Chapter 3

ISA CONCEPT FOR RING-LIKE STRUCTURES

This chapter incorporates work that has been published in the following proceedings:

J. Suh, S. P. Dassanayake, M. Thomson, and S. Pellegrino, "Scalable Concept for Reflector Antenna Assembled in Space," in *AIAA SCITECH 2024 Forum*, 2024, p. 0823. DOI: `10.2514/6.2024-0823`.

J. Suh, S. P. Dassanayake, M. Thomson, and S. Pellegrino, "In-Space Assembly of Large Mesh Reflector Antennas," in *Aerospace Structures, Structural Dynamics, and Materials Conference, SSDM 2024 [Technical Presentation]*, 2024, p. 137 740.

J. Suh, S. Dassanayake, M. Thomson, and S. Pellegrino, "Concept for In-Space Assembly of Large Reflector Antennas," in *41st ESA Antenna Workshop ESTEC*, 2023.

3.1 Motivation

As discussed in Chapter 2, large deployable reflectors present several challenges, including constraints imposed by the size of launch vehicles, the risks associated with folding and unfolding delicate components, and the difficulty in maintaining surface accuracy under these conditions. While deployable reflector systems have proven very effective for current missions, they will struggle to deliver the structural integrity and precision required for apertures spanning hundreds of meters. These limitations have driven studies of ISA, which enables the construction of large reflectors directly in orbit. This method not only offers the possibility of removing the restrictions of launch vehicle dimensions but also mitigates the risks of deployment mechanisms. Additionally, ISA provides the flexibility to build and assemble complex structures with enhanced surface accuracy and improved resilience to in-orbit conditions.

The increasing demand for larger and more precise space structures, which surpass the physical and technical limitations of traditional deployable systems, has therefore heightened the need to develop ISA concepts for reflectors. As space missions require higher-resolution imaging, improved communication capabilities, and more advanced scientific instruments, the necessary aperture sizes for reflectors have grown substantially. ISA leverages advances in robotic technologies and on-orbit servicing, allowing for the construction, maintenance, and potential upgrades of space-based reflectors. This approach not only extends mission lifespans but also facilitates the deployment of structures that are too large or complex to be pre-assembled and launched from Earth. By enabling the ISA of ultra-large reflectors, new opportunities are unlocked for next-generation space missions, such as deep-space exploration and advanced communication systems, where the size and precision of reflectors are crucial to mission success.

In this chapter, an ISA concept is proposed for mesh reflectors and similar ring-like structures with a cable-based interior. The reflector design closely follows that of the deployable AstroMesh, but with a key distinction: the concept shifts from deployment to ISA. By transitioning to an in-space approach, the constraints tied to launching fully stowed configurations are bypassed. First, the mass and stowed volume of the ISA reflectors are calculated for apertures reaching up to 200 meters, utilizing the generalized design methodology developed in Chapter 2. This step is crucial for evaluating the launch feasibility of the proposed reflector within current vehicle limits. The analysis not only takes into account the physical dimensions of the reflector but also assesses how these factors influence the viability of launching the components for ISA. Next, a detailed assembly scheme is introduced, focusing on the practical implementation of the concept. Central to this process is the use of a robotic system capable of autonomously constructing the large reflector in space. The centralized robotic system would handle the sequential assembly of the reflector's components, allowing for precise alignment and tensioning of the cables and facets to achieve the required surface accuracy. This method provides flexibility in scaling up the structure, enabling the creation of reflectors far larger than what could traditionally be deployed from Earth. The proposed approach offers a solution for building highly accurate, large-aperture reflectors, making it an ideal strategy for future space missions requiring enhanced performance and larger structural footprints.

3.2 Scaling of Mass and Stowed Volume for ISA Reflectors

ISA reflectors are designed with the same structural architecture as the deployable reflectors discussed in Chapter 2, featuring two cable nets and a perimeter truss. The same dimensions and material properties are assumed. However, all components are assumed to be modularly designed and stored separately as described next.

