

Advanced Manufacturing Techniques for Aerospace Antennas

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Review Paper

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Abstract:

The aerospace industry continually demands antennas that meet increasingly stringent requirements for performance, reliability, weight, and environmental resilience. This review paper comprehensively surveys the state-of-the-art advanced manufacturing techniques employed in aerospace antenna fabrication, focusing on their applicability, advantages, and limitations in addressing the unique challenges of the sector. It covers a broad spectrum of methods, including additive manufacturing, precision machining, composite material fabrication, and advanced integration and assembly techniques. Special attention is given to recent advancements such as hybrid manufacturing processes that combine multiple fabrication approaches, the use of smart and multifunctional materials, and the integration of nanotechnology to enhance antenna performance and durability. The paper also discusses emerging trends in the field, particularly the application of artificial intelligence and machine learning to optimize design, fabrication, and quality control processes. Through a critical analysis of recent research findings, case studies, and industrial applications, this review provides valuable insights into current capabilities and future directions. It aims to serve as a comprehensive reference for researchers, engineers, and industry professionals involved in aerospace antenna development, enabling them to harness advanced manufacturing technologies to meet the evolving demands of aerospace communication systems.

Keywords: Aerospace antennas, advanced manufacturing, additive manufacturing, precision machining, composite materials.

1. Introduction

The aerospace industry has long been recognized as a pioneer in adopting and driving cutting-edge technologies, propelled by the constant quest for improved performance, reliability, and operational efficiency [1]. This drive is particularly crucial given the challenging and often extreme environments in which aerospace systems operate—ranging from the vacuum and radiation of space to the turbulent and variable conditions of Earth's atmosphere. Within this high-stakes context, antennas play a pivotal role as essential components that enable communication, navigation, and sensing capabilities across a broad spectrum of aerospace applications, including satellite communications, radar systems, unmanned aerial vehicles (UAVs), and deep-space exploration missions [2].

Antennas are fundamental to the successful operation of aerospace platforms because they directly impact the quality and reliability of data transmission and reception. As aerospace missions become more complex and multifaceted—requiring higher data rates, greater bandwidth, miniaturization, and multifunctionality—the design and manufacturing of antennas have correspondingly become more sophisticated. The antennas must not only achieve exceptional electromagnetic performance but also withstand stringent mechanical, thermal, and environmental stresses while maintaining minimal weight and volume.

Traditional manufacturing methods for aerospace antennas, such as subtractive machining and manual assembly, are increasingly challenged by the need for precision, repeatability, and integration of novel materials and structures. These demands have catalyzed the development and adoption of advanced manufacturing techniques, including additive manufacturing (3D printing), precision micro-machining, and composite fabrication processes. Such methods enable the production of highly complex geometries, integration of multifunctional materials, and customization at reduced lead times and cost [2].

Moreover, the emergence of new materials, such as lightweight composites and smart materials with tunable electromagnetic properties, alongside technological innovations like nanotechnology and embedded sensors, requires novel fabrication approaches that can reliably integrate these elements into antenna structures. Additionally, the integration of digital technologies, such as computer-aided design (CAD), artificial intelligence (AI), and machine learning, is revolutionizing the antenna manufacturing landscape by enabling predictive quality control, adaptive process optimization, and enhanced system integration [3].

This review paper aims to provide a comprehensive examination of these advanced manufacturing techniques as applied to aerospace antennas. By surveying the latest research, case studies, and industrial practices, the paper seeks to highlight the capabilities, challenges, and future prospects of modern fabrication methods in meeting the demanding performance criteria of aerospace systems. Ultimately, it serves as a valuable resource for researchers, engineers, and industry professionals striving to push the boundaries of antenna technology within the aerospace sector.

2. Background

Antennas designed for aerospace applications encounter a distinctive set of challenges that differentiate them markedly from those used in terrestrial or commercial environments. These antennas must deliver consistent, reliable performance while enduring some of the harshest operational conditions imaginable. For instance, aerospace antennas are exposed to extreme temperature variations that can range from the intense cold of outer space to the high thermal loads encountered during atmospheric re-entry or prolonged sunlight exposure. In addition to temperature extremes, these antennas must withstand significant changes in atmospheric pressure as vehicles ascend to high altitudes, where reduced pressure can impact material properties and structural integrity.

Another critical factor is the exposure to intense mechanical stresses, including high-frequency vibrations and shocks experienced during rocket launches, flight manoeuvres, and landing operations. Such dynamic loads demand antennas that possess not only robust mechanical durability but also electromagnetic stability, ensuring uninterrupted signal transmission and reception under all conditions. Furthermore, aerospace platforms impose strict constraints on size, weight, and power consumption. The aerospace industry's ongoing pursuit of lighter, more fuel-efficient vehicles places immense pressure on antenna designers to develop solutions that are compact and lightweight without compromising on performance or reliability [4].

Historically, aerospace antennas have been fabricated using well-established conventional manufacturing processes such as precision machining, chemical etching, and manual assembly. These methods have provided reliable and repeatable results for many decades, enabling the production of antennas with relatively simple geometries and proven performance. However, as aerospace communication and sensing systems grow in complexity—demanding higher data rates, multi-band operation, conformal designs, and integration with advanced materials—traditional fabrication techniques increasingly struggle to keep pace.

Conventional processes often lack the flexibility to realize complex antenna architectures, such as 3D structures or embedded multifunctional components, and may involve time-consuming steps that limit rapid prototyping and customization. Additionally, limitations in precision and repeatability can hinder the ability to meet tight tolerances necessary for high-frequency and millimeter-wave antennas. These challenges underscore the need for adopting advanced manufacturing technologies that can deliver superior precision, scalability, and integration capabilities, thereby meeting the evolving demands of aerospace applications.

In this context, recent advancements in additive manufacturing, composite fabrication, and hybrid processes offer promising alternatives. These emerging techniques provide enhanced design freedom, enabling the realization of intricate antenna geometries with embedded features and novel materials that are difficult or impossible to achieve through traditional methods. Alongside these manufacturing innovations, the integration of smart materials and the application of artificial intelligence for process control are poised to transform the landscape of aerospace antenna production, ensuring that future antennas are not only more capable but also more adaptable to the stringent requirements of aerospace environments.

The limitations of traditional manufacturing methods include:

1. Geometric constraints that restrict the design of complex antenna structures
2. Material waste and high production costs, especially for low-volume production
3. Limited ability to integrate antennas seamlessly into aerospace structures
4. Challenges in achieving the necessary precision for high-frequency applications

These limitations have spurred the development and adoption of advanced manufacturing techniques specifically tailored to address the unique needs of aerospace antenna production [5].

2.1 Objectives of the Review

This comprehensive review aims to provide a thorough examination of the state-of-the-art in advanced manufacturing techniques for aerospace antennas. The primary objectives of this chapter are:

1. To elucidate the fundamental requirements and challenges specific to aerospace antenna manufacturing
2. To explore and analyse various advanced manufacturing techniques currently employed in the production of aerospace antennas
3. To assess the advantages, limitations, and potential applications of each manufacturing technique
4. To highlight recent research findings and case studies that demonstrate the efficacy of these advanced techniques
5. To identify emerging trends and future directions in aerospace antenna manufacturing

By addressing these objectives, this review seeks to offer valuable insights to researchers, engineers, and industry professionals involved in the design and production of aerospace antennas.

2.2 Scope of the Review

The scope of this review encompasses a wide range of advanced manufacturing techniques applicable to aerospace antenna production. These include, but are not limited to:

1. Various 3D printing technologies such as stereolithography (SLA), fused deposition modelling (FDM), and selective laser sintering (SLS) are examined for their potential in creating complex antenna geometries with high precision [6].
2. Advanced machining techniques, including computer numerical control (CNC) milling, laser cutting, and microfabrication, are explored for their role in achieving the tight tolerances required for high-frequency antennas [7].
3. The use of advanced composites, such as carbon fiber-reinforced polymers (CFRP) and ceramic matrix composites, is investigated for their potential to create lightweight, durable antennas with excellent thermal and mechanical properties [8].
4. Methods for seamlessly integrating antennas into aerospace structures, including conformal and embedded antenna designs, are discussed [9].
5. The review also touches upon cutting-edge developments such as the use of smart materials, hybrid manufacturing processes, and nanotechnology in antenna fabrication [10].

2.3 Significance of Advanced Manufacturing in Aerospace Antenna Development

The adoption of advanced manufacturing techniques in aerospace antenna production has far-reaching implications for the industry. These techniques offer several significant advantages:

1. Advanced manufacturing methods, particularly additive manufacturing, allow for the creation of complex geometries that were previously impossible or impractical to produce. This expanded design space enables engineers to optimize antenna performance without being constrained by traditional manufacturing limitations.
2. The ability to fabricate intricate structures with high precision translates to antennas with superior electromagnetic performance, including enhanced gain, bandwidth, and efficiency.

3. Advanced techniques facilitate the production of lightweight antennas through the use of novel materials and optimized structures, contributing to the overall goal of reducing aircraft weight and improving fuel efficiency.
4. While initial investment in advanced manufacturing equipment may be high, these techniques often lead to reduced material waste, faster production times, and lower costs for low-volume or customized production runs.
5. Many advanced manufacturing techniques, especially 3D printing, allow for quick prototyping and testing of new antenna designs, accelerating the development cycle and fostering innovation.
6. Advanced manufacturing enables the seamless integration of antennas into aerospace structures, potentially improving aerodynamics and structural integrity while maintaining optimal antenna performance.

2.4 Challenges and Considerations

Despite the numerous advantages, the adoption of advanced manufacturing techniques for aerospace antennas is not without challenges. Some key considerations include:

1. Ensuring that materials used in advanced manufacturing processes possess the necessary electromagnetic, thermal, and mechanical properties for aerospace applications.
2. Developing robust quality control processes to ensure consistency and reliability in antenna production, especially for safety-critical applications.
3. Navigating the complex landscape of aerospace certification requirements and establishing industry standards for advanced manufacturing processes.
4. Addressing the challenges of scaling advanced manufacturing techniques from prototyping to large-scale production.
5. Training and developing a workforce skilled in both antenna design and advanced manufacturing techniques.

