Chapter 1

LARGE STRUCTURES IN SPACE

1.1 In-Space Assembly: A Strategy for Launching Large Space Structures?

The growing demand for advanced space missions is driving the need for larger and more complex space structures. Historically, construction of large space structures has relied on deployable systems housed within a single launch vehicle. This method has been successfully employed in missions involving structures typically ranging from 10 to 20 meters in size [1]–[4], as shown in Fig. 1.1. However, on-orbit deployment poses significant challenges, primarily due to intricate mechanisms required, increasing the risk of failure and impacting mission reliability [5], [6]. Substantial portions of engineering costs and launch mass are allocated to ensuring the structure's survival during launch. As component sizes increase, these costs escalate further, driven by the complex folding mechanisms and the extensive testing needed to guarantee successful deployment. Additionally, the size of these structures is limited by the mass, volume, and stress constraints imposed by launch vehicles, as exemplified by the James Webb Space Telescope (JWST) and its 6.5-meter primary mirror, which likely represents the largest aperture achievable for single-launch telescopes [7], [8].

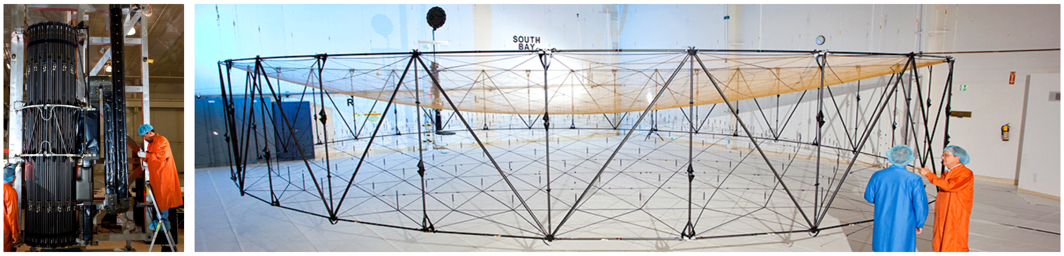
On-orbit assembly, as demonstrated by the construction of the International Space Station (ISS) using separately launched large modules, offers a promising approach to overcoming payload constraints in space missions [9], [10]. In-space assembly

(ISA) maximizes the use of a launcher's fairing capacity, enabling the construction of very large structures. This capability is especially vital for the development of large space telescopes, a key objective in space exploration, as scientists have long sought to deploy large optical systems in space with primary mirrors exceeding 10 meters in diameter. Several concepts for such telescopes have been proposed, including a scalable 30-meter space observatory operating across ultraviolet, optical, and near-infrared wavelengths [11], and a 10-meter ultraviolet-optical telescope [12], both intended to be assembled robotically in space. In the 1990s, NASA determined that deploying a 25-meter telescope mirror through mechanical means was impractical due to inefficient packaging, concluding that an erectable mirror assembled in orbit by astronauts or robotic systems would be more feasible [13].

Stowed configuration

Deployed configuration (primary mirror)

(a)



Stowed configuration

Deployed configuration

(b)

Figure 1.1: State-of-the-art deployable structures: (a) JWST (NASA, 2016) and (b) AstroMesh deployable mesh reflector (Northrop Grumman, 1999)

Extensive research into support structures for space telescopes and reflectors has highlighted the benefits of using trusses, leading to significant progress in lightweight space truss design [14], [15] (see Fig. 1.2). This research includes early designs for large, high-precision segmented reflectors [16] and a doubly-curved truss structure that was designed, fabricated, and validated for its exceptional surface precision, stiffness, and strength [17]. However, assembling trusses with large areas or spans requires a substantially greater number of lightweight truss elements, necessitating careful consideration of several key design factors [18]–[20]. These factors include the modular design of structural components to enable easy integration while maintaining sufficient stiffness when assembled, the efficient packaging and delivery of components to the target orbit, and efficient ISA concepts to achieve the desired functional configuration of the structure.

