Paradigm Academic Press
Innovation in Science and Technology
ISSN 2788-7030
MAR. 2024 VOL.3, NO.2

Optimization of Deployable Antennas: Material, Structure and Drive Mode

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doi:10.56397/IST.2024.03.08

Abstract

This research investigates the optimisation of deployable antennas by focusing on material selection, structural design, and drive mode. Deployable antennas are crucial for applications such as satellite communication and remote sensing. The study aims to enhance their efficiency and reliability through a comprehensive optimisation approach. A systematic review identifies suitable materials based on mechanical, electrical, and environmental properties. The structural design analysis explores various deployment mechanisms, such as foldable, inflatable, and tensegrity structures. Additionally, the drive mode optimisation examines actuation methods, including motor-driven, shape memory alloy, and piezoelectric systems, assessing their precision, energy consumption, and adaptability. The findings contribute to the development of more efficient, reliable, and versatile deployable antennas, improving the capabilities of communication systems.

Keywords: deployable antennas, material optimization, structural design, drive mode

1. Introduction

In recent years, the demand for deployable antennas has grown significantly due to their versatile applications in various fields, including communication systems, remote sensing, and space exploration (Tan et al., 2022). These antennas are designed to be compact and lightweight during transportation, yet capable of expanding into larger structures to achieve optimal performance once deployed. The optimization of deployable antennas is of paramount importance, as it directly influences their efficiency, reliability, and overall cost (Gibson, 2012). This research project aims to investigate the optimization of deployable antennas, focusing on material selection, structural design, and drive mode.

The study of deployable antennas is worth pursuing due to their growing importance in the era of advanced wireless communication systems and increasing reliance on satellites for various applications. Optimizing these antennas' design and functionality can lead to reduced costs, improved performance, and enhanced durability, thus benefiting a wide array of industries and end-users.

The primary aim of this research project is to analyze and optimize the critical aspects of deployable antennas, including the choice of materials, structural design, and drive mode. This will be achieved through the following objectives:

1) To investigate and evaluate the latest materials and their properties, with an emphasis on lightweight, high-strength, and low-cost materials suitable for deployable antennas.
2) To explore various structural designs and configurations to maximize the efficiency and deployment reliability of the antennas.
3) To study and analyze different drive modes, focusing on their compatibility with the selected materials and structural designs, as well as their impact on the overall performance of the antennas.

To address these objectives, the research project will seek to answer the following key questions:

1) What are the most suitable materials for deployable antennas in terms of weight, strength, and cost, and how do these materials influence the overall performance of the antennas?
2) Which structural designs and configurations provide the best trade-offs between deployment reliability, efficiency, and cost for deployable antennas?
3) How do different drive modes impact the performance of deployable antennas, and what are the most compatible drive modes for the selected materials and structural designs?

This research project will build upon recent studies and advancements in the field of deployable antennas. For instance, Tan et al. (2022) explored the design and optimization of deployable reflect array antennas. Additionally, Gibson (2012) provided valuable insights into the optimization of antenna structures and their performance. By examining the optimization of deployable antennas in terms of material selection, structural design, and drive mode, this research project aims to contribute to the body of knowledge in this field and provide valuable insights for future development and deployment of advanced antenna systems. The findings of this research project could have significant implications for various industries, including aerospace, telecommunications, and satellite-based services, as well as for the broader scientific community.

2. Literature Review

2.1 Introduction

The antenna aperture is generally required to be as large as possible, leading to a contradiction between a large, deployed aperture and a small, furled volume. Achieving this goal requires innovative knot (machine) construction, as well as the study of static and dynamic analysis along with the optimization of design problems in both deployed and furled states (Duan, B., et al., 2020). This Literature Review aims to discuss and evaluate existing research on the feasibility analysis of various postures of novel deployable antenna mechanisms, in order to attain a more ideal antenna caliber while allowing the expandable antenna to have multiple attitudes. The attitude change of expandable antennas is primarily affected by the antenna material, antenna structure, and the driving mode of the antenna; hence, this article will summarize and analyze these three topics.

