The Role of Additive Manufacturing Towards Sustainable Aerospace Structures

Joshua Rodrigues, Simon Barter, and Raj Das

Nomenclature

AM	Additive Manufacturing
TO	Topology Optimisation
CAD	Computer-Aided Design
ISS	International Space Station
ISRU	In-Situ Resource Utilisation

1 Introduction

The ambition to achieve a more sustainable aerospace sector is critical to future aerospace operations and research. The aerospace industry is a significant contributor to environmental air pollution and greenhouse gas emissions, epitomising the importance of focusing on the sector's sustainability. The unprecedented growth in aerospace has led to a surge in operations, significantly increasing local air pollution (Psanis et al., 2017). With an increase in demand for more efficient structures, engines and operations, innovative technologies are continuously being developed to realise these goals. In the case of structures (including engine components), additive manufacturing (AM) is a leading example of such innovation that has revolutionised how structures are designed and created. Since its initial use for rapid prototyping, AM technology has matured to become an established fabrication method, providing significant benefits to the aerospace industry (Attaran, 2017). The adoption of this technology has embarked on a new era for an advanced ecological

J. Rodrigues (✉) · S. Barter · R. Das
School of Engineering, RMIT University, Melbourne, Australia
e-mail: joshua.rodrigues@student.rmit.edu.au; simon.barter@rmit.edu.au; raj.das@rmit.edu.au

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sector, producing structures that are less damaging to the surrounding environments through better resource usage and high structural efficiencies.

In this chapter, the role of AM technology in a more sustainable aerospace sector is viewed. An overview of AM technology is initially portrayed, highlighting the numerous advantages this technology presents, particularly, its unique ability to create highly customised components through structural optimisation, the potential for novel materials that are not currently possible to produce by conventional methods and the introduction of functionally graded structures. The influence of these properties on sustainable aerospace is then emphasised, addressing how these benefits contribute to a more sustainable outlook. With this, the future opportunities of AM presents are outlined, including the prospective abilities of in-space manufacturing and in-situ resource utilisation (ISRU) that will be crucial for future progression in the aerospace sector.

2 Additive Manufacturing Technology

As opposed to conventional, subtractive processes, whereby material is removed from a bulk source to reveal the final structure, AM fabricates components by adding material, commonly through a layer-by-layer process. Several classes of material can be used for AM fabrication, including polymers, ceramics, and metals. These materials often come in the form of a powder or wire feedstock that is typically melted by a heat source and deposited to form the item being built. This is usually achieved in successive layers to produce the defined component geometry. Due to this unique, generative nature, AM technology greatly enhances the design freedom of complex structures and removes many of the constraints imposed by traditional manufacturing methods (Dordlofva & Törlind, 2017). Unprecedented control over the shape, function and composition of components is enabled through AM, allowing for structures with incredibly complex geometries and internal features to be created that would be otherwise difficult via conventional techniques (Huang et al., 2015).

With this ability, methods of structural optimisation have become widely applied to a variety of applications to create highly customised components tailored to suit specific loading conditions. Methods of optimisation, encompassing size, shape and topology, as well as cellular lattice designs have utilised the advanced abilities of AM, performing synergistic advantages to fabricate structures that are entirely unique to the application with effective material distribution (Tejani et al., 2018). Various methods of topology optimisation (TO) exist that can produce lightweight parts without comprising the mechanical properties required for the application (Prathyusha & Babu, 2022). Structures can be optimised for a variety of objectives, such as to minimise mass, strain or displacement, or to maximise stiffness, while enhancing the performance and mechanical properties of the structure. Multiple objectives can be incorporated simultaneously with various weightings, resulting in several potential design iterations of a single component.

3 Advantages of AM for Sustainable Aerospace

With the plethora of advantages realised through AM, it is widely considered an exceptional candidate to progress the aerospace industry towards a more sustainable sector. The space industry is poised to gain the maximum benefit of AM technology, where most parts created for spacecraft structures are highly customised with low volume part production (Sacco & Moon, 2019). Stemming from the realised complexity achievable through AM, TO and cellular designs have demonstrated numerous advantages in aerospace applications, particularly the ability to reduce component weight, part count, material wastage and the associated supply chain issues that arise with small production runs. Each of these inherent benefits significantly contributes toward more sustainable aerospace, domain as discussed in the following.

