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3D Printing – Surmounting the Challenges

For the SAF

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ABSTRACT

3-Dimensional (3D) printing is a form of Additive Manufacturing (AM) process which creates a 3D object from a model through the fusion of material. Although 3D printing started from as early as the 1980s, the technological leap to move beyond the realm of rapid prototyping only began in the 2010s. While it is clear that the Singapore Armed Forces (SAF) is gearing itself towards the utilisation of 3D printing in the near future, there are technological hurdles and associated policies that need to be overcome to maximise the use of this technology. This essay aims to look into the benefits of 3D printing for the defence industry, visit the limitations present in this novel technology, and discuss the possible solutions to navigate these roadblocks in order to maximise the use of the technology.

Keywords: Printing, Technology, Utilisation, Manufacturing, Improvement

INTRODUCTION

3D printing is a form of AM process which creates a 3D object from a model through the fusion of material. Although 3D printing started from as early as the 1980s, the technological leap to move beyond the realm of rapid prototyping only began in the 2010s. Since the insightful article '3D Printing: Revolutionising Military Operations' shared by ME5 Calvin Seah Ser Thong & ME4 Choo Wei Wen in Vol.42 No.2 of 2016, the SAF has made progress in its endeavour of 3D printing in recent years. The Memorandum of Understanding (MOU) between Headquarters for Maintenance and Engineering Support (HQ MES) and the National AM Innovation Cluster (NAMIC) was signed to collaborate on the development of qualification standards and conduct research into the military use of 3D printing.[1] In addition, 1 Air Engineering and Logistics Group (AELG) has also designed and manufactured a number of 3D printed parts to ease maintenance processes. It has also purchased a 3D printer for the quick-manufacturing of components for Ground Support Equipment. Lastly, a Project Office and webpage portal were created by the Engineering Group, Naval Logistics Department (NLD), to develop the engineering competency and awareness in 3D printing. These developments bear testament to the recognition of the potential of 3D printing by the SAF leadership across all 3 services, and have piqued much interest on the ground.

While it is clear that the SAF is gearing itself towards the utilisation of 3D printing in the near future, there are technological hurdles that need to be overcome to maximise the use of this technology. For example, the type of materials that can be 3D printed, or the size of components that can possibly be printed in an efficient and cost-effective manner need to be deliberated. In addition, associated policies regarding such relatively infant technology need to be established before the benefits can be extended to safety-critical processes; e.g. aircraft maintenance in the Republic of Singapore Air Force. These policies include the process to validate the material that can be used, and the types of components that can be manufactured via 3D printing. Nevertheless, in face of such technological and policy limitations, little steps to initiate the use of 3D printing are still very much building in momentum across the SAF. These experimentations would be useful test beds for the defence industry before bolder steps are taken to expand the usage of 3D printing.

This essay thus aims to look into the benefits of 3D printing for the defence industry, visit the limitations present in this novel technology, and discuss possible solutions to circumvent these roadblocks to maximise the use of the technology.

