

3D Printing in Aerospace

Matthew N. O. Sadiku

Department of Electrical & Computer Engineering, Prairie View A&M University,
Prairie View, TX USA

Uwakwe C. Chukwu

Department of Engineering Technology, South Carolina State University, Orangeburg, SC, USA

Janet O. Sadiku

Juliana King University, Houston , TX, USA

Abstract:

3D printing, technically known as additive manufacturing, is a manufacturing process that creates parts layer by layer until the entire three-dimensional part is complete. The technology has been transforming all industries by producing three-dimensional objects based on the commands given by software programs. It is highly valued in the aerospace industry, which has always been at the forefront of technological innovation, driving advancements in transportation, communication, and exploration. At the moment, aerospace manufacturers leverage 3D printing technology to design, build, and maintain both commercial and military aircraft. The introduction of 3D printing to aerospace has been a groundbreaking development for aerospace and defense industries (A&D). This paper examines the use of 3D printing technology in the aerospace industry.

Keywords: 3D printing (3DP), additive manufacturing (AM), 3D printing in aerospace, aircraft, aviation.

INTRODUCTION

Traditionally, a printer is used at home or in the office to print out text and images on paper. This conventional printer prints in a flat two-dimensional (2D) space using the dimensions length and width. A three-dimensional (3D) printer uses length and width but also adds depth to the print. A 3D printer has more manufacturing capacity than a traditional manufacturing machine. It is regarded as a disruptive technology that will change manufacturing. It has been used for decades in the automotive and aerospace industries. The 3D printer is also used by hobbyists, small businesses, creatives, manufacturers, architects, and most importantly contractors to instantly create a variety of products.

The aircraft industry is one of the most highly regulated industries across the world. It is constantly evolving, with new technologies being introduced to improve safety, efficiency, and performance. The demand for new commercial airplanes is skyrocketing. One such technology that has revolutionized aircraft manufacturing and maintenance is 3D printing. Although creating aircraft parts are cost- and time-consuming by traditional metalworking, additive manufacturing simplifies the process. It is the opposite of subtractive manufacturing processes like CNC (computer numerical control) machining, where the material is removed from a workpiece to create parts.

Traditional manufacturing techniques often impose limitations on design possibilities due to the constraints of tooling and molding processes. A typical traditional aircraft manufacturing plant is shown in Figure 1 [1].

The origin of 3D printing in the aerospace industry dates back to the late 1980s. The industry was a forerunner in 3D printing and contributed significantly to its development. It was one of the first industries to implement 3D printing in 1989. Since 1989, companies in this industry have been utilizing 3D printing technology, which allows for complex designs that are impossible to produce using traditional technologies such as injection molding. Aerospace engineers were instrumental in the development of the 3D printing process. Many aerospace companies use 3D printing in various capacities. Some of the major players in the aerospace industry that use 3D printing include [2]:

1. Airbus
2. Boeing
3. Bombardier
4. Embraer
5. Lockheed Martin
6. GE Aviation
7. Pratt & Whitney
8. Rolls-Royce
9. SpaceX
10. NASA

These aerospace companies have been using 3D printing technology to create parts for their aircraft. 3D printing is now used to manufacture almost all aircraft parts like engine, nozzles, cabin accessories, air ducts, engine suspension, dashboard bezels, brackets, etc.

WHAT IS 3D PRINTING?

3D printing (also known as additive manufacturing (AM) or rapid prototyping (RP)) was invented in the early 1980s by Charles Hull, who is regarded as the father of 3D printing. Since then it has been used in manufacturing, automotive, electronics, aviation, aerospace, aeronautics, engineering, architecture, pharmaceuticals, consumer products, education, entertainment, medicine, space missions, the military, chemical industry, maritime industry, printing industry, and jewelry industry [3]

A 3D printer works by “printing” objects. Instead of using ink, it uses more substantive materials—plastics, metal, rubber, and the like. It scans an object—or takes an existing scan of an object—and slices it into layers, which can then convert into a physical object. Layer by layer, the 3D printer can replicate images created in CAD programs. In other words, 3D printing instructs a computer to apply layer upon layer of a specific material (such as plastic or metal) until the final product is built. This is distinct from conventional manufacturing methods, which often rely on removal (by cutting, drilling, chopping, grinding, forging, etc.) instead of addition. Models can be multi-colored to

highlight important features, such as tumors, cavities, and vascular tracks. 3DP technology can build a 3D object in almost any shape imaginable as defined in a computer-aided design (CAD) file. It is additive technology as distinct from traditional manufacturing techniques, which are subtractive processes in which material is removed by cutting or drilling [4].