By addressing these challenges and leveraging the potential of advanced manufacturing techniques, the aerospace industry can continue to push the boundaries of antenna performance and integration, leading to more capable and efficient aerospace systems.

This paper aims to provide a comprehensive understanding of these advanced manufacturing techniques, their applications, and their potential impact on the future of aerospace antenna development. Through a detailed examination of current practices, research findings, and emerging trends, this chapter serves as a valuable resource for those seeking to navigate the rapidly evolving landscape of aerospace antenna manufacturing.

3. Fundamental Requirements for Aerospace Antennas

Aerospace antennas must meet stringent requirements to function effectively in the harsh environments encountered during flight and space operations. This section outlines the key requirements for aerospace antennas, focusing on mechanical robustness, thermal stability, and electromagnetic performance.

3.1 Mechanical Robustness

Aerospace antennas are subjected to extreme mechanical stresses throughout their operational lifecycle, particularly during launch, atmospheric flight, and in-orbit manoeuvres. To ensure long-term functionality and signal integrity, these antennas must be designed to meet stringent mechanical robustness criteria. The primary mechanical requirements include:

3.1.1 Vibration Resistance

During launch and flight, aerospace structures experience high-frequency and high-amplitude vibrations generated by engines, aerodynamic forces, and structural resonances. Antennas must be able to maintain

both their structural integrity and electromagnetic performance under these conditions. Improper vibration handling can lead to material fatigue, misalignment, or even structural failure. Materials and joint designs are often tested using random and sinusoidal vibration profiles to simulate real-world launch environments [2].

3.1.2 Shock Resistance

Launch vehicles and satellite deployment mechanisms can subject antennas to sudden and intense mechanical shocks. These shocks may occur due to stage separation, pyrotechnic events, or unanticipated impacts. Shock resistance ensures the antenna can endure these abrupt accelerations and decelerations without experiencing mechanical damage or loss in performance [4].

3.1.3 Structural Integrity

Antennas must retain their structural geometry and alignment under various loading conditions, including aerodynamic forces, g-loads during manoeuvres, and thermally induced stresses. Structural deformations can affect antenna beam patterns, gain, and polarization characteristics. Therefore, maintaining structural integrity is essential for ensuring consistent communication performance and pointing accuracy [5]. The mechanical requirements for aerospace antenna is given in Table 1.

Table 1. Mechanical Requirements for Aerospace Antennas

| Requirement | Typical Value | Description |
|-------------|---------------|--------------------------|
| Vibration | 20-2000 Hz | Random vibration profile |
| Shock | 100-10,000 g | Pyrotechnic shock |
| Load | Up to 20 g | Sustained acceleration |

Note: Values may vary depending on specific mission requirements.

3.2 Thermal Stability

Aerospace antennas are routinely exposed to extreme and rapidly changing temperatures, both in the atmosphere and in space. These variations can significantly affect the physical and electrical properties of antenna materials, potentially degrading performance. To ensure reliability and accuracy, aerospace antennas must meet stringent thermal stability requirements. These include:

3.2.1 Temperature Range

Antennas must remain operational and maintain performance across a wide temperature spectrum. In aerospace applications, this range typically spans from -65°C to $+150^{\circ}\text{C}$, depending on mission parameters and altitude. Materials used in antenna structures and components must retain their electrical and mechanical properties across this entire range. Extreme cold can make materials brittle, while high heat may cause warping or melting if not properly managed [7].

3.2.2 Thermal Cycling Resistance

Spacecraft and high-altitude vehicles often experience repeated cycles of heating and cooling—such as during orbital day/night transitions or re-entry phases. Antennas must endure thermal cycling without experiencing material fatigue, delamination, or loss of adhesion. These cycles can induce microcracks or degrade material interfaces, ultimately impacting antenna alignment and RF performance [8].

3.2.3 Thermal Expansion Control

Changes in temperature lead to expansion and contraction of materials. In high-precision antenna systems, even slight dimensional changes can distort the antenna's geometry, causing misalignment of beams or degradation in radiation patterns. Antennas must therefore be designed with low coefficients of thermal expansion (CTE) or incorporate composite materials that compensate for differential expansion [9]. Table 2 outlines the typical thermal requirements for aerospace antennas:

Table 2. Thermal Requirements for Aerospace Antennas

| Requirement | Typical Value | Description |
|----------------------------------|-----------------|---------------------------|
| Temperature Range | -65°C to +150°C | Operational temperature |
| Thermal Cycling | >1000 cycles | -55°C to +125°C |
| Coefficient of Thermal Expansion | <5 ppm/°C | For dimensional stability |

3.3 Electromagnetic Performance

The core function of aerospace antennas is the reliable transmission and reception of electromagnetic signals. In space and aerospace environments, where communication links must span vast distances and endure harsh conditions, antennas must demonstrate exceptional electromagnetic performance. This ensures not only signal clarity and reliability but also efficient use of limited onboard power resources. Key performance parameters include:

3.3.1 Frequency Range

Aerospace antennas must operate within specific frequency bands tailored to their mission objectives, such as S-band, X-band, Ku-band, or Ka-band. Many modern systems also require multiband or wideband operation to support various communication, telemetry, and navigation functions simultaneously. Precise frequency control is critical to avoid interference and meet regulatory standards [10].

3.3.2 Gain and Directivity

High gain antennas concentrate energy in a specific direction, which is vital for long-range space communication, such as satellite-to-ground or inter-satellite links. Directivity ensures that energy is radiated or received primarily in the desired direction, minimizing losses and improving signal strength. Parabolic reflectors, phased arrays, and high-gain horn antennas are commonly used to achieve these characteristics [6].

3.3.3 Polarization

To ensure efficient signal transmission and reception, antennas must maintain proper polarization—typically linear, circular, or dual-polarized—depending on the application. Matching the polarization between the transmitting and receiving antennas reduces signal loss due to polarization mismatch and improves link quality, especially in multipath or rotating platforms [11].

3.3.4 Efficiency

Antenna efficiency measures how effectively input power is converted into radiated energy. High efficiency is particularly important in aerospace systems, where available power is limited. Losses due to dielectric materials, impedance mismatches, or surface roughness must be minimized to ensure that most of the transmitted power reaches its destination. Table 3 presents typical electromagnetic performance requirements for aerospace antennas:

Table 3. Electromagnetic Performance Requirements for Aerospace Antennas

| Requirement | Typical Value | Description |
|-----------------|--------------------|--------------------------|
| Frequency Range | 1-40 GHz | Varies by application |
| Gain | >10 dBi | For directional antennas |
| Polarization | Circular or Linear | Mission-dependent |
| Efficiency | >80% | At operating frequency |

3.3.5 Radiation pattern

The radiation pattern of an aerospace antenna must be carefully controlled to ensure optimal coverage and minimize interference. Depending on the application, antennas may require highly directional patterns for point-to-point communications or more omnidirectional patterns for broader coverage [2].

3.3.6 Bandwidth

Aerospace antennas often need to operate over wide frequency ranges to support multiple communication systems or to provide flexibility in operational frequencies. Wideband or multi-band performance is crucial for many aerospace applications [4].

3.3.7 Phase stability

For applications such as phased array antennas or interferometric systems, maintaining phase stability across temperature variations and mechanical stresses is critical [7]. Table 4 presents additional electromagnetic performance requirements for aerospace antennas:

Table 4. Additional Electromagnetic Performance Requirements for Aerospace Antennas

| Requirement | Typical Value | Description |
|-------------------|------------------|------------------------------------|
| Radiation Pattern | Mission-specific | Directional or omnidirectional |
| Bandwidth | 10-30% | Percentage of center frequency |
| Phase Stability | < 5° variation | Over operational temperature range |

3.4 Environmental Resistance

In addition to mechanical and thermal challenges, aerospace antennas are exposed to a variety of environmental hazards that can compromise their performance and reliability. Whether operating in the upper atmosphere or in the harsh conditions of space, antennas must be engineered to resist degradation caused by radiation, vacuum exposure, and corrosive environments. Ensuring environmental resistance is essential for long-term mission success and minimizing maintenance or replacement needs.

3.4.1 Radiation Hardness

Antennas deployed in space are exposed to ionizing radiation from cosmic rays, solar flares, and trapped particle belts. This radiation can deteriorate dielectric materials, reduce conductivity in metallic elements, and damage embedded electronics. Radiation-hardened materials and coatings are therefore used to ensure long-term functionality, particularly in geostationary or deep-space missions [5].

3.4.2 Vacuum Compatibility

In the vacuum of space, materials must not outgas volatile substances, which can condense on sensitive components and impair performance. Additionally, the absence of atmospheric pressure and the presence of extreme temperature differentials can cause material embrittlement or delamination. Antennas must be manufactured using vacuum-rated adhesives, composites, and structural materials that remain stable and non-reactive under such conditions [8].

3.4.3 Corrosion Resistance

For aerospace antennas operating within Earth's atmosphere—particularly on aircraft—corrosion resistance is critical. Exposure to moisture, salt-laden air, UV radiation, and pollutants can lead to oxidation, pitting, or structural weakening. Protective surface treatments, such as anodizing, plating, or the use of corrosion-resistant alloys, help extend the service life of these systems [9]. Table 5 presents additional electromagnetic resistance requirements for aerospace antennas:

Table 5. Environmental Resistance Requirements for Aerospace Antennas

| Requirement | Typical Value | Description |
|----------------------|------------------------|---------------------------|
| Radiation Tolerance | Up to 100 krad | Total Ionizing Dose (TID) |
| Outgassing | <1% TML, <0.1% CVCM | As per ASTM E595 |
| Corrosion Resistance | 1000+ hours salt spray | As per ASTM B117 |

Note: TML = Total Mass Loss, CVCM = Collected Volatile Condensable Material

3.5 Size and Weight Constraints

In aerospace systems, antenna size and weight are critical design parameters that influence overall vehicle performance, structural design, fuel efficiency, and payload capacity. Because launch and flight systems operate under strict mass and volume limitations, antenna technologies must evolve to meet these constraints without sacrificing electromagnetic performance. Key considerations include:

3.5.1 Miniaturization

There is an ongoing push toward the miniaturization of antenna systems, especially in small satellites (CubeSats), UAVs, and compact spacecraft. Designers aim to reduce physical dimensions while maintaining acceptable gain, bandwidth, and efficiency. This often requires the use of novel antenna configurations (e.g., fractal, patch, and metamaterial-based designs) and high-permittivity substrates to compress the wavelength and reduce footprint [10].