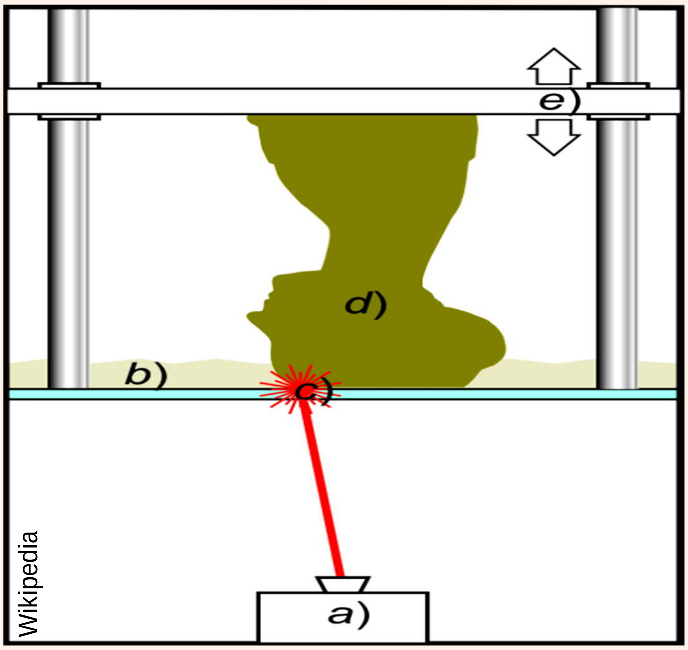
RECAPITULATION OF 3D PRINTING PRINCIPLES AND TECHNIQUES

AM is defined in the American Society for Testing and Materials (ASTM) standard F2792 as "the process of joining materials to make objects from 3-D model data, usually layer upon layer, as opposed to subtractive manufacturing technologies."[2]

A 3D model would first need to be designed and created using either Computer Aided Design (CAD) softwares (examples include Solidworks and CATIA) or by scanning the physical component via a 3D scanner. The 3D geometric data that was constructed using these programmes would then be interpreted by the computer for layered build-up of the model, which replicates the actual AM technique. This information on the layered build-up is then sent to an AM machine, where the machine would perform the building of the component, layer by layer.

Currently, there are a large number of AM methods in the market, which could be categorised under the various categories in the ASTM. The categories under AM in ASTM are:

Vat Photopolymerisation. Vat photopolymerisation manufactures the component by curing a vat of liquid polymer (resin) sensitive to ultraviolet light layer by layer. Such process has a high degree of accuracy and is quick to manufacture. However, as the product manufactured is made of resin, it is usually weak in structural strength and would require a structural framework to hold the entire structure in place, especially for large components.



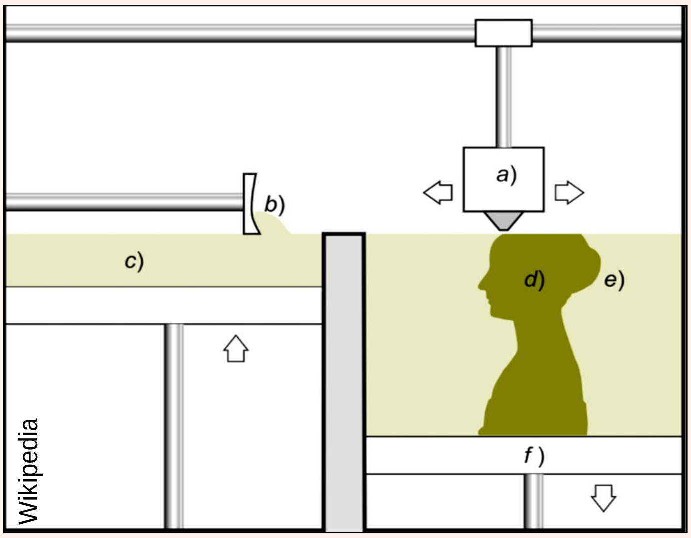
Schematic representation of Photopolymerisation; a light emitting device a) (laser or DLP) selectively illuminate the transparent bottom c) of a tank b) filled with a liquid photo polymerizing resin; the solidified resin d) is progressively dragged up by a lifting platform e).

Material Jetting. The process of material jetting is similar to that of an inkjet printer, where the printer deposits 'ink' onto the structure in layers to build up the desired component. The 'ink' is subsequently cured via ultraviolet rays. Material jetting is usually highly accurate and minimizes wastage, as the 'ink' is deposited at specific requisite locations. However, the 'ink' used is largely limited to wax or polymeric materials which lack structural strength or hardness. Hence, this method of printing is usually complemented with a structural backbone to enhance strength.

Binder Jetting. This process involves two different types of materials; a liquid adhesive binder and a powder-based reinforcement. The binder is deposited onto the powder via an inkjet print head, and undergoes partial curing after each layer. The finished component then undergoes complete curing in an oven, with excess powder reclaimed for future use. The usage of different binder-powder combinations allows mechanical properties to vary according to requirements. Nevertheless, as the process effectively entails the gluing together of powder particles, components printed have limited strength properties.