Both the front and rear cable nets, along with tension ties and metallic mesh, are fabricated and pre-assembled, then simply estimated to be compacted to one-twentieth of their original volume for stowage. The perimeter truss struts are assumed to be manufactured by cutting deployable omega beams, which are flattened and coiled onto a mandrel for compact storage. The strut spool dimensions are estimated as follows (see Fig. 3.1): the height of the core mandrel, H_{core} matches the flattened width of the strut, while the core diameter, D_{core} is set equal to the core height. As the flattened strut is coiled around the mandrel, the spool diameter increases, with the maximum diameter, D_{spool} limited to four times the core diameter. The spool height, H_{spool} remains the same as the core height. The total number of strut spools required is calculated based on the total length of the struts. The volume of the joint stack is determined based on its envelope. Once the total volume of the truss components is calculated based on these assumptions, the overall diameter and height are determined by assuming the components are packed compactly within a cylindrical envelope, where the height is twice the diameter, i.e., $H_{stowed} = 2D_{stowed}$.

The mass of the ISA reflectors can be readily calculated following the approach introduced in Sections 2.3 and 2.4, and accounting for the lack of deployment actuators in Eq. 2.10.

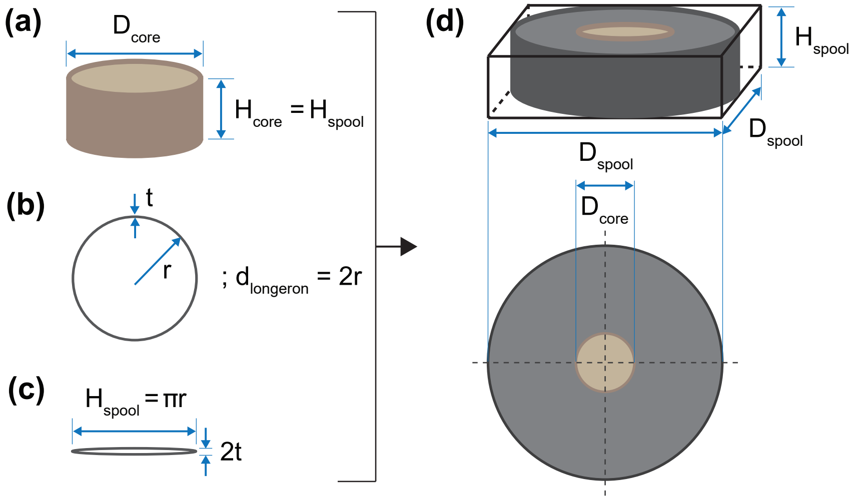

Figure 3.1: Coiled strut volume estimation: a) core mandrel, b) cross section of the strut, c) flattened strut, and d) strut spool.

Figure 3.2 shows the overall mass, stowed diameter, and height of the ISA reflector for an F/D ratio of 1.0 across a diameter range from 10 m to 200 m. The black dots represent the data points for deployable reflectors, while the red dots denote the data points for ISA reflectors. The pink and blue solid lines indicate the payload capacity limits for Falcon Heavy and Starship launchers, respectively, as previously discussed.

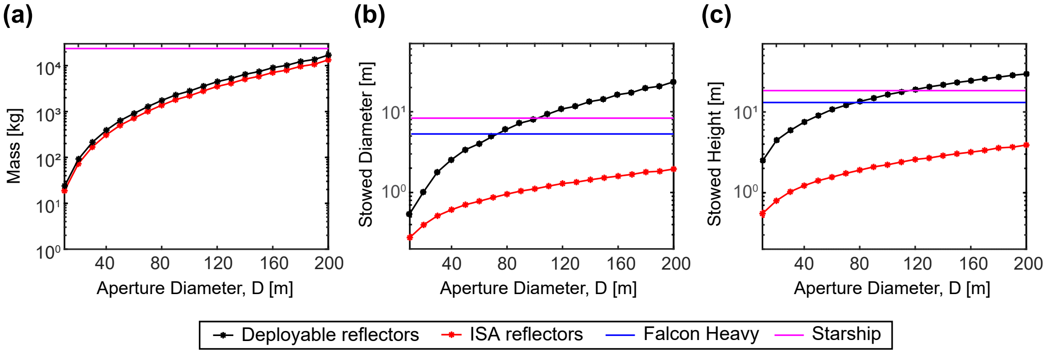

Figure 3.2: Scaling of ISA vs. deployable reflectors for $F/D = 1.0$: a) total mass, b) stowed diameter, and c) stowed height.

