Study on Deployable Antenna Technology in Space

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Abstract. Antennas play a pivotal role in modern communication, navigation, and remote sensing systems. With the development of space antenna, various kinds of deployable antennas have emerged. The deployable antenna can be folded into a small volume, significantly reducing the space and payload requirements for rocket launches. The commonly used techniques are inflatable deployable antennas, umbrella deployable antennas, memory alloy deployable antennas, and so on. Antenna deployment in the space environment, however, presents a unique set of technical challenges due to the harsh conditions of space, including microgravity, extreme temperatures, and radiation. A comprehensive overview of the current three distinct types of deployable antenna technology has been presented in this paper. Their characteristics, advantages, and applications are analyzed. Moreover, this paper also illuminates the numerous difficulties that scientists and engineers encounter while designing and deploying antennas, providing insights into potential directions for future advancement in this area. This paper may offer a reference for the development of deployable antennas.

Keywords: Deployable antenna; inflatable deployable antennas; shape memory alloys.

1. Introduction

Space exploration and communication have become integral parts of the modern world, driving the demand for advanced antenna technologies that can withstand the harsh conditions of space while providing efficient and reliable communication links. Deployable antennas, which can be folded or retracted during launch and then expanded or deployed once in space, have emerged as a key solution to address the challenges of space-based communication systems.

Deployable antennas offer several advantages that make them indispensable in space missions. Firstly, they provide a compact and efficient solution for launching satellites and spacecraft, as they can be stowed in a smaller form factor during launch and then expanded to their full size once in orbit. This reduces the payload size, which is critical for cost-effective space missions. Moreover, deployable antennas can offer greater antenna aperture, allowing for higher gain and improved signal reception or transmission. Additionally, they can enable multi-frequency and multi-beam communication, increasing the versatility and performance of communication systems in space.

Despite these advantages, deploying and implementing deployable antenna technology in space have faced various challenges. As the deployable antenna technology plays a crucial role in enabling efficient communication and data transmission in space missions, this paper aims to provide a comprehensive overview of the current state of this technology. This paper discusses the common challenges faced by deployable antennas in space, such as microgravity, enormous temperatures in space, and radiation. Additionally, this paper outlines the future directions and emerging technologies that hold promise for advancing deployable antenna technology in space, including advances in materials science and robotics.

2. Classification of Deployable Antennas

2.1. Inflatable Deployable Antennas

The development of inflatable reflector antennas has been gradual because of material and manufacturing limitations since the early 1960s. In the 1990s, the emergence of novel materials and methods greatly aided in the quick development of inflatable reflector antennas. The major components of inflatable reflector antennas are flexible materials, such as Mylar or Kevlar sheet coated with chemical resin [1]. The internal inflation is used to inflate the structure to the required location and shape. In contrast to the membrane structures, once the antenna has been inflated to the desired position and form, the film can be toughened by light to preserve the opened configuration while the antenna is illuminated by the sun. At this moment, even if the internal gas leaks, the antenna reflector surface won't lose its accuracy [1].

The most obvious feature of inflatable antennas is their deployment through gas inflation. Inflatables offer a scalable method of physical amplification to make the antenna expand from compact size to full size and shape due to flexible materials. Hence, inflatable antennas can be created in a variety of forms and sizes to fulfill certain mission requirements. This method allows inflatable antennas to be folded or rolled into a small volume, which significantly reduces the space and payload requirements for rocket launches. This compactness is crucial for optimizing launch costs and maximizing the number of antennas that can be deployed on a single mission [2]. Therefore, its unique qualities include low volume requirements for storage, low launch system complexity, simple deployment mechanisms, and the formation of lightweight and large-scale space structures [3].

NASA's experiment with an inflatable antenna with a 14-meter diameter on an airplane was a significant step in the development of inflatable antennas on May 29, 1996. This experiment is known as IAE (Inflatable Antenna Experiment). When the IAE project was first launched in the early 1990s, it was based on the L'Garde concept for a huge, offset, parabolic reflector antenna, and its related technology database [4]. The IAE mission's goal was to evaluate and characterize the mechanical function and performance of a 14-meter-diameter inflatable deployable antenna reflector structure in operational orbit. IAE was set up on the Spartan 207 free flyer platform, and then inflated in orbit [5]. IAE was regarded as one of the best examples of a low-cost technology validation project.