Material Extrusion. A filament of material is drawn from the printer nozzle, before it gets melted and deposited layer by layer to form the component. This method of AM is cheap and easy to produce. However, many variable factors can affect the quality of the final model, such as the rate of filament heating, speed of material deposition and the depositing pressure. The end product may not be as accurate as other processes.

Powder Bed Fusion. Powder bed fusion is a two step process where a layer of powder is first laid on the building platform. A laser or electron beam is then directed at the specific locations on the powder to melt it for fusion. After the completion of the first layer, the next layer of powder is laid and the process repeats itself. This method provides a large range of material options. However, high power is required to generate the laser or electron beam. The component finishing also depends heavily on powder grain size.



Schematic representation of the process: a moving head a) selectively binds (by dropping glue or by laser sintering) the surface of a powder bed e); a moving platform f) progressively lowers the bed and the solidified object d) rests inside the unbound powder. New powder is continuously added to the bed from a powder reservoir c) by means of a levelling mechanism b.

Directed Energy Deposition. Directed Energy Deposition (DED) is similar to powder bed fusion, except that powdered material is deposited on the specific area of interest instead of a whole layer. A directed laser, electron beam or plasma arc then provides the energy for fusion of the material to the component. This process enables one to control the grain structure to a high degree. However, DED is limited by the type of material that can be used.

Sheet Lamination. Sheet lamination utilises adhesive or ultrasonic welding to bind layers of sheet materials together to build a 3D model. The required shape is then cut from the laminate using laser or knife. This process is fast and low in cost. However, the finished component would possess adequate structural strength only in certain orientations due to the manufacturing methodology which has inherent weakness at the binding interfaces.

BENEFITS OF ADDITIVE MANUFACTURING

AM adds a brand new dimension to parts manufacturing with the following benefits:

On The Fly Manufacturing

When faced with harsh conditions on the go, or when components are not manufactured in bulk and thus result in spares shortage, AM is able to bridge the gap. By bringing a 3D printer on the go with all the blueprints stored or coupled with a 3D scanner, it is possible to bring the whole manufacturing plant on the go, without the need to bring loads of inventory along. This not only reduces the amount of lead time to obtain components which may be proprietary in nature, but also reduces the inventory size that is required. Such a concept is currently undergoing testing by the United States Army, where they have successfully manufactured Grenade Launchers and Barracks with 3D printing.[3] The Republic of Singapore Air Force (RSAF) has also exhibited such manufacturing feats using 3D printing when 5 AELG manufactured spares for the aircraft ladders due to a lack of spares.

An example of 3D printed limited edition jewellery. This necklace is made of glassfiber-filled dyed nylon. It has rotating linkages that were produced in the same manufacturing step as the other parts.

Rapid Prototyping

With the manufacturing plant in one's backyard, the time required to perform prototyping and testing of a product is reduced drastically. A newly designed component or tool could be manufactured in hours instead of days or weeks to allow proof of concept testing. This not only reduces the amount of wastage for the final product, but also reduces the time required from initial design to final product manufacturing. Rapid prototyping can also solve immediate issues which require the production of a new item, such as a lack of tools.

Component Assembly Improvement

Besides being able to manufacture on the fly and perform rapid prototyping, AM is able to reduce the number of sub-components required to be put together for a complex assembly. Geometrically complex components that were impossible to be manufactured as a whole previously can now be constructed as a 3D model and printed via AM. This has effectively reduced the need for separate construction of multiple sub components and eliminates the hassle of intricate assembly of these sub-components. For example, National Aeronautics and Space Administration (NASA) completed testing for its Pogo accumulator assembly which was manufactured through AM.[4] They were able to reduce the number of components to assemble from 28 to 6, and removed the need for a bolted joint and more than 100 welds to build the complex structure.[5] Such improvements in complex part assembly translates to higher efficiency and cost savings in the manufacturing process.

Overcome Obsolescence through Reverse Engineering

Military parts usually last more than 10 years. Thus, these parts are susceptible to obsolescence, especially when technology progresses and the Original Equipment Manufacturer decommission the production line of older products. With the approval by Original Equipment Manufacturer (OEM) on the release of Intellectual Properties for these obsolete parts, production of such parts become a possibility with the combination of AM and reverse engineering. This endeavour therefore provides an avenue for parts substitution and fabrication.