3.5.2 Weight Reduction

Reducing the mass of antennas contributes significantly to fuel savings, improved manoeuvrability, and increased payload capacity. Weight reduction is especially crucial in launch vehicles and long-endurance aircraft. The use of lightweight composite materials, additive manufacturing (3D printing), and thin-film technologies has enabled the production of high-performance antennas with minimal mass [6].

3.5.3 Integration with Structures

Modern aerospace systems increasingly rely on conformal and embedded antennas, which are integrated directly into the surface of airframes, fuselages, or satellite panels. This structural integration reduces aerodynamic drag, frees up internal volume, and enhances stealth in military applications. Materials such as flexible printed circuits and multifunctional composites enable these embedded solutions while preserving RF performance [11]. Table 6 outlines typical size and weight constraints for aerospace antennas:

Table 6. Size and Weight Constraints for Aerospace Antennas

| Constraint | Typical Value | Description |
|-------------|-----------------------|-----------------------------------|
| Size | Application-specific | Often limited by available space |
| Weight | <1 kg/m ² | For planar array antennas |
| Integration | Conformal or embedded | Structural integration techniques |

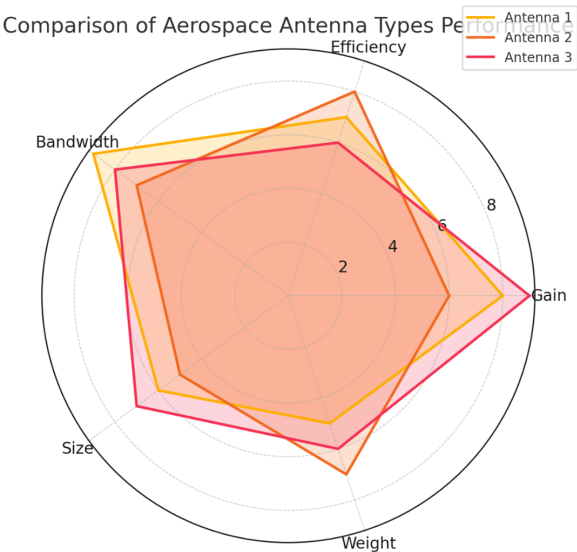


Figure 1. A spider chart comparing the performance characteristics (gain, efficiency, bandwidth, size, weight) of different aerospace antenna types.

A spider chart illustrating the comparative performance characteristics of various aerospace antenna types is presented in Figure 1. This visual representation highlights key parameters including gain, efficiency, bandwidth, size, and weight, enabling a clear assessment of trade-offs and strengths associated with each antenna type. By mapping these attributes on a unified scale, the chart facilitates a quick comparison of how different designs such as parabolic reflectors, patch antennas, helical antennas, and phased arrays perform relative to one another across critical performance metrics.

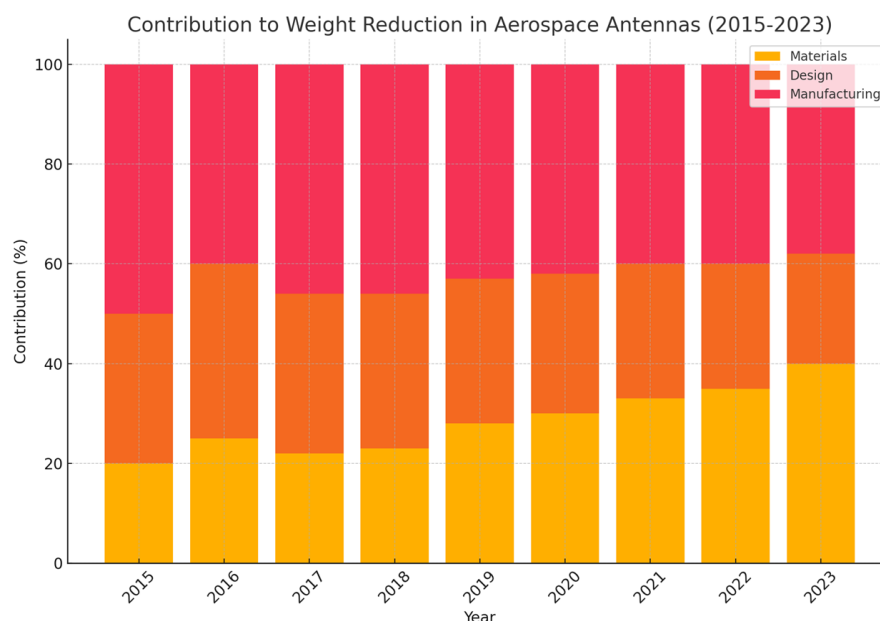


Figure 2. The contribution of various factors (materials, design, manufacturing technique) to the overall weight reduction in aerospace antennas over time

A stacked bar chart is presented in Figure 2 to illustrate the relative contributions of key factors—namely materials, design innovations, and manufacturing techniques—to the overall weight reduction of aerospace antennas over time. This visualization captures the evolving impact of each factor across different technological generations, highlighting how advancements such as lightweight composite materials, optimized structural designs, and additive manufacturing have collectively contributed to achieving significant mass savings in modern antenna systems.

In this section, we have provided a comprehensive overview of the fundamental requirements for aerospace antennas, covering mechanical robustness, thermal stability, electromagnetic performance, environmental resistance, and size and weight constraints. These requirements form the foundation for the advanced manufacturing techniques discussed in subsequent sections of this review.

3.6 Additive Manufacturing Techniques for Aerospace Antennas

Additive manufacturing (AM) has revolutionized the production of aerospace antennas, offering unprecedented design flexibility, material efficiency, and the ability to create complex geometries. This section explores the various AM techniques used in aerospace antenna fabrication, their advantages, and limitations.

3.6.1 Stereolithography (SLA)

Stereolithography (SLA) is one of the earliest and most established AM technologies, widely adopted in the aerospace industry for producing high-precision components—including parts for antenna systems. Its capability to fabricate complex geometries with fine detail makes it particularly advantageous for RF and antenna applications.

3.6.1.1 Process Overview

SLA operates by using an ultraviolet (UV) laser to selectively cure and solidify layers of liquid photopolymer resin, following the contours defined in a 3D CAD model. Each cured layer adheres to the previous one, gradually building up the final part with high resolution and surface quality. This layer-by-layer approach enables the creation of components with sub-millimeter features and smooth surfaces, which are essential in high-frequency antenna systems [7].

3.6.1.2 Applications in Aerospace Antennas

SLA is especially valuable for producing dielectric components of antennas, such as substrates, radomes, dielectric resonator elements, and supporting structures. The technique's high dimensional accuracy allows for the production of non-standard or miniaturized antenna geometries, including those used in conformal and embedded systems. These complex forms are often difficult or impractical to fabricate using conventional subtractive manufacturing methods. In addition, SLA supports rapid prototyping, accelerating the development cycle of aerospace antenna designs by enabling quick iteration and testing. Table 7 presents the Advantages and Limitations of SLA for Aerospace Antenna Fabrication.

Table 7. Advantages and Limitations of SLA for Aerospace Antenna Fabrication

| Advantages | Limitations |
|------------------------------------|-------------------------------------|
| High resolution (up to 25 microns) | Limited material options |
| Smooth surface finish | Post-curing required |
| Complex geometries possible | Relatively slow process |
| Good dimensional accuracy | Potential for warping during curing |

3.6.2 Fused Deposition Modelling (FDM)

FDM is one of the most widely used and accessible AM techniques. Its affordability, material versatility, and ease of use have made it a popular choice for both prototyping and limited-scale production of aerospace components, including antenna systems.

3.6.2.1 Process Overview

FDM builds parts by extruding thermoplastic filaments through a heated nozzle, which deposits material layer by layer according to a digital model. As each layer is deposited, it cools and solidifies, gradually forming the complete structure. The process supports a wide range of materials, including standard thermoplastics (like ABS and PLA) and specialized filaments with properties such as electrical conductivity, thermal resistance, and mechanical strength [4].

3.6.2.2 Applications in Aerospace Antennas

FDM is widely used in the development of aerospace antennas for fabricating substrates, structural housings, and even radiating or ground plane elements when using conductive or metallized filaments. Although FDM generally offers lower resolution than techniques like SLA, its cost-effectiveness and material diversity make it ideal for rapid prototyping, functional testing, and low-volume production. Furthermore, its capability to print with composite materials (e.g., carbon-fiber reinforced polymers) can improve the mechanical and thermal properties of antenna components for aerospace use. A comparison of material used in aerospace antenna is provided in Table 8.

Table 8. Comparison of Materials Used in FDM for Aerospace Antennas

| Material | Dielectric Constant | Loss Tangent | Thermal Stability |
|-----------------|----------------------------|---------------------|--------------------------|
| ABS | 2.3-2.8 | 0.005-0.01 | Moderate |
| PLA | 3.0-3.5 | 0.01-0.02 | Low |
| PEEK | 3.2-3.4 | 0.002-0.004 | High |
| Conductive PLA | Variable | Variable | Low |

3.6.3 Selective Laser Sintering (SLS)

SLS is a powerful AM technique that offers significant advantages for the fabrication of aerospace antennas, particularly where complex geometries, structural strength, and material flexibility are critical. Unlike other AM methods, SLS enables the direct production of high-performance components with minimal post-processing.