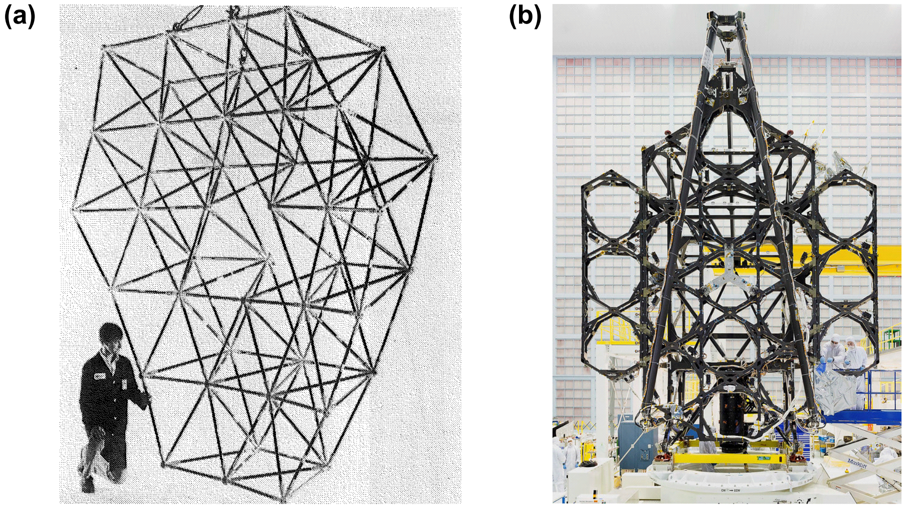


Figure 1.2: Lightweight trusses as support structures: (a) erectable 4-meter tetrahedral truss [17] and (b) JWST support structure (NASA, 2015)

1.2 Robotic Autonomous Assembly

There is a growing shift towards autonomous robotic systems in assembly, replacing traditional methods. Extra-Vehicular Activity (EVA)-based structural assembly culminated in a 14-meter diameter doubly-curved telescope truss experiment [21]–[23]. This study underscored several crucial lessons, such as the need for simple, repetitive construction tasks, the benefit of using movable work platforms, and the distribution of tasks to minimize worker fatigue. It also highlighted the importance of storing components near the crew for quick access and efficient assembly, while recognizing the limitations of manual assembly as the size of the structure increases. Manual assembly becomes impractical for large structures, necessitating the shift to centralized, autonomous assembly methods utilizing robotic systems.

In the manufacturing industry, the use of assembly robots is a well-established practice, where robots have become integral, excelling in precise, repetitive tasks that ensure efficient, high-quality product assembly and enable rapid production. However, applying robotics to construction, particularly in difficult environments such as hazardous or remote locations, has not progressed as rapidly, with only a few feasible short-term solutions available [24]–[27].

Numerous innovative structural concepts and system architectures have been developed to facilitate the autonomous ISA of large, functional structures [28]–[30]. These advancements are paralleled by the growing adoption of collective and traversing robotic assembly methods, as shown in Fig. 1.3. Noteworthy examples include the assembly of cubic truss structures by multiple aerial robots [31], a coordinated multi-robot system for assembling furniture [32] and termite-inspired climbing robots [33]. However, the use of multiple robots for assembly of structures introduces several intricate challenges, akin to those faced in EVA experiments. These challenges include ensuring seamless coordination and communication among robots to prevent interference, optimizing task distribution to enhance productivity, and managing workspace constraints to avoid collisions and provide adequate operational space (see Fig. 1.3(a-c)). Additionally, the setup and maintenance of multi-robot systems are inherently complex, often resulting in heavier robots that must be supported by the stiffness of the structure. As the structure grows larger, scalable communication and coordination become increasingly critical, and traversals become significantly longer and more time-consuming. As the complexity of autonomously assembling large trusses grows, so does the risk of encountering single points of failure that could disrupt or halt the entire process. Therefore, simplifying system architecture and operations in the autonomous assembly of large trusses is essential.