2.2 Material Considerations

Several studies have explored new materials for expandable antennas in order to address the limitations of traditional designs, such as weight and storage requirements.

2.2.1 Shape Memory Alloys and Polymers

Du, et al. (2022) investigated the use of shape memory materials, including shape memory polymers (SMP) and shape memory alloys (SMA), to reduce the weight of the antenna, storage space, and the load driven by the antenna during expansion. The research found that SMA significantly reduced the antenna’s weight, expansion angle, and folding and expansion time, but practical application remains limited. Dao, et al. (2018) applied shape memory metal to the hinges of traction and supporting antennas, demonstrating its effectiveness in a microgravity environment simulated by an air flotation platform.

2.2.2 Material Comparison and Implications for Research

Both studies demonstrate the potential of shape memory materials in addressing the shortcomings of traditional expandable antennas, but they apply these materials in different ways. Du et al. (2022) focused on the entire antenna, while Dao, et al. (2018) targeted the hinge component. These findings suggest that shape memory alloys could be applied to multiple key parts of antenna design, such as the antenna body and hinge connections, to achieve greater weight reduction and space savings. Additionally, experimental environments should be carefully considered to ensure accuracy and reliability in results.

2.3 Structural Considerations

Researchers have also examined the structures of new expandable antennas to optimize performance and efficiency.

2.3.1 Tetrahedral Module-Based Antennas

Xu, Y et al. (2013) proposed a novel deployable truss antenna composed of tetrahedral modules, using topological methods and “structure-electronic synthesis” to evaluate the electronic and mechanical properties of the antenna. This approach allows for efficient assessment of antenna performance and applicability.

2.3.2 Structural Optimization of Large Expandable Antennas

Liu, R et al. (2018) developed a structural optimization method with a dynamic constraint for maximum stiffness/mass ratio to address constraints caused by various factors, such as insufficient transmitter capacity. The authors used the nonlinear finite element method to create a dynamic model of a large expandable antenna, successfully verifying the feasibility of high-strength, lightweight antenna design.

2.3.3 Deployable Antenna Mechanisms for Synthetic Aperture Radar Satellites

Cao, W et al. (2022) proposed a new deployable antenna mechanism for synthetic aperture radar satellites and analyzed its feasibility through 3D modelling. The authors designed a mechanism with a single degree of freedom, allowing for horizontal translation of the panel without synchronous control, simplifying the drive and enabling scalability for controlling more panels.

2.3.4 Structural Optimization Implications for Research

These studies present various methods for optimizing the structure of deployable antennas, demonstrating the importance of structural design in achieving high performance and efficiency. Future research should explore further combinations of these innovative structures and the potential benefits of integrating multiple approaches, such as combining tetrahedral module-based antennas with dynamic constraint optimization methods. Additionally, researchers should continue investigating the use of advanced optimization techniques, such as the nonlinear finite element method, to improve antenna performance.

2.4 Driving Mode Considerations

The driving mode of deployable antennas is another important factor affecting their attitude change. Several studies have examined different driving modes to enhance the overall functionality and performance of these systems.

2.4.1 Electromechanical Actuators

Zhang, et al. (2019) investigated the use of electromechanical actuators for deployable antennas, focusing on the design and application of a high-precision linear actuator for an offset parabolic antenna. The authors found that the actuator provided accurate and stable positioning, highlighting the potential advantages of using electromechanical actuators in deployable antennas.

2.4.2 Inflatable Structures

Inflatable structures have been proposed as a means of deploying antennas with reduced weight and storage space requirements. Xiao, et al. (2020) explored the use of inflatable technology in deployable antennas, presenting a flexible inflatable helical antenna capable of multiple attitude changes. The authors demonstrated the advantages of this approach, including a reduction in deployment time and increased stability.

2.4.3 Driving Mode Implications for Research

Both electromechanical actuators and inflatable structures show promise as driving modes for deployable antennas, offering unique advantages and potential applications. Researchers should continue to investigate the feasibility and benefits of these driving modes and explore potential combinations with other technologies, such as shape memory materials and optimized structures, to create more efficient, lightweight, and high-performance deployable antennas.