3D printing has started breaking through into the mainstream in recent years, with some models becoming affordable enough for home use. Many industries and professions around the world now use 3D printing. It plays a key role in making companies more competitive. The gap between industry and graduating students can be bridged by including the same cutting-edge tools, such as 3D printing, professionals use every day into the curriculum. There are 3D printed homes, prosthetics, surgical devices, drones, hearing aids, and electric engine components. As shown in Figure 2, 3D printing involves three steps [5]. A typical 3D printer is shown in Figure 3 [6].

3D PRINTING IN AEROSPACE

The aerospace industry is a highly demanding environment. It requires impeccable elements that are going to be able to withstand continuous wear, and high pressure and high temperature conditions. The newest commercial airplane generation is now flying with more than 1,000 3D-printed spare parts. Designs in the aerospace industry often begin as concept models showcasing a component of an aircraft. Some manufacturers 3D-print replacement parts, while others leverage 3D printing technologies to design and evaluate complex aircraft parts. There are several different types of 3D printing that can be used in the aerospace industry. Common methods include the following [7]:

1. *Fused Deposition Modeling (FDM)*: This is a type of 3D printing that utilizes an extruded thermoplastic filament to make parts layer by layer. FDM operates by extruding heated thermoplastic materials layer by layer to create the desired object. FDM machines have several advantages including low cost, small footprint, and a wide variety of materials available for printing. FDM printing in aerospace is intended more for prototyping and design verification purposes than functional aircraft parts.
2. *Stereolithography (SLA)*: This is a 3D printing process that utilizes precisely placed photosensitive polymer resin that is cured by UV light to make parts layer by layer. The main disadvantages of SLA machines include high upfront and maintenance costs and resins are not environmentally friendly.
3. *Selective Laser Sintering (SLS)*: This is a 3D printing process that precisely sinters and fuses thermoplastic powders to form parts layer by layer. When a layer is completed, more powder is deposited, the build tray descends, and the process repeats. SLS is great for producing parts with complex geometries at high resolutions.
4. *Electron Beam Melting (EBM)*: This is a 3D printing process that uses electrically conductive metal powder and electron beams to manufacture parts layer by layer. The printing process must occur in a vacuum to prevent gas molecules from interfering with the energy emitted by the electron beam.
5. *Direct Energy Deposition (DED)*: This is a 3D printing process that uses an energy source such as an electron beam, laser, or plasma arc to melt powder or filament as it is deposited from a nozzle. The primary advantages of a DED printer are that it allows the grain structure of printed parts to be controlled and enables large parts to be made with little tooling.

A number of different materials are used in aerospace industry applications. Common materials used are listed and described below [7]:

1. *Ceramics*: Ceramics are inorganic materials. They are great for aerospace applications due to their corrosion resistance, light weight, and wear resistance. However, ceramics are exceptionally hard and brittle, making them difficult to fabricate into parts.

2. *Carbon Fibers*: These are long, exceptionally thin but strong strands of carbon atoms. Carbon fiber composites are ideal for aerospace applications since it is as strong as steel but lighter than aluminum. However, carbon fiber is expensive and difficult to produce, which limits the potential applications it can have in the aerospace industry.

3. *Glass*: This is a transparent, brittle, and amorphous material that has been used since ancient times. 3D-printed glass is not used for windows in aircraft. Instead, glass-filled filaments and powders are often used to reinforce plastics and to make glass composites which are helpful in reducing aircraft weight.

4. *Metals*: These are excellent conductors of heat and electricity compared to other materials. Metals like aluminum and titanium are widely used in aircraft due to their corrosion resistance and high strength-to-weight ratios. A major downside of metals is that they are heavy.

5. *Polymers*: They are materials composed of repeating chains of molecules. Common examples of polymers in aerospace include synthetic thermoplastics like nylon and ABS (acrylonitrile butadiene styrene). Polymers are great for aerospace applications since they are lightweight and durable.