Localised Fabrication

The Suez Canal incident has led to a standstill of logistical transportation for a significant number of days. This additional factor of unpredictability can be eliminated through AM, as AM allows localised fabrication. With the AM machine and the necessary blueprints in place, fabrication can be localised on site or near site, and thus achieving just-in time and just-in-place manufacturing.

Miniature face models (from FaceGen) produced using Ceramic Based material on a Full Colour 3D Inkjet Printer .

IMMEDIATE CHALLENGES FOR ADOPTION OF ADDITIVE MANUFACTURING IN THE SAF

Despite the recognised benefits of AM, the following key challenges prohibit the immediate utilisation of this new technology en masse in the SAF.

Manufacturing Variation in Additive Manufacturing

AM has yet to attain consistency in the quality of parts manufactured, due to inherent variations in the manufacturing process. The rapid heating and cooling cycle often associated with AM processes results in the material being constantly subjected to drastic changes at the microstructure level. This impacts the mechanical properties of the finished component. Other variations include inadequate control over dimensional tolerances, material porosity, surface roughness and possibility of defects in built-in parts. As such, in terms of achieving the requisite material specifications for component construction, AM is far from being a guarantee as compared to conventional methods. In addition, the limited range of materials currently adaptable for AM prohibits the mirroring of high strength properties from non 3D printable raw materials.[6] In this regard, the current usage of 3D products is still largely limited to low strength and support applications.

Certification

With the aforementioned manufacturing variations, it is crucial that the certification of 3D printed parts as fit-for-use in non-aesthetic applications be subjected to rigorous testing, inspection and there must be a good understanding of the manufacturing process controls in place. This is especially true for aerospace/ aircraft certification where regulatory bodies such as the Federal Aviation Administration (FAA) and European Union Aviation Safety Agency (EASA) had evidently taken a more calculated and cautious approach in approving the production of 3D printed aircraft components. To date, the only most notable example in aerospace application is that of the 3D printed fuel nozzle powering the CFM LEAP engine and GE9X jet engine, which in itself has undergone numerous testing in GE's test cell for combustion temperature resistance, strength and effectiveness in fuel-air distribution.[7] As such, while development of 3D printed aircraft parts has picked up steam, one would expect the scale of implementation translated to the RSAF from OEM to be a modest one at best due to certification challenges.

There is impetus for the SAF to surmount the associated challenges and make headway in enhancing operational readiness through 3D printing.

Cost

The cost of performing AM is primarily dependent on the price of raw material and size of the product to be manufactured. For AM using Titanium for example, the Titanium powder could cost up to US$500 per kg.[8] As compared to the cost of aircraft grade Titanium Alloy (Ti-6Al-4V), the raw material sheet stock is priced at US$65 per kg, which is almost 10 times cheaper. Hence, while savings could be reaped from a reduction in assembly costs and manufacturing labour, the cost of 3D printing could still prove prohibitive in the construction of large-sized products that require a significant amount of raw materials.

WHAT IT MEANS FOR THE SAF AND CURRENT ADAPTATION OF 3D PRINTING

After weighing the benefits and challenges with regards to 3D printing, the authors recognised that there is impetus for the SAF to surmount the associated challenges and make headway in enhancing operational readiness through 3D printing. In this regard, the three services have made progress in the 3D printing domain.

Army

HQ MES and NAMIC signed a MOU to collaborate on the development of qualification standards and conduct research into the military use of 3D printing. This agreement also allowed HQ MES to leverage the technical experience and industry connections that NAMIC possesses.[9] The new possibilities to revamp existing maintenance and engineering could unlock higher productivity of personnel and availability of equipment. Combat Service Support Command (CSSCOM) took the lead to facilitate the spurt of the Ground-up Innovation, providing the support for innovation trial and experimentation as part of the Army Innovation Framework announced in Jan 2018. In addition, with the collaboration with NAMIC, industry players, academia, and the other services, HQ MES led the effort in the creation of the Military AM Working Group. The working group aims to ensure standardisation and conformance of additively manufactured parts to uphold the quality and reliability of the technology for various military applications. Through the working group, the TR 70 'Guidelines on Selection Criteria for Metal AM Processes' was published in Oct 2019.[10]