3.6.3.1 Process Overview

SLS works by using a high-power laser to selectively sinter powdered materials—typically thermoplastics or metals—into solid layers based on a digital 3D model. The laser fuses the powder particles together, layer by layer, without the need for external support structures, as the surrounding unsintered powder acts as a natural support during the build process [5]. This allows for the creation of complex internal features, lightweight lattices, and topology-optimized designs that are difficult or impossible to manufacture with traditional methods.

3.6.3.2 Applications in Aerospace Antennas

In aerospace antenna development, SLS is particularly suited for producing structurally robust and lightweight components, such as antenna housings, substrates, and mounts. Its compatibility with nylon-based polymers (e.g., PA12) provides durability and thermal stability, while metal powder variants, such as aluminium or stainless steel, enable the direct fabrication of metallic antenna elements and RF structures. This reduces the need for complex assemblies, improves alignment accuracy, and enhances overall antenna performance. Additionally, the ability to manufacture integrated components helps reduce weight and volume—key factors in aerospace systems. The Key Parameters for SLS in Aerospace Antenna Fabrication are presented in Table 9.

Table 9. Key Parameters for SLS in Aerospace Antenna Fabrication

| Parameter | Typical Range | Impact on Antenna Performance |
|----------------------|---------------|---|
| Layer Thickness | 0.06-0.15 mm | Affects surface roughness and dimensional accuracy |
| Laser Power | 10-200 W | Influences material sintering and mechanical properties |
| Scan Speed | 0.5-2.5 m/s | Affects build time and material properties |
| Powder Particle Size | 20-100 µm | Impacts surface finish and minimum feature size |

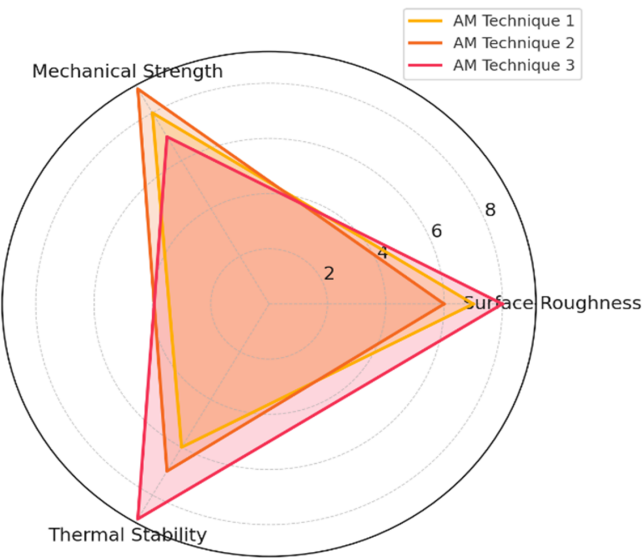


Figure 3. A radar chart comparing key performance metrics (surface roughness, mechanical strength, and thermal stability) of antennas produced by different additive manufacturing (AM) techniques

Figure 3 presents a radar chart comparing key performance metrics of antennas fabricated using different AM techniques, including SLA, FDM, and SLS. The chart evaluates and contrasts surface roughness, mechanical strength, and thermal stability, offering a visual representation of the trade-offs and strengths associated with each method. This comparison helps identify the most suitable AM approach based on specific performance requirements for aerospace antenna applications.

These AM techniques have significantly expanded the design possibilities for aerospace antennas, enabling the creation of lightweight, high-performance structures that were previously impossible or impractical to manufacture. As the technology continues to evolve, we can expect further improvements in material properties, printing resolution, and production speed, leading to even more innovative aerospace antenna designs.

3.7 Precision Machining Techniques for Aerospace Antennas

Precision machining techniques play a vital role in the fabrication of aerospace antennas, where high dimensional accuracy, fine surface finish, and geometric consistency are critical. These characteristics directly influence the electromagnetic performance, particularly in high-frequency and high-gain applications, where even slight deviations in geometry or surface quality can result in signal loss, reflection, or beam distortion. Precision machining supports the manufacturing of metallic and dielectric components that must adhere to strict aerospace specifications for reliability and performance. This section explores key precision machining methods used in aerospace antenna production, starting with CNC milling.

3.7.1 CNC Milling

Computer Numerical Control (CNC) milling is a widely used subtractive manufacturing process in aerospace antenna fabrication due to its versatility, precision, and repeatability.

3.7.1.1 Process Overview

CNC milling involves the use of computer-programmed cutting tools that move along multiple axes to remove material from a solid block (workpiece). The digital control system interprets 3D CAD models and executes complex tool paths with high speed and accuracy. This process enables the creation of precise, repeatable components with tight dimensional tolerances and smooth surface finishes [7].

3.7.1.2 Applications in Aerospace Antennas

In the aerospace sector, CNC milling is particularly effective for fabricating high-frequency antenna components such as,

- Feed horns
- Waveguides
- Slot antennas
- Mounting brackets
- Reflector elements

These components require precise internal and external geometries, often involving curved surfaces or critical alignment features. CNC milling can achieve tolerances on the order of microns, making it ideal for parts where even minimal dimensional error could degrade RF performance. Moreover, it supports the use of aerospace-grade materials like aluminium alloys, titanium, and copper, which offer excellent mechanical and electrical properties. The key parameters for CNC milling are summarize in Table 10.

Table 10. Key Parameters for CNC Milling in Aerospace Antenna Fabrication

| Parameter | Typical Range | Impact on Antenna Performance |
|---------------|------------------|--|
| Spindle Speed | 1,000-30,000 RPM | Affects surface finish and machining time |
| Feed Rate | 0.1-1000 mm/min | Influences dimensional accuracy and tool wear |
| Cutting Depth | 0.1-5 mm | Impacts surface quality and machining efficiency |
| Tool Diameter | 0.1-25 mm | Determines minimum feature size and complexity |

3.7.2 Laser Cutting

Laser cutting is a highly precise and versatile manufacturing process widely used in aerospace antenna fabrication, particularly for producing intricate features in sheet metal components. Its ability to deliver fine, accurate cuts with minimal thermal distortion makes it ideal for applications where precision and material integrity are paramount.

3.7.2.1 Process Overview

Laser cutting employs a focused, high-energy laser beam to melt, burn, or vaporize targeted areas of material. The process is typically guided by a computer numerical control (CNC) system, which interprets digital design files to execute exact cutting paths with high speed and repeatability. Because the laser can be finely tuned, laser cutting minimizes material waste and allows for extremely tight tolerances and sharp edge definitions, even on thin and delicate materials [6].

3.7.2.2 Applications in Aerospace Antennas

In the context of aerospace antennas, laser cutting is especially effective for fabricating:

- Radiating elements (e.g., dipoles, slots, spirals)
- Ground planes and backing plates
- Reflector panels for parabolic and planar antennas
- Mounting brackets and support frames

The process excels in producing complex geometries and fine features in thin metal sheets (such as aluminium, copper, or stainless steel), which are often required in high-frequency antenna designs. Additionally, laser cutting supports rapid prototyping and low- to mid-volume production, making it a practical choice for both development and deployment phases in aerospace applications. The pros and cons of the laser cutting is provided in Table 11.

Table 11. Advantages and Limitations of Laser Cutting for Aerospace Antennas

| Advantages | Limitations |
|--------------------------------|--|
| High precision (± 0.1 mm) | Limited material thickness (typically < 25 mm) |
| Minimal material distortion | Potential for heat-affected zones |
| Complex shape capabilities | Higher cost for thick materials |
| Fast processing speed | Limited to flat or slightly curved surfaces |

3.7.3 Microfabrication

Microfabrication techniques are essential for producing miniaturized antenna components and high-frequency structures, enabling the realization of compact, lightweight, and highly efficient designs that are critical for aerospace applications. These methods allow engineers to translate complex antenna geometries into practical hardware with the precision required for operation in challenging environments.

3.7.3.1 Process Overview

Microfabrication encompasses a suite of advanced processes such as photolithography, etching, thin-film deposition, and surface micromachining. Photolithography provides the capability to define antenna patterns at the micro- and nanoscale with exceptional accuracy, while etching (both wet and dry) is used to selectively remove material to achieve desired geometrical features. Thin-film deposition techniques—including sputtering, evaporation, and chemical vapor deposition—enable the formation of conductive, dielectric, or magnetic layers that are fundamental for antenna performance. Together, these processes allow for the fabrication of extremely small and precise antenna structures that can operate efficiently at millimeter-wave and terahertz frequencies [12].

3.7.3.2 Applications in Aerospace Antennas

In aerospace systems, microfabrication is particularly valuable for designing and producing antennas where size, weight, and performance must be carefully optimized. This includes millimeter-wave and terahertz antennas used for high-data-rate satellite communications, radar imaging, and deep-space exploration. Furthermore, microfabrication plays a critical role in developing MEMS-based reconfigurable antennas, which can dynamically adjust their frequency, polarization, or radiation patterns in response to mission requirements. It also supports the integration of antenna arrays with other electronic subsystems, allowing for seamless packaging and enhanced performance in compact aerospace platforms. By leveraging microfabrication, aerospace engineers can create antenna systems that are not only efficient but also highly scalable and compatible with modern miniaturized electronics. Table 12 presents an overview of the key microfabrication techniques used in aerospace antennas, highlighting their processes, advantages, and application domains.

Table 12. Microfabrication Techniques for Aerospace Antennas

| Technique | Resolution | Applications |
|----------------------|---------------------------|---|
| Photolithography | Down to 0.5 μm | Planar antenna patterns, transmission lines |
| Reactive Ion Etching | 10-100 nm | 3D antenna structures, waveguides |
| E-beam Lithography | <10 nm | Nanoantenna structures, metamaterials |
| Thin-film Deposition | 1-1000 nm | Conductive and dielectric layers |

3.7.4 Challenges in Precision Machining

While precision machining provides distinct advantages in the fabrication of aerospace antennas—such as high dimensional accuracy and superior surface finish—it also introduces several challenges that must be carefully addressed to ensure reliable performance under demanding operational conditions. These challenges primarily arise from the interaction between advanced machining processes, the unique material requirements of aerospace systems, and the high-performance specifications of antenna structures.