2.5 Conclusion

This Literature Review has examined and evaluated existing research on the feasibility analysis of various postures of novel deployable antenna mechanisms. The material, structural, and driving mode considerations discussed provide valuable insights into the design and optimization of deployable antennas. Future research should continue to explore the potential benefits of combining these technologies and methodologies, as well as developing new materials, structures, and driving modes to improve the performance and functionality of deployable antennas. By addressing the challenges and limitations of current designs, researchers can contribute to the development of more efficient, lightweight, and high-performance antenna systems suitable for a wide range of applications.

2.6 Recommendations for Future Research

Based on the literature review, the following recommendations are proposed for future research on deployable antenna mechanisms:

2.6.1 Material Innovations

Further exploration and development of new materials, such as shape memory alloys and polymers, should be conducted. Researchers should also investigate the potential of nanomaterials and advanced composites for improving the performance, weight, and storage requirements of deployable antennas.

2.6.2 Advanced Structural Designs

Future research should focus on the integration of advanced structural designs, such as combining tetrahedral module-based antennas with dynamic constraint optimization methods. Additionally, exploring other innovative structures, like origami-inspired designs or tensegrity systems, could provide new insights into the development of efficient and high-performance deployable antennas.

2.6.3 Hybrid Driving Modes

The feasibility of combining different driving modes, such as electromechanical actuators and inflatable structures, should be investigated. Hybrid driving modes could potentially enhance the overall functionality and performance of deployable antennas while addressing specific limitations of individual driving modes.

2.6.4 Multidisciplinary Approach

A multidisciplinary approach that incorporates expertise from fields such as materials science, mechanical engineering, and electrical engineering will be crucial to the development of innovative deployable antennas. Collaborative research efforts can lead to breakthroughs in material, structural, and driving mode technologies, ultimately resulting in more efficient, lightweight, and high-performance antenna systems.

2.6.5 Application-Specific Research

Research should also be tailored to the specific requirements and constraints of various applications, such as satellite communications, radar systems, and remote sensing platforms. By focusing on the unique challenges presented by each application, researchers can develop deployable antennas that are better suited to the needs and demands of their intended use cases.

By addressing these recommendations, future research can contribute to the development of more efficient, lightweight, and high-performance deployable antennas, paving the way for advancements in satellite communication, Earth observation, and other critical applications.

2.6.6 Adaptive and Reconfigurable Antennas

Future research should also investigate the development of adaptive and reconfigurable antennas that can adjust their characteristics and performance based on the operational environment and requirements. These antennas could potentially provide greater flexibility, adaptability, and resilience in various applications, such as communications, navigation, and sensing.

2.6.7 Environmental Impact and Sustainability

As environmental concerns become increasingly important, research should consider the environmental impact and sustainability of deployable antennas. This includes investigating materials and manufacturing processes with lower environmental footprints, as well as designs that facilitate recycling or reuse of components at the end of their service life.

2.6.8 Standardization and Interoperability

To facilitate the broader adoption of innovative deployable antennas, future research should explore the development of standardized interfaces and protocols that enable seamless integration with existing systems and platforms. Interoperability will be crucial for ensuring that these new technologies can be widely adopted and utilized across different industries and applications.

2.6.9 Robustness and Reliability

Given the harsh and often unpredictable conditions encountered in space and other demanding environments, research should focus on improving the robustness and reliability of deployable antennas. This includes investigating materials with enhanced resistance to environmental factors, such as radiation, thermal cycling, and micrometeoroid impacts, as well as the development of fault-tolerant designs and self-healing capabilities.

2.6.10 Verification and Validation

Finally, it is essential to develop robust methods for the verification and validation of new deployable antenna designs and technologies. This includes the development of simulation tools, experimental testbeds, and in-situ testing platforms that can accurately assess the performance and functionality of these systems under realistic operational conditions.

By addressing these additional recommendations, future research can help advance the state of the art in deployable antennas, enabling more efficient, resilient, and environmentally responsible systems that can meet the growing demands of space exploration, communication, and Earth observation applications.