3.1 Weight Reduction

One of the primary advantages that arise from component optimisation is the ability to fabricate structures with less material, resulting in significant weight reduction. Aerospace and space applications are highly sensitive to mass, which is directly proportional to the fuel required for an intended mission. Large structures, such as aircraft and rockets, require ample amounts of fuel to transport their payloads safely and complete their objective. In terms of an orbital rocket launch, the propellant component alone can contribute to almost 95% of the total mass of the rocket. This is to ensure that the structure and payload can produce enough thrust to reach orbit safely, overcoming the associated drag and gravitational resistances. The emissions from the combustion of fuels containing hydrocarbons and/or aluminium powder, primarily carbon dioxide, black carbon and alumina, present significant harm to the surrounding environments and atmosphere (Ryan et al., 2022). Gases and particles emitted from burning fuel have been shown to damage the ozone layer through heating of the middle and upper atmospheres (Kokkinakis & Drikakis, 2022).

Using TO techniques, structures can be reimagined and redesigned in a way that can reduce their mass by 50–80%, significantly decreasing the related fuel requirements (Joshi & Sheikh, 2015). Various components for spacecraft applications have demonstrated significant weight reductions through optimisation processes, including satellite antennas, brackets and CubeSats (Blakey-Milner et al., 2021). Lattice panel designs have also been shown to achieve weight reductions of 50% compared to their conventional counterparts (Blachowicz et al., 2021). Lesser fuel requirements thus, in turn, further minimise the associated environmental impact. This continual cycle of optimisation to reduce the contributed pollution from aerospace structures is highly beneficial as further developments are made in the aerospace sector. As the demand for longer, farther missions increase, structures with reduced weight will also allow for more fuel to be carried without exceeding the initial weight constraints at launch.

3.2 Reduced Material Processing Energy Requirements

The use of structural optimisation also contributes to a reduction in material usage and processing costs. While casting manufacturing techniques may be considered a direct competitor to AM, the additive nature of AM processes that do not require the need for moulds or other casting additions; runners, risers, vents, cores, is clearly advantageous. Additionally, conventional subtractive manufacturing techniques, such as milling or turning, remove material from a bulk object to realise the final structure within, and this method results in significant material wastage that is often non-recyclable for subsequent parts. AM, on the other hand, only fabricates the required geometry necessary to create the final structure, ensuring minimal material wastage. High buy-to-fly ratios also exist in subtractive manufacturing techniques, commonly exceeding 20:1, as opposed to almost 1:1 for most AM processes (Joshi & Sheikh, 2015). The abundance of material wastage further contributes to many process-related impacts including higher energy requirements and gaseous emissions that are produced.

Along with the reduction of material required for fabrication, AM technology also has the added benefit of high material reusability efficiency, which is uncommon in most other manufacturing methods. In AM processes that use powder feedstock, the unmelted feedstock can be collected after the fabricated part is removed, and then put through a filtration processes system to remove unusable or partially melted particles, producing a quantity of feedstock for reuse. Such filtration processes can recycle 95–98% of the feedstock, which is unparalleled in the manufacturing industry (Petrovic et al., 2011).

3.3 Supply Chain Reduction

AM technology provides significant advantages towards a more sustainable sector through a much simpler supply chain process. For the construction of unique components and assemblies, manufacturers, often more than one, that have the required workforce and machinery are tasked to complete the construction. These structures are then transported, either domestically or internationally, often between manufacturers and finally reach the designated buyer. This can present several obstacles to projects, including lengthy delays due to manufacturer's capability limitations, logistics costs and setbacks, and unnecessary environmental impact due to the transportation. AM enables a reconfiguration of this supply chain as parts may now be fabricated locally to the final destination using a single supplier and at more affordable costs (Ford & Despeisse, 2016). Rather than exporting the required manufacturing, industries and institutions can access AM machines to fabricate structures where they are needed. This not only reduces the associated environmental impact from component transportation but also enables industries to act independently and more responsively.

Furthermore, AM technology is ideal to enable the notion of on-demand component manufacturing. Rather than maintaining a populous inventory of large structures and repair components, AM can be used to fabricate components as needed. This minimises the necessity to transport multiple structures that can lead to potential inventory waste and risk. Traditionally, when a component is damaged, it requires either repair or replacement, depending on the severity. Obtaining these components from the manufacturer or distributor is often costly and may involve long delays, which is inefficient for limited component numbers. The economics of AM make the one-off production of parts attractive, with significant cost-effectiveness (Ford & Despeisse, 2016).