3.7.4.1 Tool Wear and Thermal Effects

One of the most critical issues in precision machining is tool wear, which directly influences both dimensional accuracy and surface integrity. Excessive tool wear can lead to deviations in antenna geometry, negatively impacting resonance frequency, impedance matching, and radiation characteristics. Additionally, thermal effects generated during high-speed machining or prolonged tool-workpiece contact can cause localized heating. This thermal accumulation may induce distortions, residual stresses, or microstructural changes in the antenna substrate, potentially degrading its electrical and mechanical performance. To address these challenges, researchers and practitioners employ advanced tool materials such as polycrystalline diamond (PCD) or cubic boron nitride (CBN), along with optimized cutting parameters and high-efficiency cooling/lubrication strategies [13]. These approaches significantly reduce tool wear rates, improve heat dissipation, and enhance the consistency of machined features.

3.7.4.2 Material Considerations

Aerospace antennas often utilize specialized materials to meet requirements of lightweight design, high electrical conductivity, and resistance to harsh environments such as extreme temperatures, vibration, and radiation. Common materials include titanium alloys, aluminum composites, ceramic-based substrates, and advanced polymers. However, these materials frequently pose machinability challenges—titanium alloys exhibit low thermal conductivity and high hardness, while ceramics are brittle and prone to cracking under mechanical stress. Such difficulties necessitate tailored machining strategies, including the use of ultra-precision diamond turning, hybrid machining techniques (e.g., laser-assisted machining), and adaptive process control systems. These methods help maintain the balance between machinability, antenna performance, and long-term durability.

Table 13 summarizes the various strategies employed to overcome precision machining challenges in aerospace antenna fabrication, outlining their advantages and applicability across different material classes and machining scenarios.

Table 13. Strategies for Addressing Precision Machining Challenges

| Challenge | Strategy | Benefit |
|-------------------|--|---|
| Tool Wear | Use of advanced coatings (e.g., TiAlN) | Extended tool life, improved surface finish |
| Thermal Effects | Implementation of cryogenic cooling | Reduced thermal distortion, enhanced accuracy |
| Material Hardness | Ultrasonic-assisted machining | Improved machinability of hard materials |
| Surface Integrity | Optimized cutting parameters | Enhanced electromagnetic performance |

Precision machining techniques continue to evolve, driven by the increasing demands of aerospace antenna applications. Future developments are likely to focus on enhancing precision, reducing manufacturing time, and expanding the range of machinable materials. Integration with other advanced manufacturing techniques, such as additive manufacturing, may lead to hybrid processes that combine the strengths of multiple fabrication methods.

3.8 Composite Material Fabrication for Aerospace Antennas

Composite materials have revolutionized the design and manufacturing of aerospace antennas by offering a unique combination of low weight, high mechanical strength, and customizable electromagnetic properties. Unlike traditional metallic structures, composites can be engineered at the material and structural levels to optimize both mechanical performance and radio-frequency (RF) characteristics. This flexibility makes them highly suitable for next-generation aerospace systems, where strict requirements for weight reduction, durability, and multifunctionality must be met simultaneously. This section discusses the use of advanced composites in antenna construction, their benefits, and fabrication strategies.

3.8.1 Advanced Composites in Antenna Construction

The adoption of advanced composites in aerospace antenna fabrication has accelerated due to their superior mechanical, thermal, and electrical properties compared to conventional materials such as aluminum or copper. Their lightweight nature directly contributes to reduced payload mass in satellites and aircraft, improving overall fuel efficiency and mission performance. Moreover, composite materials allow for integration of structural and electromagnetic functionality, enabling antennas to be embedded within load-bearing surfaces without compromising performance.

3.8.2 Carbon Fiber-Reinforced Polymers (CFRP)

Carbon Fiber-Reinforced Polymers (CFRPs) are among the most widely employed composites in aerospace antennas. CFRPs combine carbon fibers, known for their high tensile strength and low density, with polymer matrices that provide toughness and environmental resistance. Beyond their structural advantages, CFRPs offer tunable electromagnetic characteristics by adjusting fiber orientation, volume fraction, or resin composition. This makes them particularly valuable for lightweight reflector antennas, radomes, and conformal antenna arrays. Additionally, CFRPs are compatible with various fabrication methods such as filament winding, resin transfer molding, and automated fiber placement, supporting scalable production with high precision.

3.8.3 Ceramic Matrix Composites (CMC)

Ceramic Matrix Composites (CMCs) represent another important class of materials for aerospace antennas, particularly in high-temperature and high-frequency environments. CMCs are composed of ceramic fibers embedded within a ceramic matrix, offering exceptional thermal stability, low dielectric loss, and resistance to harsh operational conditions. These properties make them suitable for antennas used in supersonic aircraft, re-entry vehicles, and deep-space probes, where structural integrity must be maintained under extreme thermal loads. In addition, their electrical properties can be engineered to reduce RF losses, improving antenna efficiency at millimeter-wave and terahertz frequencies.

Table 14 presents the key properties of advanced composites used in aerospace antennas, highlighting their mechanical performance, electromagnetic characteristics, and application domains.

Table 14. Properties of Advanced Composites Used in Aerospace Antennas

| Composite Material | Density (g/cm ³) | Tensile Strength (MPa) | Dielectric Constant | Loss Tangent |
|--------------------|------------------------------|------------------------|---------------------|--------------|
| CFRP | 1.5-1.6 | 600-3000 | 2.5-6.0 | 0.001-0.005 |
| CMC | 2.0-3.5 | 200-1000 | 5.0-10.0 | 0.0001-0.001 |
| Glass Fiber | 1.8-2.0 | 400-1800 | 4.0-5.0 | 0.001-0.01 |

3.9 Benefits of Composite Materials

Composite materials provide a number of distinct advantages over traditional metallic materials in aerospace antenna applications, making them a preferred choice in modern design and manufacturing. Their unique material properties not only enhance antenna performance but also contribute to overall system reliability and efficiency in demanding aerospace environments.

3.9.1 High Strength-to-Weight Ratio

One of the most significant benefits of composites is their exceptional strength-to-weight ratio. By combining lightweight matrices with high-strength reinforcements such as carbon fibers, composites enable the construction of antennas that are both structurally robust and considerably lighter than their metallic counterparts. This reduction in weight translates directly into improved fuel efficiency, increased payload capacity, and overall performance benefits for aircraft and spacecraft systems.

3.9.2 Corrosion Resistance

Unlike metals, composites exhibit excellent resistance to corrosion and degradation when exposed to harsh aerospace environments, including high humidity, salt-laden atmospheres, and varying radiation levels. This property enhances the operational lifespan of antennas, reducing maintenance costs and ensuring consistent performance throughout extended missions.

3.9.3 Thermal Stability

Advanced composites, particularly Ceramic Matrix Composites (CMCs), demonstrate outstanding thermal stability across a broad range of operating temperatures. This makes them particularly well-suited for antennas used in extreme environments such as high-speed aircraft, space vehicles, and re-entry systems, where components are subjected to rapid heating and cooling cycles. Their ability to retain structural and electromagnetic properties under these conditions ensures both durability and reliability of communication and sensing functions.

Table 15 presents the summarized advantages of composite materials in aerospace antenna applications, highlighting their role in achieving lightweight, durable, and thermally resilient designs.

Table 15. Advantages of Composite Materials in Aerospace Antenna Applications

| Advantage | Description | Impact on Antenna Performance |
|---------------------------|--|--|
| Weight Reduction | Up to 50% lighter than metal equivalents | Improved fuel efficiency, increased payload capacity |
| Design Flexibility | Ability to create complex shapes | Enhanced antenna efficiency and directivity |
| Thermal Expansion Control | Low coefficient of thermal expansion | Improved dimensional stability in space environments |
| EMI Shielding | Tailorable electromagnetic properties | Better control of antenna radiation patterns |

3.10 Fabrication Techniques

The fabrication of composite antennas for aerospace applications requires advanced manufacturing methods capable of producing lightweight, mechanically robust, and electromagnetically optimized structures. Several fabrication techniques have been developed to meet these requirements, each offering distinct advantages in terms of structural performance, design flexibility, and production scalability.

3.10.1 Autoclave Moulding

Autoclave moulding remains one of the most widely adopted techniques for producing high-performance composite antenna structures. In this process, prepreg (pre-impregnated) composite materials are placed into a mould and subjected to elevated temperature and pressure within an autoclave. The controlled curing environment ensures excellent consolidation, low void content, and high structural integrity, making this method particularly suitable for critical aerospace applications where reliability and performance are paramount.

3.10.2 Resin Transfer Moulding (RTM)

Resin Transfer Moulding is a versatile fabrication method that enables the production of complex antenna geometries with high dimensional accuracy. In RTM, dry fiber preforms are placed into a closed mould, and resin is injected under pressure to impregnate the fibers. This technique offers advantages such as high fiber volume fractions, consistent quality, and smooth surface finish, which are crucial for achieving the desired electromagnetic performance of antennas. RTM also facilitates higher production rates compared to autoclave moulding, making it attractive for applications requiring scalability.

3.10.3 Filament Winding

Filament winding is a highly specialized technique used primarily for fabricating cylindrical or conical antenna structures. Continuous fiber tows, pre-impregnated with resin, are wound under tension onto a rotating mandrel in predetermined patterns. This process allows for precise control over fiber orientation, which directly influences the mechanical strength and electromagnetic properties of the antenna. Filament winding is especially beneficial in applications requiring optimized load-bearing capacity and tailored anisotropy.

Table 16 presents the various composite fabrication techniques employed in aerospace antenna manufacturing, highlighting their advantages and application areas.