6. *Composites*: Composite materials are composed of two or more constituent materials whose properties complement each other. Composite materials have structural benefits such as high strength and low weight. For example, titanium superalloys are highly beneficial to the aerospace industry. Using titanium in place of conventional materials has proven to significantly reduce the weight of crucial aircraft components. A downside of 3D-printed composite materials is that they are not biocompatible and can be expensive.

APPLICATIONS

The aerospace industry has always been at the forefront of innovation. 3D printing is useful for numerous applications in aerospace because this industry leans on highly custom, costly parts that do not benefit from economies of scale. Figure 4 shows different ways 3D printing is used in the aerospace industry [8]. The aerospace 3D printing global market is shown in Figure 5 [9]. Common applications of 3D in aerospace include the following [10,11]:

1. *Engine Components*: 3D printing technology gives unique freedom in the manufacturing and production of various components. Masten Space Systems started to 3D print rocket engines back in 2014. They developed small test thrusters at first and soon scaled up to a thrust broadsword engine weighing 25,000 pounds in 2016. Elliptika now enjoys faster creation of novel antenna designs and saves cash due to 3D printing end-use parts. Boeing (the world's largest aerospace company) launched the world's 1st 3D printed metal satellite antenna in 2019. Airbus has been employing 3D printing technology to manufacture and repair various parts for its aircraft for several years. It is exploiting the use of additive manufacturing for different purposes, especially replacing conventional manufacturing with an additive to lower costs. The first 3D-printed aircraft parts used were in an Airbus test aircraft. Figure 6 shows a 3D-printed jet engine [12]. The parts produced via additive manufacturing can be stronger and lighter than those made using traditional manufacturing. The following aerospace parts can all be made by 3D printing [7]:

1. Fuel nozzles
2. Wishbones
3. Housings
4. Aerofoils
5. Door latches
6. Lighting fixtures
7. Seatback

8. Panels

9. Trim pieces

2. *Prototyping*: Prototyping refers to the processes related to designing and testing new design concepts and developing the related tooling. Aerospace industry adopted 3D printing in the late 1980's for prototyping, and has never looked back since. 3D printing is a practical tool to create production costs or prototypes at a lower price at a faster speed. 3D printing is a clear fit for many prototyping and end-use applications within the aerospace and aviation industry. A&M Tool and Design develops custom machines and parts for optics, robotics, and aerospace. The shop started using 3D prints for prototyping to test function and fit. 3D printing makes it possible for the team to produce parts much faster, use the entire day, set up prints to run through the night, and use features the following day. Figure 7 shows the 3D-printed prototype of a plane [13].

3. *Structural Components*: These are interior and exterior components that help form and support the rigid body of an aircraft. Structural components like brackets and wishbones can be made by 3D printing processes like EBM and DED using titanium and titanium alloys, copper, and nickel alloys.

4. *Interior Components*: Interior components in aircraft include everything from avionics equipment to cabin accessories like door latches and light fixtures. SLA and SLS are two popular methods of 3D printing commonly used to fabricate interior components for aircraft. Figure 8 shows 3D-printed aircraft interior [14].

5. *Repairs and Maintenance*: One of the most advantageous applications of 3D printing in the aerospace sector is the ability to produce on-demand spare parts and conduct rapid repairs. 3D printing offers aerospace engineers an invaluable solution for repair and maintenance operations. Engineers can rapidly produce replacement parts on-site, minimizing downtime and reducing costs associated with grounded aircraft. Given that an aircraft typically lasts 20 to 30 years, it must undergo maintenance, repair, and overhaul (MRO) to remain safe and efficient.

6. *3D Printing in Space*: All the advantages aerospace 3D printing brings to commercial aircrafts apply equally to smaller aircraft such as satellites, space rockets, unmanned aerial vehicles (UAVs), and drones. The potential of 3D printing in the aerospace industry stretches far beyond the Earth's atmosphere. Since 1960, humankind has piloted dozens of Mars missions. Manufacturing for space applications requires a high degree of precision. 3D printing techniques like DMLS (Direct Metal Laser Sintering) and EBM (Electron Beam Melting) excel at producing parts to close tolerances. Researchers at NASA are now studying the performance of electroplated SLA parts in space. They have been 3D printing aerospace components since the 1990s. They have been able to lower costs, boost efficiency, and speed up the manufacturing process. Since many of the parts required for space missions are made of aluminum, titanium, or steel, NASA is collaborating with various small entrepreneurs to produce metal printing technologies for the International Space Station. A 3D-printed control conduit used in a space launch vehicle is shown in Figure 9 [13].