Navy

A team under Systems Readiness Engineering Centre (SREC) in Naval Logistics Command (NALCOM) is set up to build 3D printing capability within the Republic of Singapore Navy (RSN) under the RSN's 3D Printing Roadmap by the Engineering Group NLD, to drive the four key thrusts. Besides the evident need to develop engineering competency, the other key thrusts seek to promote the creation and sustenance of awareness in the field of 3D printing, as well as the monitoring of technological development adopted by the associated

OEMs. The timely follow-up on the new development could allow the RSN to possess technological flexibility and responsiveness in shipboard rectification.

RSAF

In the RSAF, adaptation of AM started off with the use of consumer grade Fused Deposition Modelling Machines for fabrication of ground tools and equipment. With traction gained from this, the RSAF continued on to pursue fabrication of aircraft parts, such as the AH-64D Water Dam, and A330-MRTT Aero Medical Equipment mounts. The RSAF has also gained a foothold on the certification process, having approval from the Technical Airworthiness Review Board on the usage of Metallic AM parts, through the proposals of means of compliance for the required airworthiness requirements.

Established finance policies and audit checks and balances would ensure the procurement of value for-money raw materials for Additive Manufacturing implementation.

PROPOSED WAY AHEAD

It is assessed that a common framework to address the aforementioned challenges is viable to advance 3D printing in the SAF. In particular, the proposals below seek to tackle the challenges of (1) Material Variation and (2) Certification. With regard to the cost challenges of 3D Printing, the authors opine that established finance policies and audit checks and balances would ensure the procurement of value-for money raw materials for AM implementation.

Severity Classification / System Safety Assessment

By virtue of the different nature of operations across the three services, the system safety assessment and severity classification of components vary across the Army, Navy and Air Force. Nevertheless, general principles may be applied to guide the broad classification of components into 'Major', 'Minor' and 'Unclassified'. The distinct classification would in turn necessitate the required level of rigour in safety assessment and accord the right level of authority for the approval of 3D printed parts.

Major Classification. The component must play a critical role in ensuring the safety of the equipment and/ or personnel. The failure of the component would otherwise lead to the cancellation of missions tasked or result in operational limitations. Such components would hence require the materials used for its manufacture to possess specific strength, fatigue or durability properties. Examples are the wheel hub on the Land Rover, the hull of the submarine and the transmission shaft on the CH-47SD. 3D printing of such components would hence be more limited in nature, since extensive testing and stringent controls on the AM process will have to be imposed to ensure the quality of these critical parts and there could be lesser tolerance for material variations in the component.

Minor Classification. The component does not affect the safety of either the equipment or personnel. The failure of the component would not impact the fulfilment of mission success or restrict the scope of operation. Such components would have less stringent requirements and thus tend to have more tolerance for variation in material properties. Examples are the seat cushion on the Light Strike Vehicle, the deck window of the Littoral Mission Vessel and the maintenance panel on the F-15SG. 3D printing of these components would be more tenable.

Unrestricted Classification. The component has no direct impact to the safety or operation of the equipment and personnel. This would include support equipment and maintenance jigs that are not used on the mission equipment during operation. Examples are oil measuring tool for vehicle maintenance, and Go/No Go assessment tool for H450 Arrestor Hook. 3D printing of these components would reap the most benefits in terms of least stringent requirements for part certification or consistency.

There are recognisable benefits to be reaped in pursuit of organisational improvement and mission success.

Resource Management

As the technology is relatively new and the cost of implementing the technology is relatively high, the effort to develop the technical know-how of using the technology should be focused as a service. The procurement of the machinery should also be approved under the service level.