3. Methodology

This section outlines the methodology employed in the study of “Optimization of Deployable Antennas: Material, Structure, and Drive Mode.” The research methodology was designed to systematically investigate the various factors influencing the performance and efficiency of deployable antennas. This methodology comprises secondary research, including a comprehensive literature review, data analysis, and synthesis.

3.1 Secondary Research Approach

Secondary research was deemed suitable for addressing the research questions, as it allows for a comprehensive analysis of existing literature and datasets to identify trends, patterns, and advancements in the field of deployable antennas (Booth, A., et al., 2016). By examining the work of various researchers and experts, secondary research provides an effective means of synthesizing current knowledge and identifying areas for further investigation.

Strengths of secondary research include cost-effectiveness, time efficiency, and the ability to leverage a wide range of existing sources to obtain a comprehensive understanding of the topic. Weaknesses include potential biases in the data, limitations in the scope of existing research, and the potential for outdated information (Baltar, et al., 2012). However, by focusing on recent literature (from the past ten years) and critically evaluating the quality of sources, these weaknesses can be mitigated.

3.2 Data Selection

The datasets utilized in this study were derived from peer-reviewed journal articles, conference papers, and technical reports focusing on the optimization of deployable antennas. The strengths of these datasets include their scientific rigor, validation by experts in the field, and their relevance to the research questions. However, these datasets may have limitations in terms of comprehensiveness and the potential for publication bias.

The selection of these datasets was guided by their relevance to the research questions and their ability to provide insights into the material, structural, and drive mode considerations for deployable antennas. This selection process involved searching relevant databases and bibliographic resources, such as IEEE Xplore, Scopus, and Web of Science, using keywords related to deployable antennas, materials, structures, and drive modes. The inclusion criteria for the datasets were their publication within the past ten years and their focus on optimization aspects of deployable antennas.

3.3 Data Analysis Approach

The data analysis approach for this study involved a systematic review and synthesis of the selected datasets. This process included:

1) Extracting relevant information from the datasets, such as material properties, structural designs, and drive modes employed in the optimization of deployable antennas.
2) Identifying patterns, trends, and advancements in the field by comparing and contrasting the findings of different studies.
3) Evaluating the strengths and weaknesses of various materials, structures, and drive modes as identified in the literature.
4) Identifying gaps and areas for further research in the optimization of deployable antennas.

This systematic review approach allowed for a comprehensive and structured analysis of the existing literature, enabling the identification of key insights and recommendations for future research in the field of deployable antennas.

3.4 Conclusion

In conclusion, the secondary research methodology employed in this study provided a rigorous and comprehensive approach to investigating the optimization of deployable antennas, focusing on material, structure, and drive mode considerations. By critically evaluating the strengths and weaknesses of existing research and synthesizing the findings, this methodology enabled the identification of trends, advancements, and areas for further investigation in the field of deployable antennas.

4. Research Findings and Discussion

4.1 Material (SMPC Hinge) Test

Smart materials have become ubiquitous in science and technology applications, enabling the development of smart structures, systems, and devices. In aerospace engineering, they are crucial in the design of telescopes, solar panels, and antennas for unmanned space exploration.

4.1.1 Introduction

Modern space applications demand advanced and intricate designs that are lightweight and flexible, prompting the development of new technologies. SMPC materials are ideal for meeting these requirements as they provide both functionality and flexibility.

A durable and shape-recoverable SMPC hinge was created using a two-sided carpenter’s tape composed of four plies of carbon-epoxy fabric and polyurethane-based SMP. The hinge utilized a gap between two sides of the tape to induce a pop-up effect.