The total mass and stowed volume of the ISA reflectors were found to scale approximately quadratically with diameter. For deployable reflectors, the mass was not the primary constraint. However, as expected, ISA reflectors are lighter than their deployable counterparts across all relevant aperture sizes. Volume, on the other hand, posed a constraint for deployable reflectors. In contrast, the stowed diameter and height of ISA reflector components fit comfortably within the fairing's limits, even for diameters up to 200 m. As a result, a single launch can accommodate an ISA reflector with a diameter exceeding 200 m, demonstrating remarkable potential.

3.3 In-Space Assembly Concept

3.3.1 General Overview

A linear in-space assembled truss concept has been proposed [9], where a three-dimensional truss is constructed as follows: three *SpiderFab* "Trusselator" heads extrude continuous 1st-order trusses to serve as longerons, while a fourth robotic head with 6 DoF fabricates and attaches cross-members and tension lines, creating a truss support structure with a 2nd-order hierarchy. As the structure extends, it simultaneously tensions and deploys a pre-built z-folded solar array blanket, as depicted in Fig. 3.3(a).

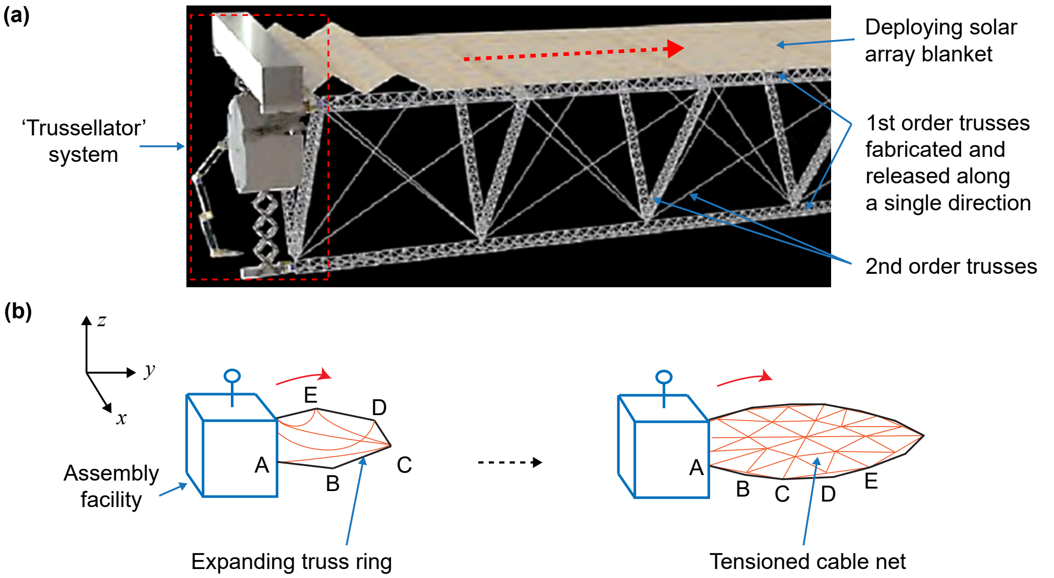

Figure 3.3: ISA concepts: (a) linear ISA trusses [9], and (b) proposed two-dimensional ISA for ring-like structures with a cable interior.