Technical Know-How. A central agency within each service should be identified to hone the knowledge and application of 3D printing. The experts in the central agency will have the technical know-how and understanding of 3D printing, providing solutions such as the type of 3D printing method(s) to be used, inspections to be carried out post-production, and the approval process for the 3D printed components. The build-up of technical knowledge could be achieved through collaboration with local and overseas agencies, such as SPRING Singapore or American Society for Nondestructive Testing (ASNT).[11] These agencies would be able to provide the standards and methodology to qualify 3D printed components, further aiding the approval process for the use of these parts on the equipment.

Maintaining 3D Printing Facility. The central agency as mentioned earlier would also be in charge of setting up and maintaining the 3D printing facilities within the service. This setup should balance cost prudency, cost effectiveness, operation and responsiveness. For example, the setup of 3D printing facility could be consolidated in a central location to reap economies of scale, and satellite facilities of a smaller scale may be set up to enhance responsiveness. The central agency should also identify the type of scanner, printer and common raw materials to be used, based on the required precision, strength properties and application to operational requirements. The setup should also be kept in tab with the local industries, and be able to link up with them for production that is beyond the current setup within the services.

Approving Authority/ Policies. Vide the two previous mentioned pointers, the ground-up innovations which do not have stringent requirements would typically require speedy actions to translate idea into a prototype for validation. For this class of innovation and those components with unrestricted classification, the central agency proposed should be vested with the authority to approve the usage of the printed components. The satellite facilities may be delegated with the authority for unrestricted components. For Minor classification, the engineering branches or centres that is of interest (e.g. Structures Branch in AELD for 3D printed structural components), together with the central agency, would be the approving authorities for usage of 3D printed parts. This serves as a check and balance to ensure the quality and standard of the components being manufactured. For major classification, the current system safety processes in the SAF i.e. Weapon Systems Safety Advisory Board and its supporting Working Groups, should remain as the relevant endorsing or approving authority. The lead of the central agency would then be a permanent member in the relevant Working Groups such as Technical Airworthiness Review Board. Information such as the method of 3D printing used, the material used for 3D printing, NDI method and results post 3D printing should be furnished to aid in the approval process.

Growing Local Industries for 3D Printing. As 3D printing changes the production process from a centralised process to a decentralised process, with the added benefit of production based on requirements, it is an opportunity that SAF can look into to develop the local industries for 3D printing. Not only will this benefit the SAF in terms of resolving spares shortage especially for obsolete parts, this arrangement will also not be disrupted by global logistical issues.

CONCLUSION

3D printing has caught the wind of progress over the last few years. Despite the challenges to be surmounted, there are recognisable benefits to be reaped in pursuit of organisational improvement and mission success. The SAF has made its own progress in this domain, through the various Top-down and Ground up endeavours. Holistic policy development and a certain extent of organisation structure alignment are required to keep up with the trend, along with constant monitoring and collaboration with the industry.

ENDNOTES

1. MOU signing between Singapore Armed Forces Headquarters for Maintenance and Engineering Support (SAF HQ MES) and NAMIC. NTUitive - the innovation & enterprise company of Nanyang Technological University. November 7, 2017. Accessed on November 8, 2017. http://www.ntuitive.sg/news-detail/mou-signing-between-singapore-armed-forces-headquarters-for-maintenance-and-engineering-support-hq-mes-and-national-additive-manufacturing-innovation-cluster-namic.

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6. Material specifications includes physical specifications such as strength, hardness, conductivity, Poisson ratio etc

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11. The standards for AM is governed by Singapore Standards Council in SPRING Singapore locally, and American Society for Testing and Materials (ASTM) in USA. Both standards are in line with ISO/TC 261, AM.

ME5 Yap Yong Han, an Air Force Engineer by vocation, is currently a Staff Officer in Structures Centre, Air Engineering and Logistics Department (AELD), focusing on the structural aspects of the F-16 and A330-MRTT aircraft, and also supporting additive manufacturing development in the RSAF. He co-drafted the RSAF Approach to Certification of Metallic AM parts, which was approved by the Technical Airworthiness Review Board in 2020. This approach is currently being used as the way to certify additive manufactured metallic parts being used on the aircraft. He graduated from the Nanyang Technological University (NTU) with a Bachelor of Engineering (Aerospace Engineering)

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