Streamlining processes and reducing reliance on complex subsystems improve reliability and operational robustness while preserving the advantages of autonomous assembly. Jenett and Cheung [34] aimed to simplify truss assembly by developing inchworm-inspired bipedal “Relative Robots” (see Fig. 1.3(d-f)). These robots are designed to interact with their structured environment, using the modular three-dimensional lattice they are constructing as support. As they traverse the lattice, they manipulate and transport the building blocks needed for assembly. While this concept comes closest to the idea of ‘Space Legos’ by using identical robots and modular building blocks, simplifying control mechanisms and enhancing reliability through fault-tolerant connections, it still relies on coordinating multiple robots. Strengthening the reliability of large truss assembly and advancing autonomous construction capabilities in space and other challenging environments remain key goals.

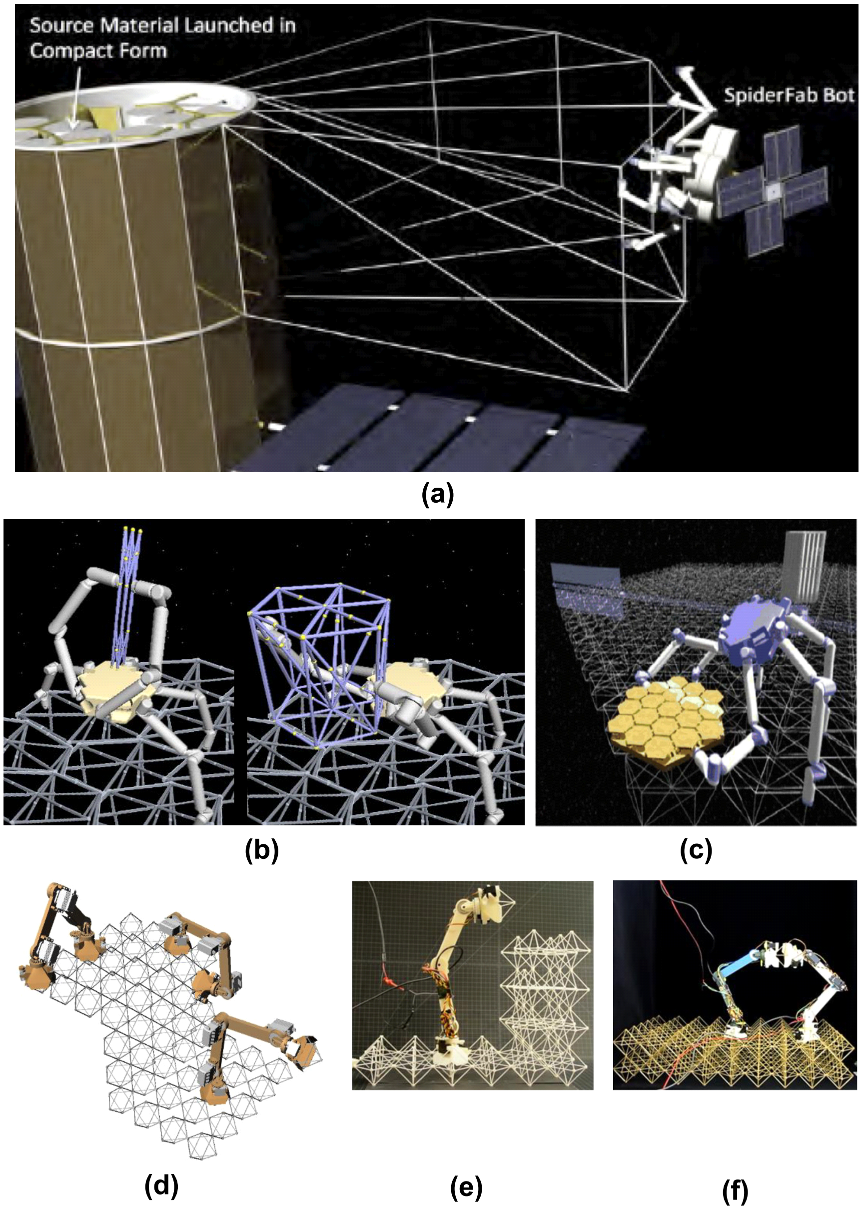


Figure 1.3: Advancements in robotic assembly: (a) SpiderFab robot constructing a support structure for functional elements [9], Robot-Assembled Modular Space Telescope (RAMST) architecture [29]: dexterous hexbot (b) deploying and assembling truss and (c) traversing and assembling mirror module and BILL-E: robotic platform [34]: identical bipedal robots (d) using the truss as support for traversing, (e) placing and (f) moving identical truss modules.

1.3 Reflector Antennas

Large reflector antennas have garnered significant interest for space missions due to their requirement for high resolution and bandwidth in communication and imaging, with commercial systems available from companies such as Astro Aerospace Northrop Grumman, L3 Harris, and Tendeg. Mesh reflectors were selected as the primary structure of interest for the research described in this thesis, guided and supported by funding from the DARPA NOM4D (pronounced “NOMAD”) program [10].

Early designs for deployable reflectors, such as the umbrella-type with metallic wire mesh stretched over parabolic ribs [35], and the wrap-rib type where thin shell elastic ribs with a parabolic edge profile were wound around a central hub mechanism [36], achieved compact stowage but struggled to deliver high surface accuracy for larger apertures. To address these