A defining characteristic of the mesh reflector architecture we are focusing on is its prismatic, ring-like perimeter truss. This allows for a similar, but two-dimensional, assembly concept compared to the Trusselator approach. In this concept (see Fig. 3.3(b)), a truss ring is constructed and extended from an assembly facility, gradually expanding as additional components are added. The cable interior, initially slack, becomes tensioned during the deployment process, ensuring that the required structural stiffness and precision are achieved upon completion.

The core principle of the ISA concept thus developed for mesh reflectors is to design reflector components as modular units, or "Lego bricks," allowing them to be efficiently stored and transported within a specialized assembly facility, known as the *Truss Builder*. This facility, shown in Fig. 3.4, serves as the central hub for the entire construction process once the components reach their target orbit.

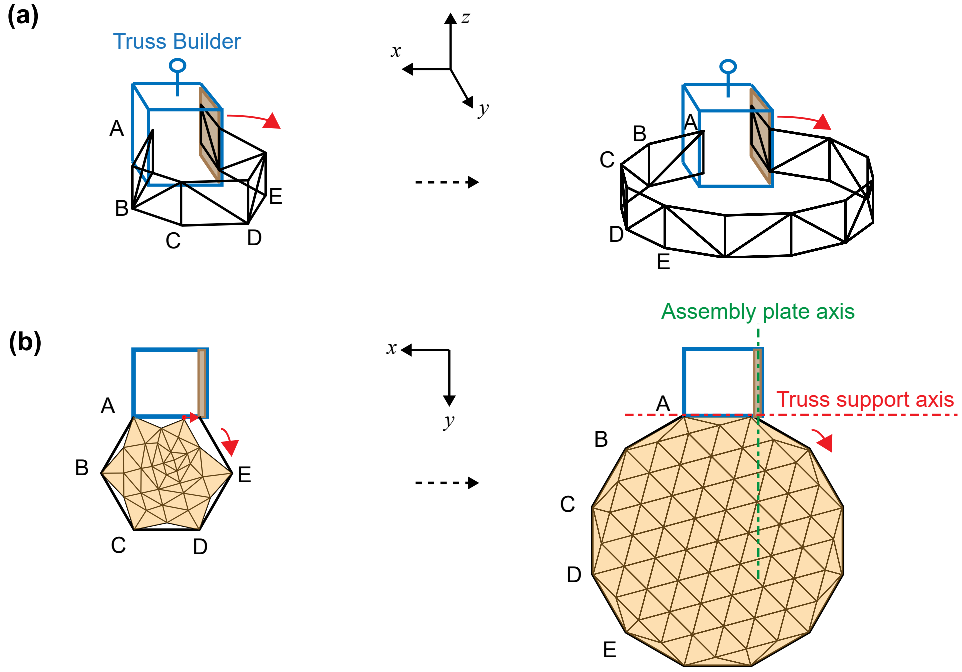

Figure 3.4: Schematic drawing of in-space polygonal ring assembly with cable interior: (a) truss assembly, and (b) cable net deployment.

The assembly process is highly streamlined and relies on simple, repetitive operations. Upon arriving in orbit, the truss builder begins assembling the structure by constructing a single bay of the perimeter truss. After each bay is completed, the corresponding node of the pre-folded cable net is connected to it (Fig. 3.4(b)) prior to bay release. The sequence is repeated—constructing and releasing each bay one at a time—until the entire reflector is fully assembled. The process is complete when the final bay is released from the truss builder, resulting in a fully deployed reflector.

The significance of this concept lies in the use of a single, stationary robot—the truss builder—for the autonomous assembly of large, polygonal, ring-like structures with a cable interior. By utilizing a stationary robot that remains in place throughout the construction, the planning complexity of the assembly process can be significantly reduced. This design eliminates the need for multiple mobile robots, long challenging traverses or complex coordination between moving parts, which would otherwise increase the risk of failure and add to the overall system cost. Moreover, the modular nature of the components and the repetitive nature of the assembly process make this method highly scalable. The same approach can be applied to reflectors of various sizes, from small-scale to ultra-large structures, without significant changes to the assembly strategy.

