production requires a much higher level of automation
- High precision requires many highly integrated and interactive steps already, and it is unrealistic to assume AM will differ. An automated machine systems typically cost ~ 10s of £M.
- There are 6 laser sintering companies globally who own all the patents
- There is a significant barrier is space qualification of materials and processes

3.1.3 Q3: How can CEOI-ST/SAC/HVMC and UKSA help consortia both exploit new manufacturing techniques, whilst addressing repeatability, quality and space qualification challenges?

The following comments were made on this topic:

- There is a perception of a lack of ability to market what we do, fabrication is unlikely to come back exclusively to the UK, as other nationalities can also exploit these technologies
- Trying to get UK private investment is very difficult, and for instance City investors would have to be convinced that UK has sufficient capability. Timescales for ROI with space is seen as too long e.g. for investment in coolers, typically 2 years is demanded. In addition there is the asymmetric investment problem when considering the potential benefits vs potential downside
- There was a strong message from the meeting of the need to identify and invest in manufacturing technologies with multiple potential markets.
- Overall there was seen to be a lack of UK investment, private and public. There is a need for a concerted effort from UK industry and Government, since there will be strong global competition. For instance, innovative developments will be required for automated manufacture of satellite constellations. If UK is to be competitive, we need to take some risks, and it was noted that RCUK Grants awards are often risk averse.
- The case needs to be made to HMG to underwrite a private consortium investment to advance this technology. The objective would be to get UK to leading edge of the technology, to attract investment and create jobs and growth. We need UK Govt to act as an initial customer
- A UK National AM Strategy is being produced
    - Collecting evidence across range of sectors
    - Complete in 6-12 months
    - HVM Catapult can make proposal to Innovate UK

- It was suggested that a small programme should be implemented as an initial step, UK Govt funded, for a series of space missions. This could include a UK 'AM' TechDemoSat-like mission as a focus.   There is long term interest in manned space habitation construction

3.1.4 Q4: What are the next steps for all? – (e.g. visits to advanced manufacturing centres, future workshops, themed project calls etc., - incorporation into national strategy?

The following suggestions were made

- To increase the uptake of AM by UK industry would need a large investment. The University of Southampton has made significant investment and can make facilities available by arrangement – initial contact A.Grubisic@soton.ac.uk

- We would benefit from a UK inventory of capital investments (which may be a part of the national strategy). A round robin on current capabilities and facilities to attendees could be a first step.

- A follow up meeting should be held with a broader scope, possibly in co-operation with the HVM Catapult

- We could set up a Satellite AM Working Group (cf propulsion WG). It is expected that AM will be a topic in the just-starting revision of the space technology roadmaps

- UK Space Agency noted that space is doing relatively well from Govt investment but budgets are likely to be constrained. There would need to be a good quality business case. It is possible that the European Fund for Strategic Investment could be a route to funding or loan finance.

4 Annexe A – Attendees

First name	Last name	Company
Ben	Anderson	Additive Components
Simon	Ashby	Ordinance Survey
Sarah	Baker	ESA
Andy	Barnes	ESA/ECSAT
Mat	Beardsley	STFC/RAL
Andy	Bennett	KTN Ltd
Lee	Boland	UK Space Agency
Chris	Brownsword	CEOI-ST/RAL
Chris	Brunskill	Satellite Applications Catapult
Davide	Bruzzi	STFC/RAL
Chris	Burton	Hamamatsu Photonics UK Limited
Helen	Butcher	STFC/RAL
Ilie	Ciobanu	Thales Alenia Space UK Ltd
Martin	Cockerill	ASDEC, University of Leicester
Rhys	Cowsill	ASDEC, University of Leicester
Tony	Crawford	University of Leicester
Martin	Crook	STFC/RAL
David	Cullen	Cranfield University
Mike	Curtis-Rouse	STFC/RAL
Raymond	Davies	Machinists Inc
Robin	Devonshire	Sheffield University
David	Downie	QinetiQ, Space UK
Rueben	Edeson	Thales Alenia Space UK Ltd
Maria	Fetta	Hamamatsu Photonics UK Limited
Paul	Fitzsimons	NPL
Alberto	Garbayo	AVS Solutions
Rob	Goddard	SSTL
Rob	Goldsmith	COM DEV international Systems
Pauline	Graham	Loughborough University
Angelo	Grubisic	University of Southampton
Chris	Hamar	SSTL
Robert	Hardie	STFC/RAL
Matt	Hills	STFC/RAL
Mick	Johnson	CEOI-ST/RAL
Shaun	Kenyon	SSTL
Christian	Killow	Glasgow University
Fiona	Lambert	Microsemi
Andrew	Larkins	Airbus Defence and Space
Doug	Liddle	In-Space Missions Limited
Sungwoo	Lim	Open University
Alistair	Maclenan	Quarry One Eleven Ltd
Martina	Meisnar	ESA
Kevin	Middleton	STFC/RAL
Carlos	Mingo Roman	NPL

First name	Last name	Company
Grant	Munro	ESR Technology Ltd
David	Nethercott	Space and Sensing Systems Group
Mikko	Nikulainen	ESA/ECSAT
Steve	Northam	Surrey NanoSystems Ltd
Dan	Peters	STFC/RAL
Martin	Pointer	COM DEV international Systems
Ian	Rule	Met Office
Emma	Ryan	Lockheed Martin UK
Adam	Scott	STFC/RAL
Rob	Scott	CEOI-ST/RAL
Ebby	Shahidi	Haydale Composite Solutions Ltd
Bernd	Sierk	ESA/ESTEC
Jonathan	Sykes	Leicester University
John	Taylor	e2V
Daniel	Thompson	National Composites Centre
Ray	Thompson	Airbus Defence and Space
Ross	Tierney	Horizon Space Technologies Ltd
Richard	Trask	University of Bath
Alex	Trolley	e2V
Daniel	Underhill	e2v technologies
Tristan	Valenzuela-Salazar	STFC/RAL
Bryan	Vaughan	Lockheed Martin UK
Dan	Veal	NPL
David	Walker	UCL, Glyndwr Univ., Huddersfield Univ.
Berend	Winter	MSSL/UCL
Robin	Young	Applied Materials Technology Limited
Paul	Williams	ISP International Space Propulsion Ltd
Christine	Dent	Strathclyde University
Samuel	Shore	Southampton University
David	Brackett	The Manufacturing Technology Centre