challenges, a concept with a faceted reflective surface [37], [38] emerged, utilizing triangular mesh facets on a prestressed cable net to form a tension truss (see Fig. 1.4(a)). This innovation led to the development of the *AstroMesh* reflector by Hedgepeth and Thomson [39], [40], which features two doubly curved cable nets tensioned across a deployable perimeter truss (see Fig. 1.4(b)). This design has proven effective in achieving superior surface accuracy, mass efficiency, and packaged volume, leading to its adoption for a variety of space missions with diameters ranging from 3 to 25 meters [41]–[43]. It has become a widely accepted standard for deployable mesh reflectors, inspiring numerous adaptations of the original design by Hedgepeth and Thomson [44], [45].

Most of the existing research on deployable mesh reflectors has primarily targeted radio frequency (RF) efficiency improvements, leaving the relationship between aperture size, focal length, and the practical aspects of mass and stowed volume underexplored. This gap is particularly evident in system-level studies, where understanding these dependencies is crucial for the design and optimization of large-scale deployable mesh reflectors. Although some studies, such as Thomson’s work [41] on reflectors up to 25 meters in diameter, have addressed mass scaling, the broader implications for very large reflectors and across different scales remain insufficiently investigated. There has been a significant focus on form-finding techniques to improve the surface accuracy and stability of cable nets [46]–[49], and on the dynamic behavior of reflectors to prevent coupling with spacecraft attitude control systems [50]–[53]. While several numerical and experimental studies on the dynamic behavior of mesh reflectors have been conducted [52], [53], high-fidelity models and experimental approaches fall short when it comes to analyzing extremely large reflectors or studying them across a broad range of scales due to the rapidly increasing number of structural elements involved. The lack of comprehensive data underscores the need for further research to accurately predict and optimize key metrics such as mass, stowed volume, and fundamental natural frequency of vibration, particularly in the design of very large reflectors and in determining the limits of current technology.