4.1.2 Test Result of SMPC Hinge

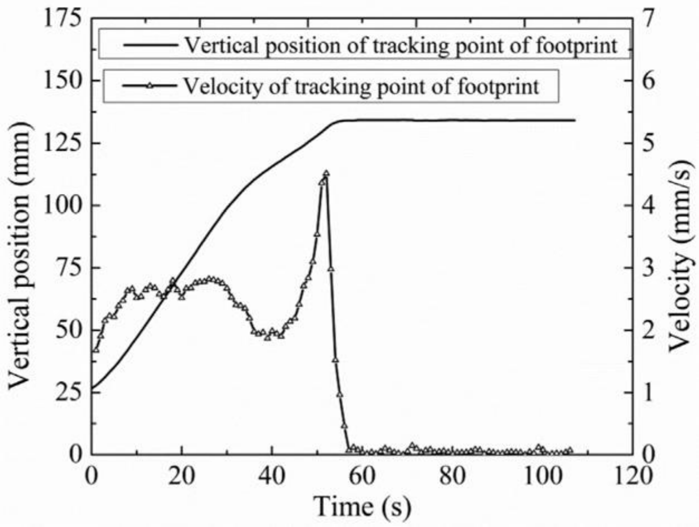

Figure 1. Vertical position and velocity of the tracking point embedded in the moving footprint. (Dao, et al., 2018)

Figure 20 demonstrates the vertical position and velocity of a tracking point on the moving footprint during recovery. The velocity remains constant at 2.5 mm/s for the first 40 seconds before significantly increasing and reaching a peak of 4.51 mm/s at 52 seconds. This is due to the SMPC hinge's special tape design, which results in a "pop-up" phenomenon when the curved shape becomes flat, and releases stored energy. After this, the velocity decreases to 0, and the hinge approaches full deployment, stabilizing the vertical position of the tracking point from 60 to 107 seconds.

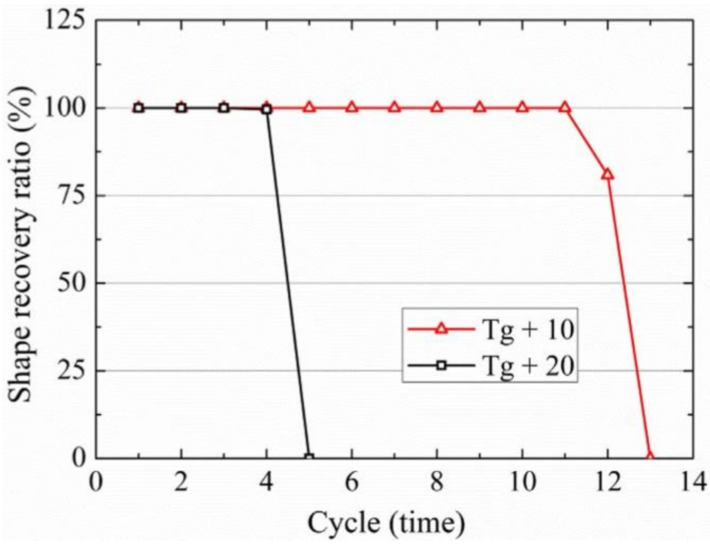

Figure 2. Shape recovery ratio versus the folding cycle of the SMPC hinge at T_g+10 and T_g+20. (Dao, et al., 2018)

In Figure 2, the shape recovery ratio of the SMPC hinge is shown versus the folding cycle at Tg+10 (80.9°C) and Tg+20 (90.9°C). The SMPC hinge had a recovery ratio of approximately 100% for 11 cycles at Tg+10 but only 4 cycles at Tg+20 due to the curing of the epoxy resin at that temperature. Cured epoxy increased stiffness and brittleness, making the tapes brittle and hard to bend, resulting in increased damage. However, the recovery ratio remained at approximately 100% for four cycles.

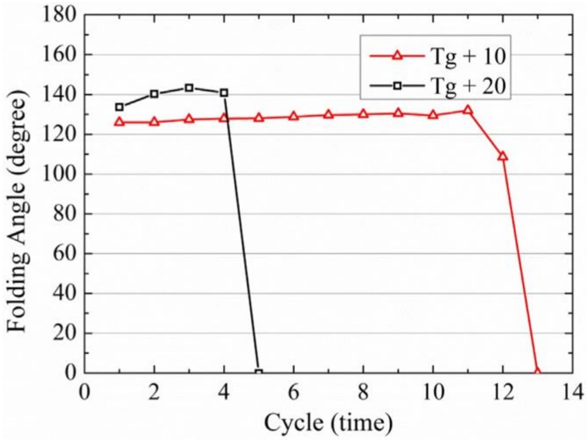

Figure 3. Folding angle versus the number of cycles for the SMPC hinges at Tg+10 and Tg+20. (Dao, et al., 2018)

Figure 3 shows the folding angle versus the folding cycles of the SMPC hinge at Tg+10 and Tg+20. The Tg+20 case had a larger folding angle due to the complete release of stress inside the tape layers. Additionally, the folding angle slightly increased with the folding cycle, likely due to surface damage that made the hinge easier to fold.