BENEFITS

The benefits of using 3D printed components for aerospace are plentiful. 3D printing technology has the benefits of maximizing production output, shortening time-to-market, reducing costs, and more. 3D printing helps keep aerospace industry aloft. Improved airplane design is a major benefit of 3D printing for the aerospace sector. Other benefits of 3D printing in aerospace include the following [7,8]:

1. *Reduced Weight*: One of the most notable benefits of manufacturing parts through 3D printing is the reduced weight. In an industry where weight reduction (lightweighting) can lead to huge cost savings, 3D printing has enabled aerospace manufacturers to create lighter and more fuel-efficient aircraft in a more cost-effective manner. 3D printing can be used to replace metal parts with lighter

plastic parts. Components produced by 3D printing will reduce the aircraft's overall weight, which consequently reduces fuel consumption and improves the aircraft's performance.

2. *Customization*: The flexibility of 3D printing allows for customization on a level that is not possible with traditional manufacturing methods. 3D printing technologies significantly impact the aerospace industry when a substantial improvement in aircraft performance can justify the cost of highly complex one-off components. The technology is particularly useful in the aerospace industry, where every aircraft is unique, and modifications are often necessary to meet specific customer requirements. Parts can be tailored to a specific aircraft (custom, lightweight bracketry) or type of aircraft (cargo, passenger or even helicopter).

3. *Prototyping*: Like other industries, the aerospace industry uses rapid prototyping to produce ready-to-use parts from initial design concepts. Prototyping is a common practice in the aerospace industry. Engineers can use the appropriate 3D printer and 3D printing material to create prototypes rapidly with varying forms, fits, and functionalities. Engineering materials for 3D printing also allow for full testing and validation of prototype performance.

4. *Design Freedom*: The aerospace industry benefits from the freedom additive manufacturing offers in designing complex structures. Several companies have experienced design freedom due to additive manufacturing. Improved aircraft design is a major benefit of 3D printing for the aerospace sector. Although simplification is a key benefit, 3D printing also offers the opportunity to manufacture complex designs that cannot be made using traditional methods like injection molding.

5. *Enhanced Supply Chain*: The development and construction of an airplane is a vast operation. 3D printing enhances manufacturing efficiency and reduces supply chain lead times by producing a wide range of components from a wide range of raw materials

6. *Cost-Effectiveness*: 3D-printed parts can be made in far fewer process steps than parts produced by traditional manufacturing processes. This helps reduce overall production costs and waste. Airlines are looking at how they can use 3D printing to lower the cost of replacement parts.

7. *Material Efficiency*: By using only the amount of material required to fill the part's final volume, 3D-printed designs cut down on waste. Compared to conventional subtractive manufacturing techniques, 3D printing minimizes waste by only adding material where it is needed.

8. *Faster Production*: Manufacturing companies using 3D printing say the technology is at least twice as fast as traditional manufacturing methods. With the on-demand manufacturing, easy customization and part consolidation enabled by additive manufacturing, aerospace manufacturers can significantly shorten their time-to-market. In addition to producing functional parts on-demand, 3D printing technologies help engineers repair functional parts in a short amount of time.

9. *On-site Production*: An enormous benefit of 3D printing is on-site production. Transporting parts and materials incurs costs of both time and money. With additive manufacturing, customized components can be printed on site.

10. *Sustainability*: Aerospace, like every industry, is under pressure to become more sustainable. Sustainability and environmental considerations are becoming integral components of the aerospace industry's ethos. Aviation influx comes at a cost; twice the number of planes circling the earth means heavier carbon emissions, more fuel consumption, and greater noise roaring from overhead. 3D printing can mitigate the impact of aircraft on the environment.