2.2. Deployable Umbrella Antenna

The deployable umbrella antenna design consists of a collapsible umbrella-like structure that can be easily expanded. The antenna's radiating components are the umbrella ribs, and its feedline is the center pole. The antenna looks like a real umbrella. An antenna that emits horn radiation serves as the feed, adequately illuminating the deployable reflector. To hold the ribs firmly, a robust reflector is positioned at the base of the antenna assembly. Only at the hub are the parabolic beams that make up the reflector shape hinged; elsewhere, they simply fold in the direction of the feed structure [6]. An actuator placed at the rigid reflector can produce the movement forces necessary for the mechanisms. The force then can move through the rigid reflector and into the first, second, and then the other beams thanks to connectors. As a result, the connector allows for the force to be transferred from the second and third beams to the other ones, resulting in the mobility of the connections [6]. In the antenna’s stowed or transport configuration, it is folded or collapsed into a compact form, with the reflective surface generally flat or nearly flat. When it is time to deploy the antenna, the actuation mechanism is initiated. This mechanism begins extending the ribs or struts outward from the central hub. As the ribs extend, the reflective surface material attached to the ribs is stretched or curved, conforming to the desired parabolic shape. The curvature is essential for focusing radio waves or other electromagnetic signals. Once fully expanded and shaped into a parabola, the antenna is in its operational state, ready to transmit or receive signals. The parabolic shape allows it to focus signals on the focal point, which may house a feed horn or other radiation source or sensor.

The deployable umbrella antennas have a significant impact on communication and remote sensing. Their portability and ease of deployment make them valuable tools in emergency communication and satellite-based applications. Therefore, the rapid deployment capability and efficient signal reception and transmission functions of the deployable umbrella antenna show application potential in many fields and help promote the development of modern technology. The deployable umbrella antennas excel in scenarios where high gain, frequency versatility, durability, and ease of maintenance are critical. Their adaptability, scalability, and reduced interference capabilities further enhance their utility across a range of communication, radar, and military applications. Therefore, deployable umbrella antennas offer compelling advantages that make them highly suitable for various applications, especially those requiring rapid deployment, mobility, and compactness.

RainCube (Radar in a CubeSat) mission is an excellent example of using a deployable umbrella antenna in the space application. RainCube is a technology demonstration mission developed by NASA to evaluate and validate using a small, lightweight radar instrument for observing precipitation from a CubeSat, a type of miniaturized satellite. The deployable umbrella antenna is a crucial component of this mission. RainCube's primary goal is to demonstrate the feasibility of using advanced radar technology in a CubeSat to observe and study precipitation and cloud dynamics in Earth's atmosphere [7]. The RainCube CubeSat features a compact, deployable umbrella-like antenna called Ka-band deployable radar antenna. This antenna unfolds and extends into a large dish-like structure once the CubeSat is in orbit. RainCube's technology demonstration has implications for weather monitoring and climate research, as it can provide valuable data on precipitation patterns and cloud dynamics, contributing to a better understanding of Earth's water cycle [7].

2.3. Shape Memory Alloy Deployable Antenna

An antenna system known as a memory alloy deployable antenna makes use of shape memory alloys (SMAs) to achieve compact storage and effective deployment in environments like space. SMAs are materials that, in response to a particular stimulus, such as heat or electrical current, may remember a specific shape and return to it. This process is the consequence of a martensitic transformation [8]. These alloys can be employed in antenna design to produce small, easily storable antenna systems that can be swiftly deployed into the desired operating configurations.

Ti-Ni alloy is a commonly used material for the antenna, which is processed into a parabolic antenna in the state of the alloy matrix and then cooled to below the martensite-start-temperature point to produce martensite. Hence, the antenna can be folded and crumpled into small groups and fitted into the satellite since this variety of martensite is easily bent. The alloy wire is heated using heat or solar energy after the satellite enters space orbit. The alloy wire that has been folded into tiny clusters experiences a reverse phase shift, opens entirely, and transforms back into the parabolic antenna shape after the temperature reaches more than the austenite-final temperature [9]. Therefore, the shape memory alloy antenna will alternate between unfolding and folding in response to temperature changes.

In the aerospace field based on complex engineering, SMA deployable antennas are gradually becoming attractive active material candidates through their unique properties. Compared with a system using traditional technology, the SMA component reduces the complexity of the system [10]. SMAs enable compact storage during transportation and efficient deployment in space, making them suitable for applications with size and weight constraints. Consequently, it is possible to implement such structure and actuator integration in a small configuration.

During space deployment, the need for antenna accuracy is very strict, as it is essential for space operations. As the memory alloy can be expanded and folded by temperature changes, its performance can be well controlled and tested before space operations, and its work in space missions can be mastered and rehearsed. Thus, SMA deployable antennas allow for precise control of the deployment process, ensuring the optimization of antenna performance characteristics. SMA is very useful for space applications.

Based on shape memory alloy composite tape and polyimide film, a research team from China designed and created a flexible spatially deployable antenna model with good self-folding and deployable bidirectional form memory effect. A spatially deployable antenna model based on SMA matrix composite strips was designed and fabricated, and the bidirectional shape memory behavior driven by direct temperature and Joule heat can be self-folded and self-deployable. The influence of thickness and circulation characteristics of the SMA strip was also considered in the bidirectional reversible folding development experiment [11]. The results of the research show that as the thickness increases from 6 mm to 10 mm, the development angle of the SMA strip at low temperatures decreases almost linearly from 35.5° to 4° to achieve full development [11]. Subsequently, to validate the bidirectional SME under direct temperature driving, the self-folding process at high temperatures of 110°C and the self-unfolding process at normal temperature were both proven. When compared to a direct temperature drive, a 1-node antenna model based on the Joule heating actuation approach successfully reduced the folding time from 10 minutes to 90 seconds. The design and use of space-deployable antennas can be guided by these experimental results. Additionally, the two-way shape memory effect of reversible self-folding and deployable space deployable antennas enhances the capability to avoid space debris in future applications [11].

