Chapter 7

SUMMARY AND PERSPECTIVES

7.1 Summary

This thesis has presented an in-depth exploration of mesh reflector design and simulation for In-Space Assembly (ISA). It has introduced a generalized design method to evaluate key performance measures, including mass, stowed volume, and natural frequency. A two-dimensional finite element model has been developed to predict the kinematics of large ring-like structures with a prestressed cable interior, assembled by a stationary robot.

The first part of the thesis has presented a rapid design approach for deployable mesh reflector antennas, based on the advanced AstroMesh architecture. It targets key metrics—mass, stowed volume, and natural frequency—for reflectors up to 200 meters in diameter, with focal length-to-aperture (F/D) ratios of 0.5, 0.7, and 1.0, at an operational radio frequency of 10 GHz and adhering to a surface accuracy requirement of 0.6 mm. The study has emphasized that optimizing prestress distribution and reducing cable net tension requirements can lead to much lower structural mass. Analytical scaling laws reveal that stowed volume, rather than mass, is the primary constraint for deployable mesh reflectors, supporting feasibility for launch diameters up to 70 - 100 meters with commercial launch vehicles. Additionally, a high-fidelity model and a semi-analytical model have been introduced for estimating fundamental natural frequencies of reflectors, the latter offering computational efficiency and validity for all F/D ratios.

The next part of the study has explored the design and feasibility of mesh reflectors for ISA, emphasizing their stowage in current launch vehicles. Building on the previously developed generalized design method, the research has examined reflectors up to 200 meters in diameter and introduces a novel ISA concept featuring a stationary robotic assembly facility. This facility, which remains compact during launch, assembles a perimeter truss in space by sequentially adding unit cells and attaching boundary nodes. The ISA method, leveraging the AstroMesh reflector architecture, minimizes launch envelope requirements and offers substantial benefits over traditional deployable designs. The truss builder's straightforward and scalable robotic operations provide a viable solution for constructing large, complex structures essential for future space missions, including high-resolution imaging and advanced communications.

A two-dimensional finite element model has been introduced for predicting the kinematics of large ring-like structures with a prestressed cable interior during assembly. This model, implemented in ABAQUS/CAE, refines the proposed ISA concept by simulating a six-sided perimeter truss with a simple cable net, focusing on improving computational efficiency and accuracy. The simulation uses a dynamic time integration to capture the assembly process, including the sequential addition of truss bays and cable net attachment, revealing successful achievement of the desired regular hexagon shape for various assembly plate orientations. Sensitivity studies of the damping coefficients indicated minimal impact on cable extension variations, with lowest coefficients that ensure stability chosen for the study. The results emphasize the need for precise planning and simulation to achieve stable final structures in space.

This numerical simulation setup lays the groundwork for improving assembly efficiency and robustness of the stationary robot. The thesis focused on a twelve-sided truss structure with a complex internal cable network to understand its nonsymmetric deployment in space. The study examines how assembly sequences, assembly plate orientation (notably $\theta = 60^\circ$), and prestressed cable management affect the stability and desired final configuration. Key findings highlighted the need for precise prestressing and careful sequencing to prevent disruptions and emphasize the importance of an accurate cable stiffness model to meet design specifications. These insights are crucial for optimizing autonomous assembly systems and enhancing the precision and efficiency of large-scale space structures.

A lab-scale prototype developed to validate the ISA concept features a twelve-sided perimeter truss and a 1.4-meter diameter. Designed and tested by a team at the Caltech Space Structures Lab, the prototype has confirmed the ISA concept and verified the simulation approach. Experiments demonstrated that large, high-precision ring-like structures can be assembled in space using the proposed robotic system. Successful assembly, especially with a 60° plate orientation, confirmed the qualitative predictions and highlighted the need for angle stops together with the minimal interference gravity offload system to ensure accurate predictions. The simulation techniques provide a solid foundation for identifying key design considerations crucial for scaling to full-sized applications and future space missions.

Overall, this research has advanced the design and deployment of large structures in space, with significant implications for the future of space construction, potentially leading to new space habitats, satellite systems, and critical infrastructure necessary for extended space missions.

7.2 Future work

This thesis established the foundational background for designing mesh reflectors, introduced an ISA concept to address current limitations, and developed simulation techniques for evaluating the proposed concept and ISA of other large, ring-like structures with a prestressed cable interior.