CHALLENGES

Additive manufacturing utilization may be in its infancy in some forms, but we are seeing adoption for parts that have a higher risk associated with it. Integrating 3D printing with traditional aerospace manufacturing workflows presents a challenge in terms of compatibility, standardization, and coordination. Other challenges of 3D printing in aerospace include the following [7,15]:

1. *Limited Materials Available:* While many widely used plastics and metals are compatible with 3D printing, thousands of alloys and compounds are still incompatible. This fact limits the potential applications for which 3D printing can be used in the aerospace industry.
2. *Weak Part Structure:* Because 3D-printed parts have been fused together layer by layer, the parts may be surprisingly weak under certain tensions. Some 3D printing methods, like FDM and SLS, produce parts with anisotropic properties. This can be undesirable for certain load-bearing parts and limits the potential of various 3D printing applications for the aerospace industry.
3. *High Cost:* The 3D printers were a costly investment, they were slow and too small to have large-scale industrial applications. Now costs related to set-up and running have significantly reduced. Additive manufacturing is the perfect technology for small maintenance tasks. Although large printers can produce bigger objects, the machines take up more space and are significantly more expensive compared to benchtop printers.
4. *Regulation:* Ensuring safety and regulatory compliance remains a critical challenge. Aerospace components must adhere to rigorous standards and certifications to guarantee their performance, reliability, and safety.
5. *Economies of Scale:* Aerospace 3D printing can produce a single item or small batch of items faster and more efficiently than traditional manufacturing methods. Additive manufacturing excels in aerospace but it is badly suited for large batches of identical parts. This is because with 3D printing, cost correlates with quantity directly. In industries that rely upon economies of scale, 3D printing is not often viable.
6. *Parts Are Not Smooth:* Most 3D-printed parts finish with rough layer lines and surface inconsistencies. This makes 3D printing unviable for certain industries.
7. *Part Size:* 3D printers have inherent size constraints that make them incapable of producing large components. They have not caught up to the scale of products required by the aerospace industry,

CONCLUSION

The aerospace sector has been leveraging 3D printing for many years. The technology is no longer a new technology for the aerospace industry and manufacturers who have been creating solid objects from digital files for more than a decade. The advancements in 3D printing technology and aerospace-grade materials have reshaped the way aerospace manufacturers approach design and production. 3D printing is transforming aerospace manufacturing, revolutionizing how planes land and take-off, how engines can operate efficiently.

As the understanding of 3D printing continues to spread through the aerospace industry, the technology will continue to reshape the way we build and maintain aircraft and spacecraft. We can expect more companies to begin developing on-site 3D printing operations and investing in the technology. Applications today and in the future are widespread. By embracing the full potential of 3D printing, the aerospace sector is set to soar to new heights. Without 3D printing, the aircraft of the future will never be able to get off the ground. More information about 3D printing technology in the aerospace industry can be found in the book [16].

REFERENCES

1. S. Moore, "3D printing titanium in aerospace manufacturing applications," May 2020, <https://www.azom.com/article.aspx?ArticleID=19272>
2. "8 Uses of 3D printing in the aircraft industry," May 2023, <https://www.xometry.com/resources/3d-printing/uses-of-3d-printing-in-the-aircraft-industry/>