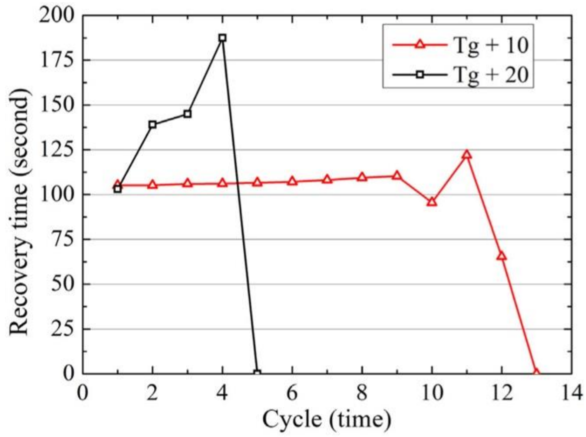

Figure 4. Recovery time versus number of cycles of the SMPC hinges at T_g+10 and T_g+20. (Dao, et al., 2018)

Figure 4 displays the recovery time versus the number of cycles of the SMPC hinge at Tg+10 and Tg+20. The recovery time increased with the number of cycles and was more significant for the Tg+20 case due to cured epoxy resin, resulting in increased brittleness and decreased energy storage. This affected both durability and recovery time. Additionally, the rubbery SMP resin could not withstand external force, leading to a significant increase in recovery time through the test.

4.1.3 Discussion

The optimal operating temperature for an SMPC hinge in real applications, such as antenna deployment, varies depending on the specific use case. For installation in a spacecraft, Tg+20 is preferable to Tg+10 as it allows for a larger folding angle, saving space and making the system more compact. However, if durability and recovery time are important, Tg+10 is recommended.

This test successfully fabricated and tested SMPC hinges using a combination of carbon-epoxy composite, MP5510, and epoxy resins. The procedure was detailed, and the hinges were tested at Tg+10 and Tg+20. Results showed excellent shape recovery ratios and durability, with the operating temperature dependent on specific application needs. Additionally, we carefully observed and investigated damage to the hinges, revealing their characteristics and causes. Overall, the SMPC hinge is a promising candidate for spacecraft antenna use.

4.2 Structure Optimization

4.2.1 Introduction

Deployable structures need to have a high natural frequency to achieve stiffness and avoid resonance. Structural parameters greatly affect dynamics performance, but the structure's mass is limited by launcher capability. Therefore, optimization should maximize natural frequency and stiffness and minimize mass. A genetic algorithm is used to solve the optimization model efficiently. The optimized parameters can be used for pre-tension optimization of tensioned cables (R. Liu, et al., 2017). The iterative process continues until the antenna system design requirements are met.

4.2.2 Test Result and Discussion

Optimized beams with fixed constraints have the largest diameters. The upper beam connected to the constraint point can be optimized as a single design variable to further reduce the overall mass of Model 2 in figure 5. An improved Model 2 shows in figure 6 is developed with the constraint upper beam diameter d6 as a new design variable.

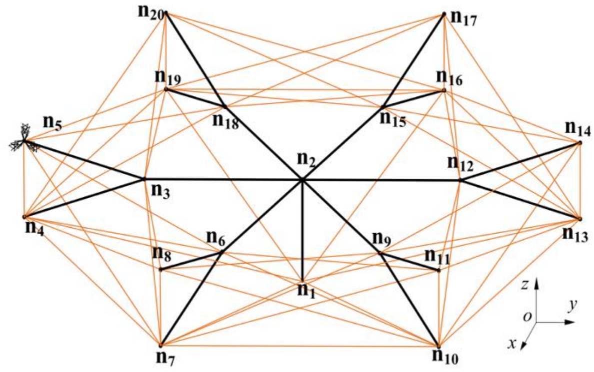

Figure 5. Model 2 of cable-rib tension deployable structure. (Liu, et al., 2018)