There are at least three significant research directions that stem directly from the findings of this thesis. First, minimizing the cable element tension requirement through alternative reflective surfaces such as corrugated Kapton films to reduce structural mass, and shifting from magnet-based assembly systems to mechanical latches to resolve performance issues in space. Second, developing strategies to optimize the packaging of components and the assembly facility to accommodate increasingly large structures. Third, improving the accuracy of two-dimensional simulation techniques by incorporating out-of-plane deformations, comparing quantitative simulation predictions with experimental data, and ensuring that the model effectively captures mass and stiffness properties of the structure.

As described in Chapter 2, the minimum tension requirement of cable elements is driven by the length of the cable elements, and the biaxial prestress of the reflective metallic mesh. This thesis explored methods to shorten cable elements, but current metallic meshes necessitate high biaxial prestress. Reducing this prestress is essential for decreasing the load on the perimeter truss, which can lead to smaller component sizes, enhancing mass and volume efficiency. In collaboration with the Bargatin Group at the University of Pennsylvania, alternative reflective surfaces are being investigated, including perforated Kapton films with an aluminized side for enhanced reflectivity, see Fig. 7.1(a). These materials have shown the potential to achieve lower prestress levels of about 0.1 - 0.2 N/m—approximately a $1/50$ reduction—while significantly reducing the structural mass without sacrificing performance. Figure 7.1(b) shows that as biaxial prestress decreases, the mass of a 200-meter diameter structure is significantly reduced, decreasing from about 11,000 kg to approximately 2,200 kg. Future work will involve exploring the integration of perforated Kapton films with the cable net, focusing on their attachment methods and performance to ensure that the structural efficiency and reflectivity of the system meets design specifications.

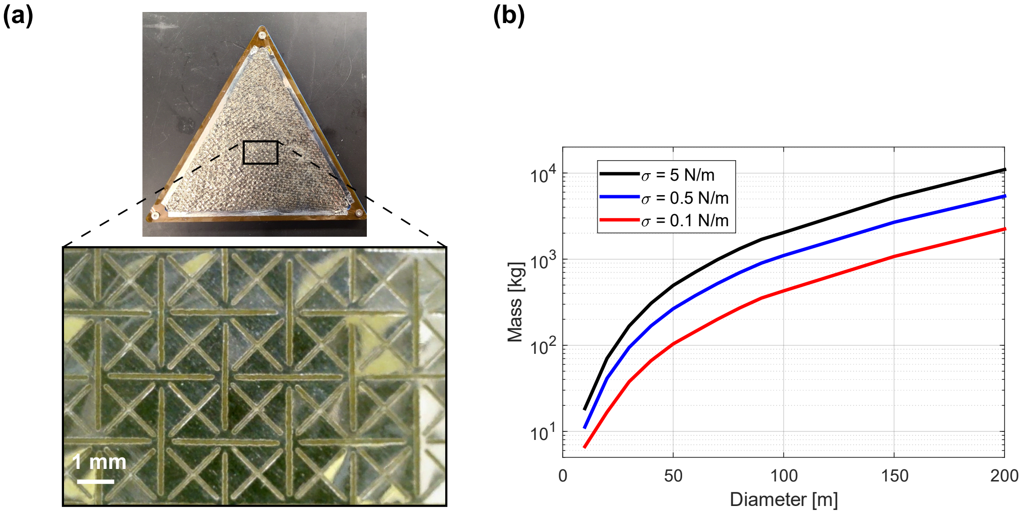

Figure 7.1: Perforated Kapton films, 25.4 μm thick, with a 100 nm aluminized coating on one side for reflectivity: a) a single facet of cable net, with a magnified view of the perforation, patterned using a CO_2 laser, and b) achievable reduction of mass with lowered biaxial prestress, σ for $F/D = 1.0$.

The current assembly system uses permanent and electromagnets for securing and releasing components. However, permanent magnets pose several challenges in space, including risks of radiation-induced and thermal demagnetization [68], [69], oxidation in Low Earth Orbit (LEO) [70], and brittleness that can lead to fracturing [71]. These issues necessitate protective measures such as Alodine-coated aluminum shielding and encapsulation with thermal epoxy to ensure mechanical bonding and thermal conductivity. To address these challenges, the design should evolve to potentially eliminate magnets altogether. Instead, mechanical latches could be used for part handling and assembly mechanisms. If magnets are retained, they must undergo rigorous qualification tests, including thermal vacuum cycling, vibration, shock testing, and CTE mismatch analysis.