3. F. R. Ishengoma and T. A. B. Mtaho, "3D printing: Developing countries perspectives computer engineering and applications," *International Journal of Computer Applications*, vol. 104, no. 11, October 2014, pp. 30-34.
4. M. N. O. Sadiku, S. M. Musa, and O. S. Musa, "3D Printing in the chemical industry," *Invention Journal of Research Technology in Engineering and Management*, vol. 2, no. 2, February 2018, pp. 24-26.
5. D. Pitukcharoen, "3D printing booklet for beginners,"
<https://www.metmuseum.org/-/media/files/blogs/digital-media/3dprintingbookletforbeginners.pdf>
6. D. Mikkelsen, "3D printing revolutionising aerospace and defence logistics, predicts GlobalData," April 2024,
<https://www.defsecme.com/defence/tech/3d-printing-revolutionising-aerospace-and-defence-logistics-predicts-globaldata#:~:text=The%20burgeoning%203D%20printing%20market,exceed%20%2470%20billion%20by%202030.>
7. "3D printing in aerospace: Materials, processes, and classifications," May 2023,
<https://www.xometry.com/resources/3d-printing/3d-printing-in-aerospace/>
8. C. Huskamp, "Printing is the future of aerospace & defense manufacturing,"
<https://www.jabil.com/blog/3d-printing-in-aerospace-and-defense-manufacturing.html>
9. "Aerospace 3D printing market size & share analysis - Growth trends & forecasts (2024 - 2029),"
<https://www.mordorintelligence.com/industry-reports/3d-printing-in-aerospace-and-defense-market>
10. "Enhancing the aerospace industry: Exploring 3D printing applications for companies,"
<https://www.cadcrowd.com/blog/enhancing-the-aerospace-industry-exploring-3d-printing-applications-for-companies/>
11. "The best applications of 3D printing in the aerospace industry,"
<https://additive-x.com/blog/applications-of-3d-printing-aerospace-industry/>
12. "3D printing for aerospace and aviation,"
<https://www.hubs.com/knowledge-base/aerospace-3d-printing-applications>
13. "What does 3D printing contribute to the aerospace industry?" 2022
https://filament2print.com/gb/blog/152_what-does-3d-printing-contribute-to-the-aeros.html
14. "Top 3 ways 3d printing is transforming aircraft interiors,"
<https://www.designworldonline.com/top-3-ways-3d-printing-is-transforming-aircraft-interiors/#:~:text=Paneling%2C%20seat%20trays%2C%20framework%2C,the%20production%20of%20aerospace%20parts.>
15. "3D printing aerospace parts: Why it's no threat to CNC machining,"
<https://readingplastic.com/3d-printing-aerospace-machining/>
16. P. A. Maxwell, *3D Printing Technology: From Medicine to Aerospace (Technology 101 Book 26)*. Independently Published, 2023.

ABOUT THE AUTHORS

Matthew N.O. Sadiku is a professor emeritus in the Department of Electrical and Computer Engineering at Prairie View A&M University, Prairie View, Texas. He is the author of several books and papers. His areas of research interest include computational electromagnetics, computer networks, and marriage counseling. He is a life fellow of IEEE.

Uwakwe C. Chukwu is a professor in the Department of Industrial & Electrical Engineering Technology of South Carolina State University. He has published several books and papers. His research interests are power systems, smart grid, V2G, energy scavenging, renewable energies, and microgrids.

Janet O. Sadiku holds bachelor degree in Nursing Science in 1980 at the University of Ife, now known as Obafemi Awolowo University, Nigeria and doctoral degree from Juliana King University, Houston, TX in December 2023. She has worked as a nurse, educator, and church minister in Nigeria, United Kingdom, Canada, and United States. She is a co-author of some papers and books.



Figure 1 A typical aircraft manufacturing plant [1].