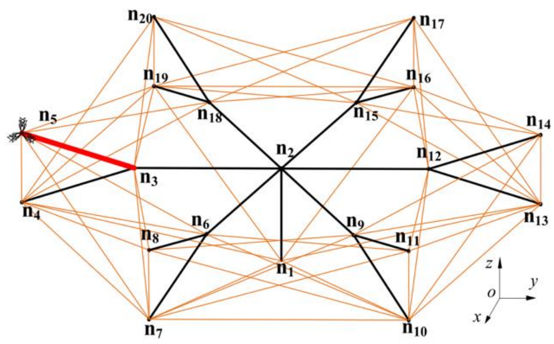

Figure 6. Improved Model 2 of cable-rib tension deployable structure. (Liu, et al., 2018)

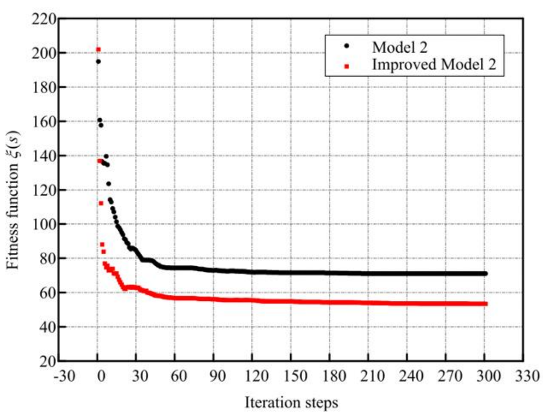

Figure 7. Comparison of convergence curves of Model 2 and improved Model 2. (Liu, et al., 2018)

Improved Model 2's structural parameters are optimized after 300 iterations of 50 populations within approximately 21 min and 57 s. Result shows in figure 7. The convergence rate of the optimization procedure is higher than that of the original Model 2, and eventually converges to 53.40. The fitness function value of the improved Model 2 is better than that of Model 2 (70.98), indicating better performance.

Table 1: Parameter optimization results for Model 2 and improved Model 2. The addition of the constraint beam as an independent variable resulted in better optimization results for the improved Model 2, with a 20% reduction in total mass and 6% increase in frequency.

Table 2 demonstrates that the optimization method successfully increased the natural frequency by 57% and decreased the total weight by 23%, enabling a lightweight design for large-scale cable-beam structures with stiffness constraints.

Table 1. Parameter optimization results of Model 2 and improved Model 2. (Liu, et al., 2018)

Items	d_1 (mm)	d_2 (mm)	d_3 (mm)	d_4 (mm)	d_5 (mm)	d_6 (mm)	t_i(mm)	f_1 (Hz)	W(kg)
Model 2	52.9	63.9	148.8	61.1	1.8	–	1.1	0.83	58.91
Improved Model 2	65.2	60.5	68.0	69.3	1.8	142.2	1.08	0.88	46.99

Table 2. Initial design and optimum results. (Liu, et al., 2018)

Items	Initial value	Optimum value	Improvement (%)
Natural frequency (Hz)	0.56	0.88	57
Structural weight (kg)	61.17	46.99	23

4.3 Drive Mode Optimization

This paper presents two driving modes for space ring deployable mechanism: cable-driven, which is called driving mode 1, and torsion spring driven, which is called driving mode 2. No matter which kind of driving mode, synchronous deployment is ensured for each unit through double crank-slider mechanisms and slider synchronous cable system on the vertical support rod for a single module.