3. Challenges and future development

3.1. Challenges of Antenna Deployment in Space

One of the most significant challenges of deploying antennas in space is the absence of gravity. On Earth, antenna structures may be deployed and maintained with the help of gravity. However, in space, antennas must rely on other methods. During deployment, microgravity makes it difficult to manage the movement and stability of antenna elements, thus it is crucial to design systems that can operate well in such circumstances.

Another difficulty is the enormous temperature range in space, which ranges from bitterly cold to sweltering hot. The performance and structural integrity of antenna materials and systems may be impacted by these temperature variations. To assure long-term performance, deployable antennas must be built to tolerate these temperature variations.

In addition, the radiation in space, including solar radiation, cosmic rays, and high-energy particles, may harm antenna components and impair the quality of the signal. The shielding and materials that have been radiation-hardened are crucial in order to protect antennas from these harmful effects.

3.2. Future Development Trends in Deployable Antenna Technology

There are several promising trends in the development of deployable antenna technology. One notable development is the application of new materials, such as lightweight, high-strength materials with outstanding thermal stability and radiation resistance. These substances, which can improve antenna performance and durability in space, include advanced composites, graphene, and carbon nanotubes.

The development of autonomous deployment techniques is another trend. As they can overcome the difficulties of microgravity by applying advanced robotics and artificial intelligence, these mechanisms are essential for maintaining the dependability of space antennas. These devices can decrease the need for human interaction while increasing the precision and speed of antenna deployment. Artificial intelligence (AI) will play a crucial role in monitoring and maintaining the good condition of deployable antennas in space. Algorithms for predictive maintenance can detect potential issues before they become urgent, allowing for quick repairs or modifications. In accordance with current information and mission objectives, AI can also help optimize antenna performance [12].

4. Conclusion

Deployable antennas have become an important tool for communication in space exploration and are constantly being updated and developed. A comprehensive overview of the current three distinct types of deployable antenna technology and their advantages and characteristics have been presented in this paper. The antenna deployment technology faces substantial technological obstacles because of the unique characteristics of the space environment. Nevertheless, innovative possibilities in the works bode well for the future of deployable antenna technology. The future of space-based antenna systems will be shaped using new materials and the integration of artificial intelligence. These developments will not only improve the accuracy and efficiency of remote sensing, communication, and navigation in space but also make more ambitious space exploration missions possible.

References

[1] Duan, B. (2020). Large spaceborne deployable antennas (LSDAs)—A comprehensive summary. Chinese Journal of Electronics, 29(1), 1-15.

[2] D. Anderson et al. (2017). Inflatable Antennas for Small Satellite Missions. Small Satellite Conference.

[3] Mark Schenk, Andrew D. Viquerat, Keith A. Seffen, and Simon D. Guest. (2014). Review of Inflatable Booms for Deployable Space Structures: Packing and Rigidization. Journal of Spacecraft and Rockets.

[4] Geoportal. IAE (Inflatable Antenna Experiment). May 30, 2012.

[5] Wayback Machine. L'Garde Programs - INFLATABLE ANTENNA EXPERIMENT. Oct 15, 2006.Retrieved on September 9, 2023.

[6] Vahid Hasanzade, Seyed Hassan Sedighy, and Majid Shahravi. (2017). Compact Deployable Umbrella Antenna Design with Optimum Communication Properties. Journal of Spacecraft and Rockets Vol. 54, No. 3.

[7] NASA. CRS-9 Cygnus: What’s on Board? Retrieved on September 10, 2023.

[8] E. W. Hurd, J. A. Flint, and I. H. Daniel, Shape-memory alloys in reconfigurable antennas, 2014 Loughborough Antennas and Propagation Conference (LAPC), Loughborough, UK, 2014, pp. 363-367

[9] Clithy, E. (2020). Application of Shape Memory Alloy. Sci Insigt, 33(3),167-174

[10] Hartl, D. J., & Lagoudas, D. C. (2007). Aerospace applications of shape memory alloys. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, 221(4), 535-552

[11] Du, H., Yao, Y., & Zhao, Y. (2022). A space deployable antenna model based on shape memory alloy composite with folding-deploying two-way behavior. Polymers for Advanced Technologies, 33(12), 4214-4222.

[12] Russo, Antonia, and Gianluca Lax. 2022. "Using Artificial Intelligence for Space Challenges: A Survey" *Applied Sciences* 12, no. 10: 5106.