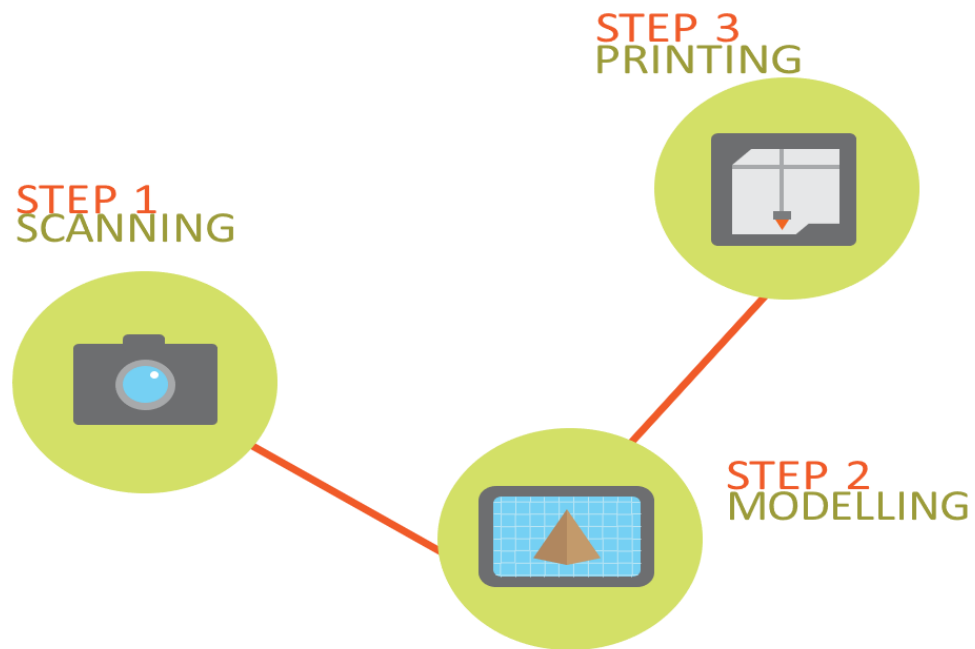


Figure 2 3D printing involves three steps [5].

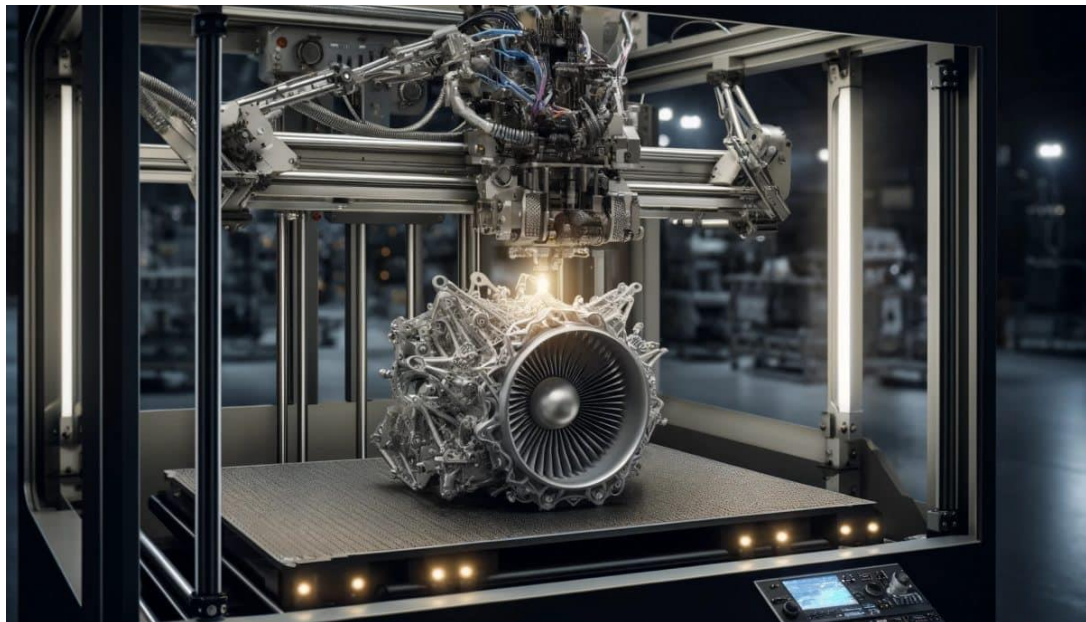


Figure 3 A typical 3D printer [6].



Figure 4 Different ways 3D printing is used in the aerospace industry [8].