Table 16. Composite Fabrication Techniques for Aerospace Antennas

| Technique | Advantages | Limitations | Typical Applications |
|-------------------------|--------------------------------------|-------------------------------|--|
| Autoclave Moulding | High quality, low void content | High equipment cost | Reflector antennas, radomes |
| Resin Transfer Moulding | Complex shapes, good surface finish | Tooling complexity | Conformal antennas, antenna housings |
| Filament Winding | Precise fiber control, high strength | Limited to symmetrical shapes | Cylindrical array antennas, feed horns |

3.11 Application Examples

Composite materials have become integral to modern aerospace antenna systems due to their unique combination of lightweight properties, structural strength, and tailored electromagnetic performance. Their adaptability allows engineers to design antennas that meet the stringent requirements of aerospace platforms, where weight, durability, and performance under extreme conditions are critical.

3.11.1 Reflector Antennas

One of the most prominent applications of composites is in large reflector antennas used for satellite communication and deep-space missions. Carbon Fiber-Reinforced Polymers (CFRPs) are particularly valuable in these structures because of their exceptional dimensional stability, low thermal expansion, and reduced mass compared to metallic alternatives. These properties ensure that reflector surfaces maintain their precise geometrical shape even under harsh thermal cycling in space, resulting in high gain and low signal distortion. By lowering antenna mass, CFRP reflectors also contribute to significant reductions in launch costs and improved payload efficiency.

3.11.2 Conformal Antennas

Composite materials also play a pivotal role in the development of conformal antennas, which are designed to integrate seamlessly with the curved surfaces of aircraft, spacecraft, or unmanned aerial vehicles (UAVs). The

use of composites enables antennas to be embedded or mounted flush with the fuselage or wings, enhancing aerodynamics and stealth characteristics while maintaining robust communication capabilities. These antennas are particularly advantageous in military aerospace systems, where minimizing radar cross-section (RCS) without compromising signal quality is essential. Moreover, the electromagnetic tailoring of composites allows for frequency agility and wideband operation, broadening their range of applications.

Table 17 presents representative examples of composite antenna applications in aerospace systems, highlighting how materials such as CFRPs and ceramic matrix composites (CMCs) are leveraged to enhance performance across different antenna types.

Table 17. Examples of Composite Antennas in Aerospace Systems

| Antenna Type | Composite Material | Key Performance Characteristics |
|--------------------------|------------------------|--|
| Satellite Reflector | CFRP | High dimensional stability, low mass, wide temperature range operation |
| Aircraft Conformal Array | Glass Fiber Composite | Aerodynamic integration, wide bandwidth, low radar cross-section |
| Radome | Quartz Fiber Composite | Low signal attenuation, high impact resistance, thermal protection |

3.11.3 Challenges and Future Directions

Although composite materials provide substantial benefits in aerospace antenna applications, several challenges must be addressed to fully exploit their potential.

3.11.3.1 Manufacturing Complexity

The fabrication of composite-based antennas often involves specialized mouldings, curing, and assembly processes that require high-precision equipment and skilled labour. Techniques such as autoclave mouldings or resin transfer mouldings (RTM) ensure structural integrity but also increase production costs and extend lead times. Furthermore, scaling these processes for large or intricate antenna geometries remains a technical challenge.

3.11.3.2 Electromagnetic Property Control

Another critical challenge lies in achieving consistent and predictable electromagnetic performance across large composite structures. Variations in fiber orientation, resin content, or curing conditions can alter dielectric properties, leading to deviations in antenna performance. Advanced material characterization and multi-physics simulations are therefore essential to accurately model and control these properties during the design and manufacturing phases.

3.11.3.3 Joining and Integration

The integration of composite antenna components with metallic structures, such as aircraft fuselages or satellite mounts, poses additional difficulties. Differences in thermal expansion coefficients, bonding reliability, and mechanical stress distribution must be carefully managed to prevent delamination or signal degradation. Hybrid joining techniques, including advanced adhesives and mechanical fasteners, are under active investigation to enhance structural and electromagnetic compatibility.

3.11.3.4 Future Directions

Ongoing research is exploring several promising avenues to overcome these challenges. Future developments in composite antenna fabrication are likely to focus on:

- **Advanced modelling techniques** that enable precise prediction of structural, thermal, and electromagnetic performance in composite antennas.
- **Novel composite materials**, such as nanocomposites or metamaterial-enhanced composites, designed to improve dielectric uniformity and electromagnetic tunability.
- **Improved manufacturing processes**, including additive manufacturing and out-of-autoclave curing methods, to reduce costs while maintaining high precision.

- **Integration of multifunctionality**, where composite antennas also serve as structural elements with embedded sensing, thermal management, or structural health monitoring capabilities.

As composite technologies advance, their role in next-generation aerospace antennas will expand significantly, enabling lighter, more efficient, and multifunctional systems. These innovations will be critical for supporting the increasing demands of satellite communications, deep-space exploration, and defense applications where performance and reliability are paramount.

3.12 Integration and Assembly Techniques for Aerospace Antennas

The integration and assembly of antennas within aerospace structures pose unique challenges but also offer opportunities to enhance overall system performance, reduce weight, and improve stealth and aerodynamic properties. This section examines advanced techniques for embedding antennas into aerospace platforms, with a particular emphasis on conformal antennas and their manufacturing considerations.

3.12.1 Conformal Antennas

Conformal antennas are engineered to follow the natural contours of aerospace vehicles, such as fuselages, wings, or satellite bodies. Unlike traditional protruding antennas, conformal designs minimize drag, improve stealth characteristics by reducing radar cross-section (RCS), and enable seamless integration with structural surfaces. Their ability to blend into the host platform makes them especially valuable in modern military and high-performance aerospace systems.

3.12.2 Manufacturing Methods for Curved Surfaces

Fabricating antennas that can accurately conform to curved or complex surfaces requires advanced manufacturing approaches. Flexible printed circuit board (PCB) fabrication is a common technique, allowing antenna elements to be deposited onto bendable substrates that adhere to the vehicle's geometry. Composite layup techniques, where conductive materials are embedded within or on top of composite laminates, offer structural reinforcement along with electromagnetic functionality. Additionally, advanced additive manufacturing (3D printing) enables the creation of intricate curved antenna geometries with high precision and reduced material waste, supporting lightweight designs while maintaining electrical performance.

3.12.3 Integration with Aerospace Structures

The integration process must account for the host platform's material composition, surface topology, and electromagnetic interactions. For instance, the dielectric properties of the underlying structure can significantly influence antenna performance, requiring co-design of both antenna and host materials. Mechanical considerations, such as bonding strength, thermal expansion compatibility, and vibration resistance, also play a critical role in ensuring durability under extreme flight conditions. Furthermore, integration strategies often involve hybrid techniques—such as embedding antenna traces within composite layers or co-curing conductive films with structural materials—to achieve seamless functionality.

Table 18 presents a comparative overview of the manufacturing methods commonly employed for conformal antennas, highlighting their suitability, advantages, and limitations in aerospace applications.

Table 18. Comparison of Manufacturing Methods for Conformal Antennas

| Method | Advantages | Limitations | Typical Applications |
|-------------------|---------------------------------------|-------------------------------------|------------------------|
| Flexible PCB | Thin profile, lightweight | Limited to simple curvatures | Aircraft skin antennas |
| Shaped Composites | High strength, complex shapes | Higher cost, longer production time | Satellite antennas |
| 3D Printing | Rapid prototyping, complex geometries | Material limitations | UAV antennas |

3.13 Embedded Antennas

Embedded antennas are integrated directly into the load-bearing or protective structural components of aerospace platforms. This approach provides several advantages, including efficient use of limited space, reduced weight by eliminating the need for separate housings, and enhanced protection of the antenna from harsh environmental conditions such as mechanical stress, thermal fluctuations, and electromagnetic

interference. By serving both structural and communication functions, embedded antennas contribute to the development of multifunctional aerospace systems.

3.13.1 Techniques for Incorporating Antennas into Structural Components

A variety of advanced techniques have been developed for embedding antennas into structural components. In-mould electronics (IME) involves embedding conductive traces and antenna elements within composite laminates during the mouldings process, enabling antennas to become integral parts of the structure. Structural electronics extend this concept by embedding entire electronic systems—beyond just antennas—within structural materials, thereby enhancing system compactness and functionality. Multi-material 3D printing represents another promising technique, as it allows for the precise co-fabrication of conductive and dielectric materials within a single manufacturing step, creating highly integrated and lightweight antenna structures. These methods enable aerospace engineers to design structures that simultaneously meet mechanical and electromagnetic performance requirements.

3.13.2 Challenges and Solutions

Despite their advantages, embedded antennas present several technical challenges. Maintaining consistent antenna performance can be difficult due to the influence of surrounding structural materials, which may alter electromagnetic properties such as dielectric constant and loss tangent. Ensuring structural integrity is equally critical, as embedding conductive elements should not weaken the host material or compromise load-bearing capacity. Additionally, thermal management becomes a concern, since embedded antennas may be subjected to heat generated during operation or by the host structure in extreme aerospace environments. Solutions to these challenges include careful material selection, where composites and dielectric layers are tailored to minimize electromagnetic interference while preserving strength. Innovative design approaches, such as topology optimization and co-simulation of structural and electromagnetic properties, are increasingly used to balance antenna performance with mechanical requirements. Moreover, thermal management strategies, such as integrating heat-dissipating layers or employing materials with high thermal conductivity, help ensure long-term reliability.

Table 19 summarizes the key challenges and potential solutions associated with embedded antenna integration in aerospace systems.

Table 19. Challenges and Solutions in Embedded Antenna Integration

| Challenge | Solution | Impact on Performance |
|----------------------|---------------------------------|---|
| Signal Attenuation | Use of low-loss materials | Improved antenna efficiency |
| Structural Integrity | Multi-physics simulation | Optimized structural-electromagnetic design |
| Thermal Management | Integration of cooling channels | Enhanced reliability in high-power applications |

3.14 Impact on System Performance

The integration of antennas into aerospace structures has a profound influence on the overall performance of the platform, affecting not only communication and sensing capabilities but also aerodynamic efficiency, structural strength, and electromagnetic compatibility. Figure 4 illustrates the relationship between antenna integration level and aerodynamic efficiency, highlighting the performance benefits of advanced integration approaches compared to conventional protruding antennas.