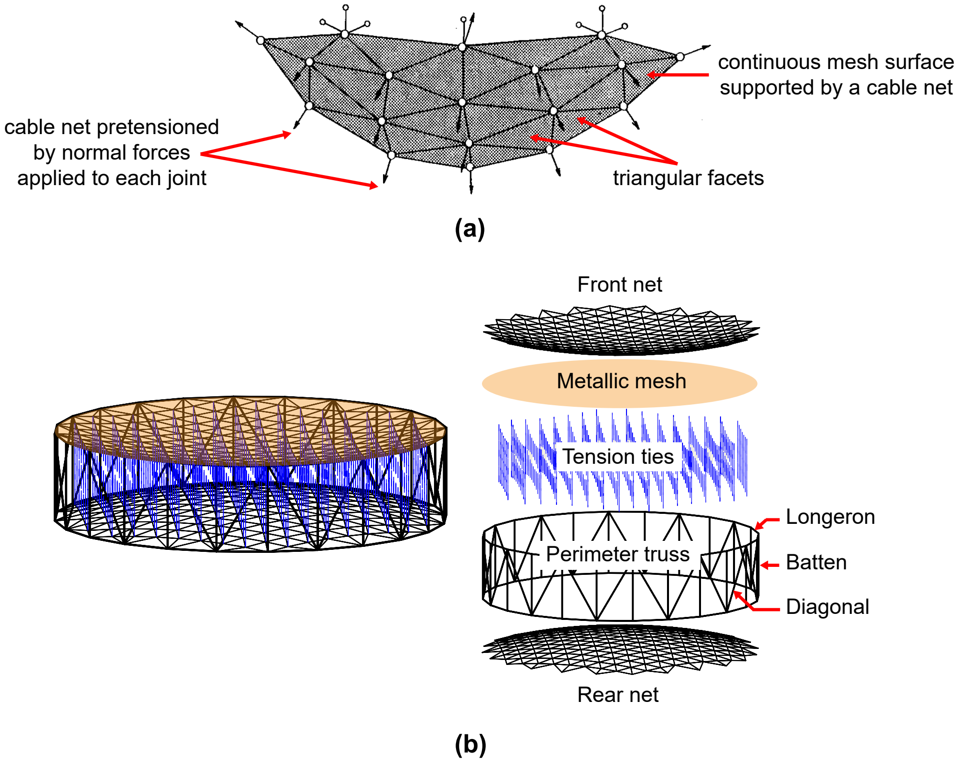


Figure 1.4: Faceted reflective surface: (a) tension truss concept and (b) structural architecture of faceted deployable mesh reflector, based on [40].

A critical aspect in designing mesh reflectors for ISA is the assembly of the reflective surface itself. However, existing robotic systems have yet to explore this challenge. Using traversing robots complicates the assembly process, as it requires managing both the construction of the truss structure and the assembly of the reflective surface simultaneously. Hence, this thesis considers a simpler, fixed robotic system specifically tailored for the assembly of reflectors and similar ring-like structures with a cable interior.

1.4 Feasibility of In-Space Assembly Concepts

As noted in [18], [54], ISA presents a series of challenges that escalate with the increase in the number of structural units and the complexity of installation sequences. Key issues during assembly include ensuring smooth integration of components without snagging or jamming and maintaining structural stability throughout the process. As the size of the structure grows, these challenges become more pronounced, complicating the prediction of component interactions and increasing the risk of interference and misalignment. The greater the number of components, the higher the likelihood of obstructions and delays caused by interference. The sequence of assembly plays a crucial role in facilitating smooth integration and preserving structural integrity, necessitating meticulous planning to avoid misalignments and excessive stresses. Addressing these challenges effectively demands advanced numerical simulations that can accurately model the entire assembly process, track kinematic evolution, and identify potential issues. Such simulations are essential for optimizing the assembly sequence, ensuring the stability and functionality of the structure as it scales and new components are integrated.

Even with reliable simulations, experimental validation of numerical simulation results is still critical to accurately evaluate the feasibility of ISA. However, as systems are scaled to larger size, relying on simulated outcomes becomes essential for assessing the effectiveness of the proposed ISA concept. To build confidence in these simulations, it is vital to ensure that the results align with experimental observations, particularly in smaller-scale cases where experiments are still feasible. This alignment between simulation and experiment serves as a foundational step in confirming the reliability of the models before applying them to larger and more complex systems.