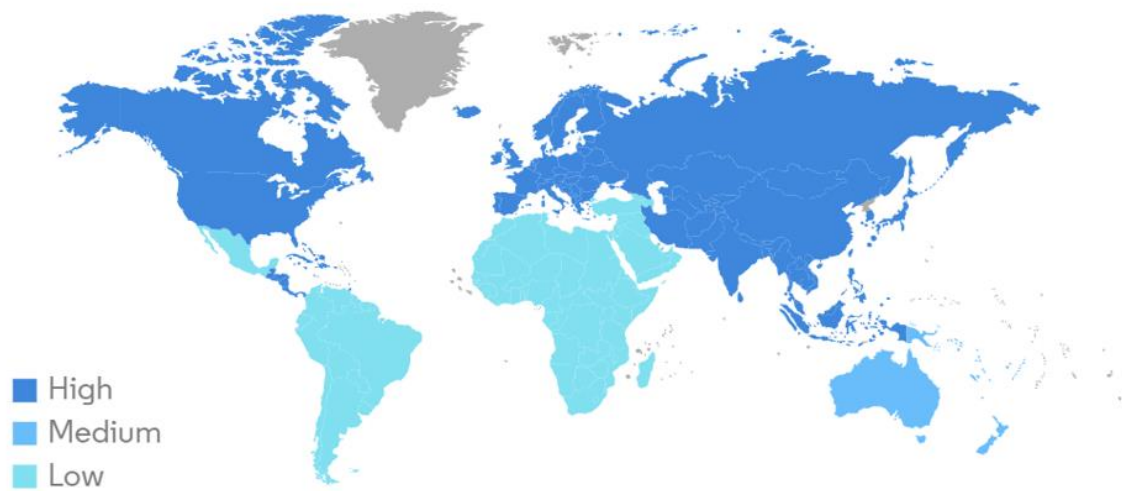


Figure 5 The aerospace 3D printing global market [9].

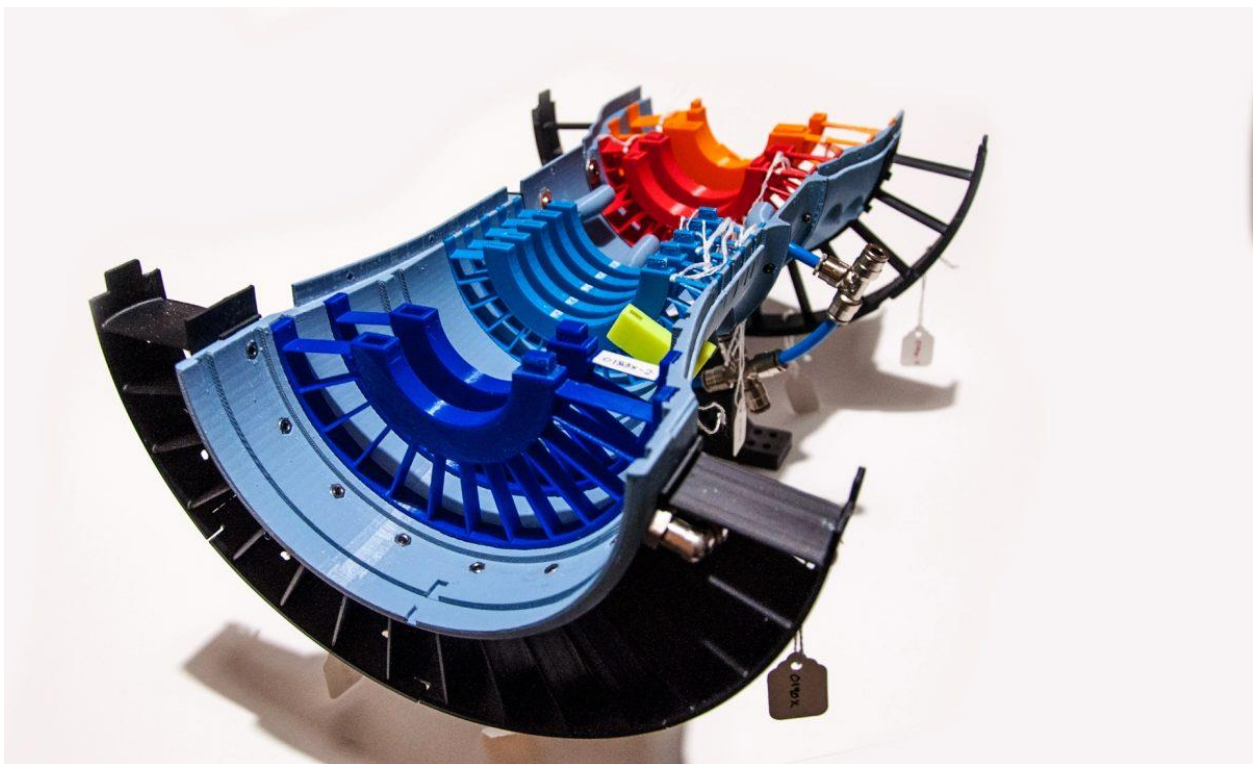


Figure 6 A 3D-printed jet engine [12].



Figure 7 A 3D-printed prototype of a plane [13].



Figure 8 3D-printed aircraft interior [14].



Figure 9 A 3D-pinted control conduit used in a space launch vehicle [13].