3.14.1 Aerodynamic Considerations

Traditional protruding antennas disrupt the smooth airflow around an aerospace vehicle, increasing drag and reducing fuel efficiency. In contrast, conformal and embedded antennas are seamlessly integrated into the surface or structure, enabling streamlined aerodynamics. This results in lower drag coefficients, enhanced fuel economy, and improved manoeuvrability, particularly in high-speed aircraft and space vehicles where aerodynamic efficiency is critical. Additionally, reduced protrusions enhance stealth capabilities by minimizing radar cross-section (RCS).

3.14.2 Structural Integrity

When antennas are embedded within or conformally attached to aerospace structures, they can be designed to complement the host material's load-bearing function. Properly integrated antennas reduce the need for additional housings, brackets, or mounts, thereby lowering the platform's overall weight. In some cases, advanced composites allow antennas to function as multifunctional structural elements, simultaneously carrying loads and enabling communication. This dual functionality is especially beneficial for spacecraft and unmanned aerial vehicles (UAVs), where weight savings directly translate to extended mission durations and payload capacity.

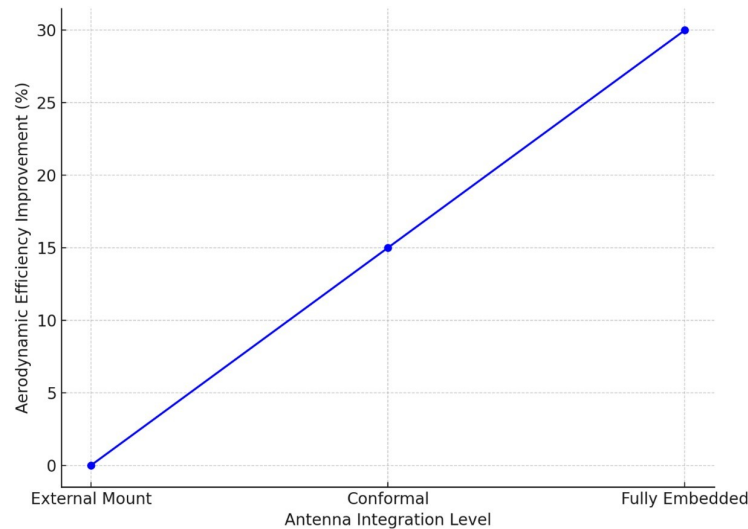


Figure 4. A line graph showing the relationship between antenna integration level and aerodynamic efficiency.

3.14.3 Electromagnetic Compatibility (EMC)

One of the main challenges of antenna integration is ensuring electromagnetic compatibility with other onboard systems. Proximity to avionics, sensors, and power systems can lead to interference that degrades performance. Integrated antennas require precise electromagnetic modelling and shielding techniques to minimize mutual coupling, interference, and signal distortion. Careful co-design of structural materials and antenna elements—such as controlling dielectric properties and grounding schemes—helps maintain reliable operation without compromising communication or sensing functions.

Overall, the integration of conformal and embedded antennas enhances aerospace platforms by improving aerodynamics, reducing weight, and maintaining structural integrity while ensuring electromagnetic reliability. These improvements contribute to next-generation aerospace systems that are lighter, more efficient, and capable of supporting increasingly complex mission requirements.

Table 20 shows the Impact of Antenna Integration on System Performance.

| Table 20: Impact of Antenna Integration on System Performance | | |
|---|---|---|
| Performance Aspect | Conformal Antennas | Embedded Antennas |
| Aerodynamics | Significant drag reduction | Minimal impact on existing aerodynamics |
| Weight | Slight increase due to conforming materials | Potential weight reduction through multifunctionality |
| EMC | Improved due to reduced protrusions | Challenges due to proximity to other systems |

3.15 Future Trends in Antenna Integration

Emerging trends in antenna integration for aerospace applications are increasingly focused on achieving multifunctionality, adaptability, and enhanced performance.

3.15.1 Smart Skins with Integrated Sensing and Communication

Smart skins represent a transformative approach to antenna integration, where antennas and sensors are directly embedded into the structural surfaces of aerospace vehicles. By combining communication and sensing functionalities within the skin of the aircraft or spacecraft, these systems eliminate protruding antenna structures, thereby reducing aerodynamic drag and improving stealth capabilities. Moreover, smart skins enable distributed communication networks and structural health monitoring, ensuring resilience and fault tolerance in critical aerospace missions. This multifunctional approach is particularly relevant for next-generation UAVs, stealth aircraft, and satellites where weight, efficiency, and survivability are crucial.

3.15.2 Metamaterial-Based Conformal Antennas

Metamaterial-based conformal antennas leverage engineered electromagnetic properties to achieve enhanced gain, bandwidth, and beam-steering capabilities in compact and low-profile designs. Unlike conventional antennas, these structures can manipulate electromagnetic waves in novel ways, enabling high-frequency operation, reduced radar cross-section, and reconfigurability. Their conformal nature allows seamless integration with curved aerospace surfaces, supporting applications in satellite communications, hypersonic vehicles, and advanced radar systems. By combining structural adaptability with superior electromagnetic performance, metamaterial antennas hold strong potential for improving both communication reliability and stealth characteristics in aerospace missions.

3.15.3 4D Printed Adaptive Antennas

4D printed antennas extend the concept of additive manufacturing by incorporating materials that respond dynamically to environmental stimuli such as temperature, pressure, or electromagnetic load. These antennas can adapt their geometry or electromagnetic properties in real time, allowing the system to optimize performance under varying flight conditions. For instance, an antenna may expand its aperture for long-range communication at high altitudes or reconfigure itself for short-range, high-capacity links in dense operational environments. This adaptability makes 4D printed antennas particularly suitable for flexible aerospace systems, including reusable spacecraft, UAV swarms, and next-generation satellites. By enabling real-time reconfiguration, 4D antennas push aerospace communication technology toward a new era of versatility and resilience.

3.16 Emerging Trends and Future Developments

As the field of aerospace antenna manufacturing continues to advance, several emerging trends and future developments show significant potential for enhancing antenna performance, functionality, and production efficiency. Innovations in smart materials, adaptive designs, and novel manufacturing methods are paving the way for next-generation aerospace antenna systems that are lighter, more efficient, and highly reconfigurable. This section highlights key advancements and their expected impact on the aerospace industry.

3.16.1 Smart Materials in Antenna Manufacturing

The integration of smart materials into antenna design and manufacturing has emerged as a promising research area. Smart materials enable the creation of antennas that are adaptive, reconfigurable, and capable of responding to changes in the surrounding environment. Such capabilities are particularly vital in aerospace applications, where conditions such as temperature, pressure, and electromagnetic interference can vary dramatically during operation.

3.16.2 Shape Memory Alloys (SMAs)

Shape Memory Alloys are metallic materials that can return to a pre-defined shape when subjected to specific stimuli, such as temperature changes. In antenna applications, SMAs can be used to dynamically alter the geometry of the antenna, enabling optimal performance across different flight regimes. For example, an SMA-based antenna can adjust its length or curvature to switch between frequency bands or improve gain under

varying conditions. This adaptability reduces the need for multiple antenna systems, leading to weight savings and higher efficiency in aerospace platforms.

3.16.3 Piezoelectric Materials

Piezoelectric materials deform in response to applied electrical signals, offering unique opportunities for creating tunable and reconfigurable antenna elements. By incorporating piezoelectric actuators within antenna structures, it becomes possible to fine-tune resonance frequencies, adjust polarization states, or modify radiation patterns in real time. Such tunability is crucial in aerospace systems that require secure, interference-resistant communication and adaptive responses to mission-critical scenarios.

3.16.4 Applications of Smart Materials in Aerospace Antennas

The applications of smart materials such as SMAs and piezoelectric elements extend across a wide range of aerospace use cases. These include:

- Frequency-agile communication systems for aircraft and satellites
- Lightweight, reconfigurable antennas for UAVs and drones
- Adaptive beam steering for radar and surveillance systems
- Self-healing and damage-tolerant antenna structures for extended mission lifespans

Table 21 shows the Applications of Smart Materials in Aerospace Antennas, highlighting how these technologies are being leveraged to achieve greater adaptability, efficiency, and resilience.

Table 21. Applications of Smart Materials in Aerospace Antennas

| Smart Material | Property | Potential Application |
|----------------------------|--|---------------------------------|
| Shape Memory Alloys | Shape change with temperature | Reconfigurable antenna elements |
| Piezoelectric Materials | Deformation under electric field | Tunable antenna components |
| Magnetostrictive Materials | Shape change in magnetic fields | Adaptive antenna structures |
| Electroactive Polymers | Large deformation under electric field | Morphing antennas |

3.17 Hybrid Manufacturing Processes

The adoption of hybrid manufacturing processes is gaining traction in aerospace antenna production, as it allows manufacturers to combine the strengths of different techniques for improved efficiency, precision, and performance. By integrating additive, subtractive, and adaptive methods into a single workflow, aerospace manufacturers can address the challenges of producing lightweight yet complex antenna structures while maintaining high reliability and quality standards.

3.17.1 Additive-Subtractive Hybrid Manufacturing

Additive-subtractive hybrid manufacturing merges the flexibility of additive manufacturing (AM), such as 3D printing, with the high-precision capabilities of subtractive processes like CNC machining. Additive manufacturing enables the creation of intricate and lightweight designs, including conformal antenna geometries and complex internal features that would be impossible to produce using traditional methods alone. Subtractive machining then refines these structures, achieving the required dimensional accuracy, smooth surfaces, and tight tolerances needed for aerospace applications. This dual approach ensures both innovation in design and consistency in performance.

3.17.2 In-Situ Monitoring and Adaptive Manufacturing

A critical advancement in hybrid processes is the integration of in-situ monitoring systems that continuously track and adjust the manufacturing process in real time. Equipped with advanced sensors and data analytics, these systems can detect deviations, optimize material deposition, and fine-tune process parameters during production. This adaptability not only improves overall quality and repeatability but also minimizes material waste, reduces production time, and enhances reliability of the final antenna product. For aerospace applications, where performance consistency is non-negotiable, adaptive manufacturing ensures antennas meet stringent safety and operational standards.