1.5 Thesis Outline

Chapter 2 of this thesis presents a comprehensive and rapid design approach for deployable mesh reflector antennas, based on the state-of-the-art AstroMesh architecture. This design method is then employed to estimate key metrics such as the total mass, stowed volume, and fundamental natural frequency of vibration for antennas with varying aperture diameters and focal lengths, assuming an operational RF of 10 GHz. A detailed analysis is carried out on the distribution of prestress within the inner tension structure by formulating a prestress optimization problem. Analytical scaling laws are then derived for the mass, stowed volume, and natural frequency of optimally prestressed reflectors with aperture diameters up to

200 meters. The study then identifies the maximum achievable aperture diameters for deployable reflector designs based on the constraints of current and near-future launch vehicle capabilities. Additionally, a semi-analytical homogenization model is introduced to estimate the fundamental natural frequencies for various boundary conditions. This model offers accurate and rapid dynamic performance predictions, serving as a more efficient alternative to the use of a high-fidelity model.

Chapter 3 examines the design of mesh reflectors for ISA and assesses their feasibility for stowage within current commercial launch vehicles. This is demonstrated through a detailed scaling study of mass and stowed volume, leveraging the generalized design method introduced in Chapter 2. These ISA mesh reflectors are based on the same structural architecture as deployable reflectors. Building on this analysis, a novel ISA concept for large mesh reflectors is introduced, broadly applicable to ring-like structures with cable interior. A stationary robotic assembly facility is key to this concept, which is folded and stowed in the launch vehicle. Once deployed in space, the facility simultaneously assembles a perimeter truss that expands in diameter with each added unit cell. Boundary nodes of the cable interior are attached to the perimeter truss before each unit cell is released, and the assembly is completed when the facility releases the last unit cell and secures the final node of the cable interior.

Chapter 4 introduces a two-dimensional finite element model to predict the kinematics of large ring-like structures with a prestressed cable interior assembly. This model is utilized to enhance understanding of the proposed ISA concept in Chapter 3 and evaluate design considerations for the stationary robot assembling a ring-like truss. The numerical simulation setup, established using the commercial finite element software ABAQUS/CAE [55], is described along with the modifications and simplifications made to the original designs developed in Chapter 2 to improve computational efficiency. A structure featuring a six-sided perimeter truss and a simple cable interior is used to identify key parameters and techniques for accurate simulation, allowing for the refinement of the developed simulation methods.

Chapter 5 delves into the application of the developed simulation techniques to model the assembly process of a twelve-sided perimeter truss and a network of internal cables that is representative of a reflector antenna. By exploring various assembly sequences and configurations, this chapter aims to gain a comprehensive understanding of the nonsymmetric deployment of the structure, assessing how different approaches influence the overall stability and integrity of the assembly process, and obtaining the desired final configuration. Key design considerations are examined to improve assembly efficiency and robustness, with particular attention to the strategic positioning of the stationary robot, the management of prestressed cables, and the sequence in which truss components are integrated. These factors are crucial for achieving precise autonomous construction of the target ring-like structure with a cable interior in the challenging environment of space, without human intervention. The simulation results, while showcasing the scalability of the developed techniques, offer valuable insights for optimizing the design and operation of autonomous assembly systems for large-scale space structures.

Chapter 6 provides an overview of a lab-scale prototype developed and tested to validate the proposed ISA concept. The prototype, with its twelve-sided perimeter truss and 1.4 meter-diameter is a continuing endeavor by fellow team members of the DARPA NOM4D project at the Space Structures Laboratory at Caltech. Utilized to experimentally model critical elements of the ISA process, this effort not only serves to confirm the viability of the ISA concept but also acts as a tool for validating the qualitative conclusions drawn from simulations. Successful demonstration of the concept indicates that constructing large, high-precision ring-like structures in space using robotic systems is feasible. Experimental observations are compared with simulation results, and these comparisons reveal that, despite using a two-dimensional model, the simulations effectively capture key effects observed in the experiments, providing valuable insights that inform the prototyping process. This qualitative analysis demonstrates the virtual model's ability to offer crucial guidance and enhance understanding during the development of ISA prototypes, especially as structures increase in size.