3.3.2 Operations of the Truss Builder

In the proposed assembly scheme, the truss builder, along with all structural components (i.e., struts, joints, and the cable net), is folded and stowed during launch. On reaching the target orbit, the truss builder is deployed, making the reflector ready for assembly. The proposed truss builder is equipped with a metrology system for precise shape accuracy and vibration measurements. It also features multiple robotic subsystems designed to facilitate the construction and release of each bay of the perimeter truss, a central element of this assembly concept. The assembly plate, crucial to the process, serves as the platform where each bay is constructed. It is designed to slide in and out of the truss builder to release the completed bays, increasing the diameter of the ring-like structure. Joint and strut dispensers are located behind the assembly plate, holding the modules required for bay assembly. A gantry robot, acting as the *Manipulator* with three translational and one rotational DoF, is responsible for picking up and connecting the structural components. During the assembly, two truss supports, labeled S_1 and S_2, hold the ends of the perimeter truss. The edge of the truss builder in between serves as the bay that completes the truss ring. The folded cable net, stowed along this truss support axis (see Fig. 3.4(b)), has its net joints $C_{edge,i}$ secured by net attachment devices. As each bay is constructed, the slack net nodes $C_{edge,i}$ are attached to the corresponding truss nodes N_i. As the cables tighten, the interior net nodes C_j adjust accordingly. The reflective surface (i.e., the metallic mesh), is pre-attached to the front net and folded together with it. Consequently, the antenna assembly is completed once the truss builder releases the final bay and secures the net.

Figure 3.5 shows a two-dimensional view of the steps involved in the proposed assembly operation. As described, the truss bays B_i are sequentially assembled and released outward from the truss builder. Key components include the sliding assembly plate, the manipulator, and the net attachment device.