3.4 Prototyping Ability

The unique nature of AM to fabricate components directly further enables the ability to prototype components before implementation in full-scale critical structures. In AM processes, parts are geometrically created using computer-aided design (CAD) technology, where structures are modelled to a high degree of accuracy and strict structural requirements. During fabrication, dimensional tolerances are critical to ensure that the final component is suitable for the application. These models can be adjusted with ease through CAD software, compared to traditional methods, scaling and modifying their shape as required. This allows smaller structures to be produced with the same relative ratios and dimensions that can be initially tested. Using this as a proof-of-concept approach, these structures can be fabricated much faster than full-scale models. This can also eliminate the potential risk of wastage if the final model is not suitable.

Through CAD technology, models of structures can easily be shared once created. Associated contributors can easily view and modify these models to ensure the structure is suitable for their requirements. This is much more favourable as opposed to an entire redesign of a system after fabrication (Ford & Despeisse, 2016).

4 Future Opportunities

As the aerospace and space industries grow, the use of AM will be imperative for future operations. With the increase of interest in space exploration and research, future mission objectives will aim to explore deeper into untouched areas of space with significantly longer mission durations. For this to occur, however, innovative structures and techniques must be realised to reduce costs and increase capabilities. The uniqueness of the AM processes has already reimagined how components are fabricated, which has further enabled the ingenious use of AM for in-space manufacturing capabilities and ISRU. With the versatile process of AM, launch vehicles now do not necessarily have to be designed to support large payloads as part of the mission launch but can be fabricated during the mission timeline, resulting in longer and further exploration profiles. Both of these innovative uses of AM are outlined in the following.

4.1 In-Space Manufacturing Capability

With the urge to explore further into space, it is evident that innovative structures that have the capability to do so are necessary. One option for this is to increase the size and capacity of current structures to accommodate larger payloads such as satellites. However, this is not a sustainable method to progress aerospace operations; larger structures will require more manufacturing and production, as well as even larger amounts of fuel to achieve launch. Both of these factors are already significant contributors to environmental damage from aerospace operations. Stemming from this, AM technology provides the unique ability to fabricate complex structures in space, presenting an abundance of opportunities for future in-space manufacturing and sustainment concepts.

Rather than developing large launch vehicles to accommodate larger payloads, compact material feedstock can be supplied and components can be fabricated once in space. This provides several advantages for future missions, where it can enable the fabrication of components on-demand required for extended missions without the need to return to Earth (Mitchell et al., 2018). Alongside the economic advantages of not requiring a larger launch structure, sensitive and ultra-lightweight structures can be fabricated that do not need to survive the harsh conditions of launch. The material feedstock can be supplied with maximum volume efficiency, and these optimised structures can be manufactured in orbit without the risk of damage during launch.

Whilst in-space manufacturing capabilities have already been utilised for smaller, less critical applications, such as for manufacturing spare parts and tools on the International Space Station (ISS), the fabrication of large-scale structures is yet to be explored in depth (Zocca et al., 2022). Space stations, much like the ISS, can be used as development platforms, where structures can be fabricated through on-board AM machines, and then launched from there. An added advantage is access to the vacuum of space during the build, a condition that is often difficult to achieve on Earth. AM in space will allow ultra-lightweight and optimised components to be created, without the need to endure an orbital launch, with materials that may be difficult to use in any other atmosphere other than a vacuum. Such components will require less fuel to explore further into deep space. The potential for entire space station platforms to be developed in orbit can also transpire, whereby a plethora of these structures can be used as a constellation system for future missions and possible habitation for extended periods.

4.2 *In-Situ Resource Utilisation*

Stemming from the potential for large-scale in-space manufacturing, the ability of ISRU through AM technology also presents several opportunities for future exploration. For long-duration interplanetary missions, the creation of large-scale infrastructure is necessary. The concept of ISRU takes full advantage of the surrounding conditions by using natural regolith as the feedstock for AM processes, where with the abundance of this material on inter terrestrial planets, structures and components can be used as a self-sustaining method of construction (Isachenkov et al., 2021). Through this technology, the weight of launch vehicles can be reduced furthermore, as only the AM machine itself is required. The significant mass saving of material will also lead to more efficient launches, reducing the associated environmental impact.

5 Conclusion

Whilst still in the research and development phase for many applications, AM technologies demonstrate great potential for significant advancements towards a more environmentally conscious aerospace sector. The unique combination of AM and TO techniques provides several advantages that will further contribute to a sustainable industry. Through optimisation methods, component weight and material processing can be significantly reduced, leading to less fuel and energy consumption, respectively. The ability to manufacture components and prototypes on demand reduces the associated supply chain and transportation impact, and the innovation of in-space manufacturing capabilities and ISRU also provides an abundance of future opportunities for the advancement of this technology. With the constantly evolving aerospace industry, the use of AM technology will inevitably become an essential tool in progressing this sector towards a more sustainable outlook.

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