4.3.1 Result and Conclusion of Two Drive Modes Test

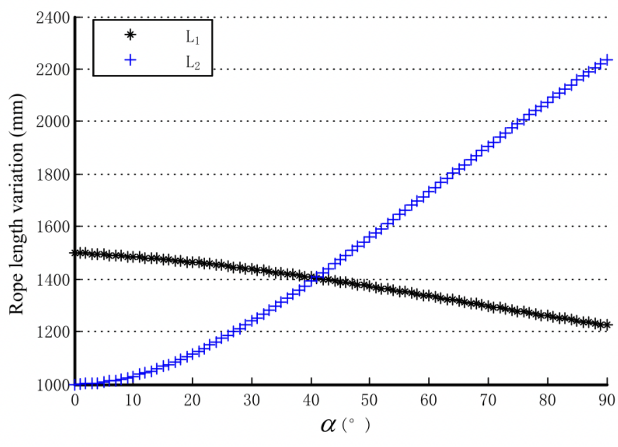

Figure 8. Tendencies of cable length with change of deployment angle. (Qi, et al., 2016)

The variation tendencies of cable length with the change of deployment angle under two kinds of drive modes were studied, which shows in figure 8. It was found that the cable length L1 slowly decreased with the change of the angle α from 0◦ to 90◦, which indicates that the cable is tightening. However, the cable length L2 was fast increased, indicating that the cable is released. For the same geometry parameters of the mechanism, the range of cable length variation in driving mode 1 was much smaller than driving mode 2. This is because the slide block movement range is small in cable-driven mode, but the motor drive torque is bigger. On the other hand, the release cable is longer in torsion spring driven mode, but the motor drive torque is small and does less work.

In conclusion, each driving mode has its merits. Cable-driven mode is suitable for situations where high torque is needed, while torsion spring driven mode is suitable for situations where low torque is sufficient and energy consumption needs to be minimized. The selection of the appropriate driving mode depends on the specific requirements of the mechanism and the available resources.

5. Conclusion/Recommendations

In conclusion, the present study has explored various aspects of the optimization of deployable antennas, focusing on material, structure, and driving mode. Through a comprehensive analysis of the current state of research, this study has identified key advancements and opportunities in each area, which can potentially contribute to the development of more efficient, lightweight, and high-performance deployable antennas suitable for a wide range of applications such as satellite communications, radar systems, and remote sensing platforms.

Material innovations, particularly the use of shape memory alloys and polymers, have shown promising potential in enhancing the performance of deployable antennas by providing self-deploying capabilities and improving structural efficiency (Margoy, et al., 2021). The exploration of nanomaterials and advanced composites can further expand the range of materials suitable for deployable antenna applications, offering potential improvements in weight and storage requirements. Advanced structural designs, such as tetrahedral module-based antennas and origami-inspired structures, have demonstrated their potential in optimizing deployable antenna systems (Meng, et al., 2022). Further research into innovative structures, including tensegrity systems and the integration of dynamic constraint optimization methods, can lead to new insights and breakthroughs in the development of efficient and high-performance deployable antennas. In terms of driving modes, electromechanical actuators and inflatable structures have been found to offer unique advantages and potential applications in deployable antennas. The feasibility of combining different driving modes, such as hybrid systems, should be investigated further to enhance the overall functionality and performance of deployable antennas while addressing specific limitations of individual driving modes.

To ensure continued progress in the field, a multidisciplinary approach that incorporates expertise from materials science, mechanical engineering, and electrical engineering will be crucial. Collaborative research efforts can lead to breakthroughs in material, structural, and driving mode technologies, ultimately resulting in more efficient, lightweight, and high-performance antenna systems.

Additionally, future research should be tailored to the specific requirements and constraints of various applications. By focusing on the unique challenges presented by each application, researchers can develop deployable antennas that are better suited to the needs and demands of their intended use cases.

Considering the findings of this study, the following recommendations are proposed for future research:

1) Continue exploring and developing new materials, including nanomaterials and advanced composites, for use in deployable antennas.
2) Investigate the potential of integrating advanced structural designs, such as tensegrity systems and dynamic constraint optimization methods, to enhance deployable antenna performance.
3) Examine the feasibility of hybrid driving modes, combining electromechanical actuators and inflatable structures, to improve overall functionality and performance.
4) Foster a multidisciplinary approach, incorporating expertise from various fields, to accelerate innovation in deployable antenna technologies.
5) Focus research on application-specific challenges and requirements to ensure that deployable antennas are optimized for their intended use cases.

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