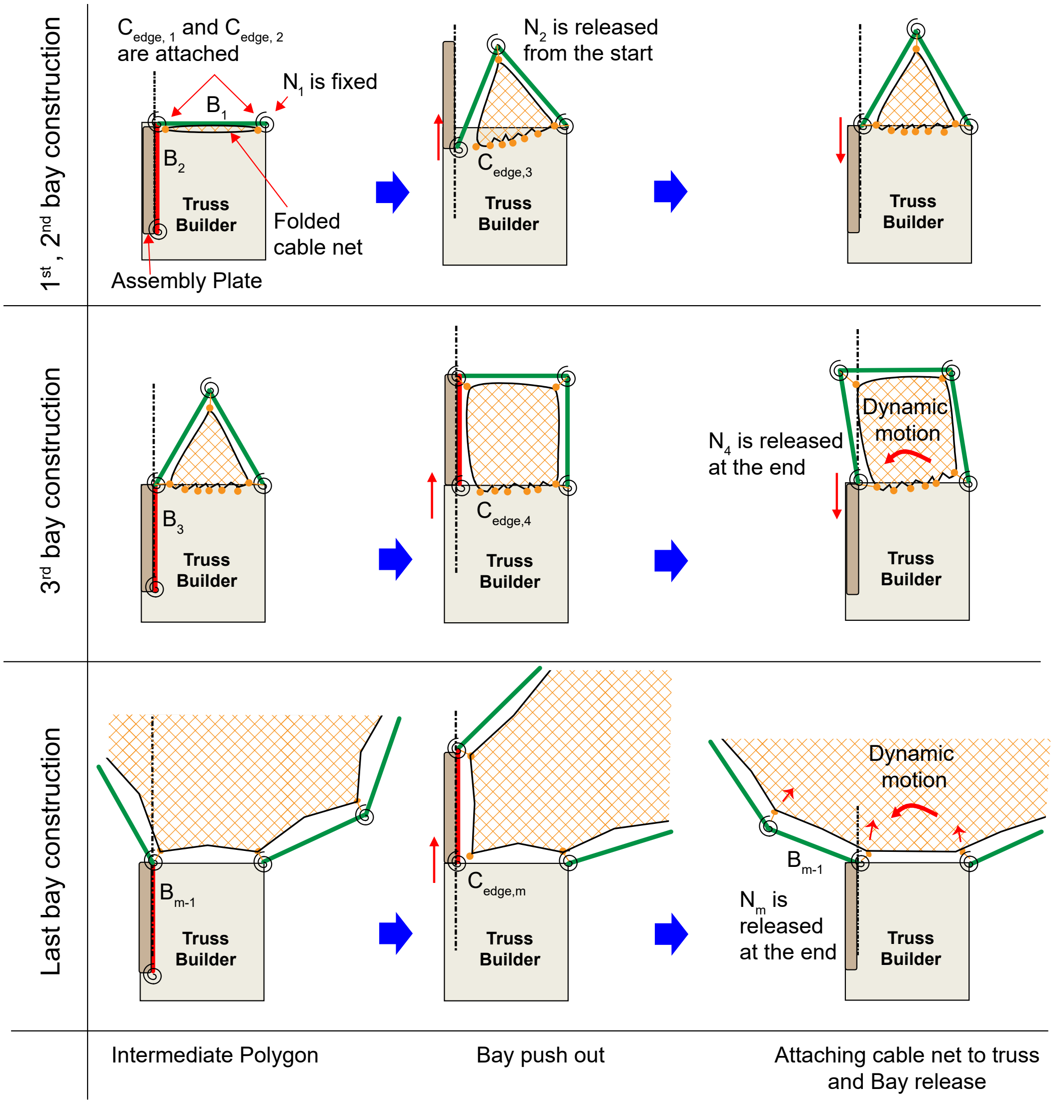

Figure 3.5: Two-dimensional view of truss assembly process: first, second, third, and final bay assembly.

At the start, two pre-built bays, B_1 on the outer wall and B_2 on the assembly plate, are connected to the truss builder, with their truss nodes N_1 and N_2 attached to the corresponding net nodes $C_{edge,1}$ and $C_{edge,2}$. The process begins with the assembly plate pushing out the pre-built bay B_2, after which the net attachment device connects net node $C_{edge,3}$ to the truss joint N_3, and the assembly plate retracts, deploying B_2. The remaining bays are similarly constructed. The manipulator picks up the joints and struts from storage, assembling each bay on the plate (indicated by red lines in Fig. 3.5), and the net attachment device connects the net nodes to the truss (indicated by orange dots in Fig. 3.5). Once a bay is completed, the assembly plate pushes it out (released bays are indicated by green lines in Fig. 3.5) and retracts to prepare for the next bay. This process continues until all bays are assembled, with the push-out of the final bay, B_{m-1} (where m represents the number of sides in the final polygonal ring), and the application of a state of prestress to the fully assembled reflector. To ensure the structural stability of the partially complete structure during assembly, the joints are designed to be elastically deformable in torsion, with angle stops that maintain a polygonal shape for the released bays.

3.4 Chapter Conclusions

This chapter has introduced a novel scheme for robotically assembling large reflectors, based on the AstroMesh reflector architecture. The approach to the structural design of the reflector has been described, including the determination of mass and stowed volume for apertures up to 200 meters in diameter. The findings highlight the significant advantages of ISA reflectors over traditional deployable designs, particularly in terms of reducing the required launch envelope.

The proposed ISA scheme utilizes a centralized truss builder facility, launched into orbit with all necessary structural components and a simple robotic system. The truss builder automates the reflector assembly through a sequence of simple operations: constructing a bay of the perimeter truss, attaching the corresponding outer node of the cable net to the bay, and then pushing the completed bay out of the truss builder. The chapter outlines and discusses the detailed operations of the assembly facility for bay construction and release.

The flexibility of the proposed ISA concept is crucial for future space missions, which will require large reflectors for their applications in high-resolution imaging, advanced communications, and scientific observations. By simplifying the assembly process and enabling the construction of high-precision reflectors directly in space, the truss builder represents a significant advancement. This method offers a practical and scalable solution for building large, complex structures that would be challenging or infeasible with conventional deployable systems.