3.17.3 Advantages of Hybrid Manufacturing for Aerospace Antennas

By combining additive, subtractive, and adaptive techniques, hybrid manufacturing delivers several advantages for aerospace antenna production, including:

- Greater design flexibility for complex and lightweight structures
- Improved dimensional accuracy and surface quality
- Real-time quality assurance through in-situ monitoring
- Enhanced production efficiency and reduced material waste
- Customization and scalability for diverse aerospace platforms

The specific advantages of hybrid manufacturing processes in aerospace antennas are summarized in Table 22.

Table 22. Advantages of Hybrid Manufacturing for Aerospace Antennas

| Hybrid Process | Advantages | Challenges |
|---------------------|---|---|
| AM + CNC Machining | Improved surface finish, tighter tolerances | Process complexity, cost |
| AM + Electroforming | Enhanced conductivity, reduced weight | Material compatibility, process control |
| In-Situ Monitoring | Real-time quality control, reduced waste | Data management, sensor integration |

3.18 Nanotechnology in Antenna Fabrication

The integration of nanotechnology into antenna fabrication is transforming aerospace systems by enabling unprecedented levels of miniaturization, efficiency, and multifunctionality. By leveraging nanomaterials and nanostructured designs, antennas can achieve superior electrical and electromagnetic properties compared to conventional counterparts, making them ideal for advanced aerospace applications where size, weight, and performance are critical.

3.18.1 Nanomaterials for Enhanced Performance

Nanomaterials such as carbon nanotubes (CNTs) and graphene have remarkable electrical, mechanical, and thermal properties that can significantly improve antenna performance.

- Graphene-based antennas offer ultra-high conductivity, excellent flexibility, and wide tunability, enabling compact, high-frequency designs.
- Carbon nanotube composites provide reduced resistive losses and improved radiation efficiency, especially valuable for lightweight aerospace platforms. By integrating these nanomaterials, antennas achieve improved bandwidth, signal strength, and energy efficiency while maintaining minimal mass and volume.

3.18.2 Nanostructured Surfaces

Nanostructured surfaces involve engineering materials at the nanoscale to precisely control electromagnetic interactions. By designing periodic nanostructures or surface patterns, it becomes possible to manipulate wave propagation, scattering, and absorption in highly controlled ways.

- Plasmonic nanostructures can enhance resonance effects, improving sensitivity and gain.
- Nano-patterned coatings reduce reflection losses and enable multi-band operation.
- Reconfigurable nanostructures allow antennas to adapt dynamically to different operating frequencies and environments.

These advancements open pathways for multifunctional aerospace antennas capable of combining communication, sensing, and stealth features within a single compact device. The specific roles of nanomaterials and nanostructures in aerospace antenna manufacturing are detailed in Table 23.

Table 23. Nanomaterials in Aerospace Antenna Manufacturing

| Nanomaterial | Property | Potential Benefit |
|-------------------------------|-------------------------------------|---|
| Carbon Nanotubes | High conductivity, low weight | Improved efficiency, reduced antenna size |
| Graphene | Extremely thin, flexible | Conformal antennas, wideband performance |
| Nano-engineered Metamaterials | Tailored electromagnetic properties | Enhanced gain, beam steering capabilities |

3.19 Artificial Intelligence in Manufacturing

The integration of Artificial Intelligence (AI) and Machine Learning (ML) into aerospace antenna manufacturing is reshaping the way antennas are designed, fabricated, and validated. By leveraging intelligent algorithms and data-driven decision-making, the industry can achieve higher efficiency, improved precision, and reduced production costs. AI-driven manufacturing not only accelerates innovation but also ensures reliability in highly demanding aerospace environments.

3.19.1 Design Optimization

AI algorithms can evaluate vast design spaces far beyond traditional methods, rapidly identifying antenna geometries that maximize performance metrics such as gain, bandwidth, and efficiency. By incorporating manufacturing constraints directly into the optimization process, AI ensures that proposed designs are not only high-performing but also practical to fabricate. Techniques such as generative design and neural network-based modelling allow engineers to produce innovative antenna architectures tailored for aerospace applications.

3.19.2 Process Control and Quality Assurance

AI and ML play a pivotal role in real-time monitoring and adaptive process control during antenna production.

- Defect prediction and prevention: Machine learning models trained on historical manufacturing data can detect early signs of flaws, reducing rejection rates.
- Parameter optimization: AI systems continuously adjust variables such as temperature, deposition rates, or machining precision to ensure stable quality.
- Automated inspection: Computer vision and ML tools enable fast, accurate defect detection in finished antennas, guaranteeing compliance with aerospace standards.

These capabilities enhance overall production efficiency, minimize waste, and ensure consistent antenna performance. A list of applications of AI in aerospace antenna manufacturing is provided in Table 24.

Table 24. The applications of AI in Aerospace Antenna Manufacturing

| AI Application | Function | Benefit |
|------------------------|--|--|
| Design Optimization | Automated parameter tuning | Improved antenna performance |
| Process Control | Real-time adjustment of manufacturing parameters | Enhanced product consistency |
| Quality Inspection | Automated defect detection | Reduced errors, improved reliability |
| Predictive Maintenance | Anticipating equipment failures | Minimized downtime, increased efficiency |

Figure 5 presents a bubble chart that illustrates the potential impact of emerging technologies on critical antenna performance metrics such as efficiency, bandwidth, adaptability, and reliability. The size of each bubble represents the relative significance of the technology, while its position reflects the degree of improvement expected in specific performance domains.

These emerging trends and future developments highlight the transformative direction of aerospace antenna manufacturing. As innovations such as smart materials, hybrid manufacturing, nanotechnology, and AI-driven design continue to mature, their integration will drive antennas toward unprecedented levels of performance, adaptability, and production efficiency. Collectively, these advancements will play a pivotal role in shaping next-generation aerospace systems, ensuring antennas remain highly reliable, multifunctional, and capable of meeting evolving mission demands.

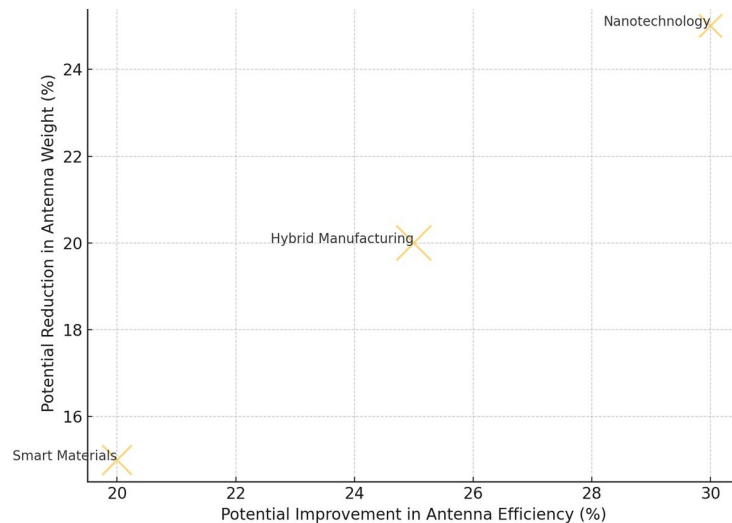


Figure 5. A bubble chart illustrating the potential impact of emerging technologies on key antenna performance metrics.

4. Conclusion and Future Directions

This comprehensive review has highlighted the transformative impact of advanced manufacturing techniques on the design and production of aerospace antennas. As the aerospace sector increasingly demands high-performance, lightweight, and durable components, these cutting-edge methods are proving essential in addressing such challenges. From additive manufacturing and precision machining to innovations in composite materials and structural integration, the manufacturing landscape is evolving rapidly to meet the complex needs of modern aerospace systems.

Key Takeaways

- **Additive Manufacturing** has opened new frontiers in antenna design with its unparalleled geometric freedom and material efficiency.
- **Precision Machining Techniques** are enabling the fabrication of antennas with superior accuracy and surface finish, critical for high-frequency applications.
- **Advanced Composites** are offering an ideal balance of strength, weight, and thermal stability, essential for demanding aerospace environments.
- **Integration and Assembly Innovations** such as conformal and embedded antennas are enhancing system-level performance while optimizing aerodynamics and structural integrity.

Future Outlook

The future of aerospace antenna manufacturing is poised for exciting developments driven by emerging technologies:

- **Smart Materials & Adaptive Antennas:** Materials that respond to environmental stimuli—such as shape memory alloys and piezoelectric elements—are expected to enable dynamically reconfigurable antennas for mission-adaptive performance.
- **Hybrid Manufacturing Approaches:** The fusion of additive and subtractive techniques will allow manufacturers to capitalize on the advantages of both, leading to more efficient and optimized antenna designs.
- **Nanotechnology Integration:** Nanomaterials and nanoscale fabrication methods will enhance conductivity, reduce signal losses, and allow further miniaturization without compromising performance.
- **AI-Driven Manufacturing:** Artificial intelligence and machine learning will increasingly support the optimization of design, quality control, and real-time process monitoring, driving significant gains in manufacturing speed, reliability, and cost-effectiveness.

Implications for the Aerospace Industry

The continued evolution of manufacturing techniques holds profound implications for the aerospace domain:

- Improved antenna performance will enable more reliable communication, navigation, and sensing systems across aviation and space platforms.
- Lighter and more efficient antennas will contribute to reduced fuel consumption and increased payload capacity.
- The ability to fabricate multifunctional, highly integrated antenna structures could pave the way for revolutionary aerospace designs.
- Streamlined and cost-effective manufacturing processes may accelerate innovation and reduce time-to-market for next-generation aerospace systems.

Final Thoughts

As these advanced manufacturing methods continue to mature and converge with emerging technologies, the aerospace industry stands on the cusp of a new era in antenna design and production. The antennas of the future will not only meet the ever-growing demands for performance and efficiency but will also redefine the possibilities of aerospace communication, navigation, and sensing systems.

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