As structures increase in size, the ISA concept will require a more efficient packaging scheme to accommodate the growing number of struts and joints within the truss builder. This includes optimizing the stowage configuration to compactly store all components during launch and deploy them efficiently in space. Future advancements could integrate deployable booms as struts and utilize in-space manufacturing techniques, such as additive manufacturing [72], to construct and connect components (see Fig. 7.2). An additional crucial development is the stowage of the truss builder itself. Strut length dictates bay size, directly impacting the overall dimensions of the truss builder. For example, at $D = 100$ m, the truss builder size would expand to around $6 \times 6 \times 14$ m^3, reaching the capacity of current commercial launch vehicles. Therefore, it is essential to devise an efficient method for folding and deploying the truss builder, ensuring that the components and assembly mechanisms remain intact throughout the process.

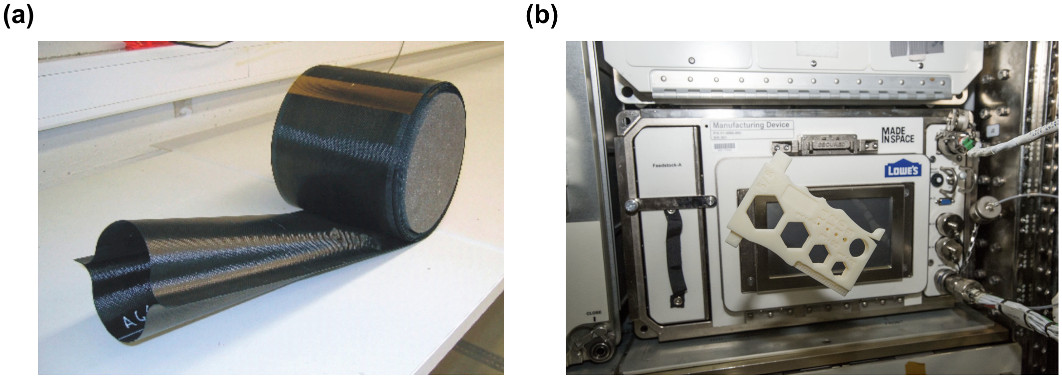

Figure 7.2: Potential enhancements to improve packaging efficiency: (a) deployable coilable Omega boom [73], and (b) additive manufacturing of components in space [74].

The accuracy of the two-dimensional model's quantitative predictions must be evaluated, particularly in capturing assembly process effects that may require a three-dimensional model. To achieve this, the simulation should be expanded to account for out-of-plane deformations, such as misalignments between the top and bottom rings of the perimeter truss. Comparing the two-dimensional and three-dimensional simulation approaches with experimental results will help ensure whether such effects are minimal and further validate the reliability of the two-dimensional model. Moreover, analyzing the natural frequencies of the intermediate polygonal structures—which lack stiffness due to absence of prestress—is crucial if assembly time scales are longer than the vibration periods, as unaddressed vibrations could affect the continuity and accuracy of the assembly process. Future adaptations could also include a three-dimensional model to measure the accuracy of the cable net's paraboloid surface at the end of assembly. This can be a direct extension of the two-dimensional model and therefore more computationally efficient than a high-fidelity model.

This thesis presented a solution space for assembling ring-like structures with a stationary robot. However, continued research is required to optimize various design elements of the proposed ISA concept, including the orientations of the assembly plate and methods for prestressing. Identifying configurations that minimize distortions while maintaining stability and precision will be crucial for improving the feasibility of space-based structures, particularly for future missions that require large apertures.

7.3 Perspectives

The proposed ISA concept marks a pivotal shift in the design and construction of large-scale space structures. Utilizing a stationary robot for scalable, simple, and repetitive operations, this concept offers a versatile approach to assembling extensive space infrastructure, paving the way for groundbreaking advancements in space exploration and technology.

The core innovation of ISA lies in its departure from traditional deployable systems, which often face limitations in scalability and complexity due to constraints imposed by the launch vehicle's payload envelope. This paradigm shift is particularly significant for missions requiring vast infrastructure, such as space-based solar power systems, where large solar arrays could be assembled in orbit. Such applications not only advance space exploration but also hold promise for sustainable energy solutions on Earth.

This research renews interest in ISA by addressing technical challenges and exploring modular assembly techniques that have the potential to revolutionize the construction of space-based structures. The successful demonstration of the ISA concept through lab-scale prototype testing has validated the assembly process for reflectors using stationary robotic systems, demonstrating the potential of ISA to revolutionize large space-based infrastructure assembly and providing a robust foundation for future developments.

The transformative impact of this research extends well beyond technical feasibility, offering a new perspective on space construction and expanding possibilities for future space missions. Structures assembled using ISA could significantly improve imaging and communication technologies, enabling pioneering discoveries and a deeper understanding of our solar system and the universe. This advancement underscores the importance of continued research and development in this field.

AN ILLUSTRATION OF ISA REFLECTORS: CAN E.T. “PHONE HOME” AFTER ALL?