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Development of Space-Borne Antenna Reflector via 3D Printing

Jaya Kori[1*], Sampurna Patnaik[1], Somnath Chattopadhyaya[1], and Sayan Chatternjee[2]

[1]Department of Mechanical Engineering, Indian Institute of Technology (Indian School of Mines), Dhanbad, India
[2]Department of Electronics and Telecommunications, Jadavpur University, India

emails: *[*1]jayakori1996@gmail.com; [1]18je0719@mech.iitism.ac.in; [1]somnathchattopadhyaya@iitism.ac.in, and [2]sayan1234@gmail.com*

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ABSTRACT

The growing necessity of large aperture-based structures for many aerospace applications emphasizes the need to deploy large antenna structures in space. The space antennas should be light in weight and have low stowage volume, with efficient membrane packaging. The concept of additive manufacturing has been introduced to reduce weight as well as cost. In this paper, a comparative study has been done to analyze the advancement made in reducing weight with adequate strength. Based on the study, the main objectives are to develop a 3D-printed spherical reflector model with high specific strength and to assess the consistency of the model's shape. For determining the specific strength, tensile testing is performed on four different infill densities (20%, 40%, 60%, and 80%) with a grid infill pattern. It was observed that the specimen with 80% infill density has the highest tensile strength, 36.56 MPa, which is 23.51% more than 20% infill. However, the specimen with 20% infill density has the highest specific strength of 19.323 GPa/kg among the four specimens, which is approximately 64.64% higher than the 100% infill density. As a result of the testing, the spherical reflector model is 3D printed with 20% infill density, and it was found that the model achieves its shape stability and shape consistency with adequate specific strength.

1. INTRODUCTION

Recent developments in satellite antennas demand a large gain-to-weight ratio; to fulfill this demand, the aperture of an antenna needs to be huge. This rising need for huge aperture antennas for different space applications has piqued the attention of space researchers in deployable antennas. Compared with conventional antennas, membrane antennae can be easily stowed in less space, attain higher scalability with lightweight, and minimize the cost. Currently, two different kinds of antenna structures for space-borne applications exist the parabolic and planar membrane antenna structures (Iida & Wakana, 2003). These structures mainly consist of a membrane surface, support structures, and tensioning cables. Since the 1970s, several nations, including the United States, Europe, and Japan, have been doing research on membrane antennas (Li *et al.*, 2022). Limited research has been conducted on membrane antennas with diameters exceeding 14 meters due to numerous challenges. To boost membrane antenna advancement, examining the development of a deployable membrane is vital. Small satellites like CubeSats have been developing capabilities and are being considered for more challenging mission objectives. A significant challenge is inadequate data downlink rates from CubeSat communication systems. This is due to volume and mass restraints imposed by CubeSat reference standards—the Platform size also restraints the power system on board (Chandra *et al.*, 2020). Conventional High Gain Antenna (HGA) technology for small satellites is constrained to reflect arrays and mechanical linkage systems. Such systems do not stow very effectively into existing payload volumes on CubeSats. Further, the complications in the deployment mechanism introduce various points of potential failure. Hence, such systems are not readily deployable to larger sizes needed for more excellent capability (Babuscia *et al.*, 2016).

This paper includes a comprehensive review of various antenna types, with a focus on their development over the past decade, particularly highlighting the innovative concept of origami folding and its application in recent antenna design using additive manufacturing processes. Following this, the study selects 3D printable materials to fabricate tensile specimens with varying infill densities and specific input parameters. Through a comparative analysis of their specific strengths, the research identifies the infill density of high specific strength and subsequently develops a spherical reflector model having shape stability and consistency.

2. RECENT DEVELOPMENTS

Over the past decade, numerous researchers have made significant contributions to the field of deployable space antennas. For example, Bouzidi *et al.* have developed a space inflatable membrane reflector having a parabolic reflector shape of the material of neoprene-coated Kevlar for solar concentrator or radiometer system application (Bouzidi & Lecieux, 2012). Hong-Jian *et al.* experimented and made a prototype of an inflatable space-borne antenna of parabolic shape using a Kapton/aluminum membrane for the outer surface and a Kapton membrane for the inner reflector surface. Three cylindrical struts were made of aluminum-coated Mylar membranes to apply passive microwave sensing of ocean temperature, wind, and precipitation (Wang *et al.*, 2012). Xu *et al.* also experimented with a high-precision inflatable antenna reflector of parabolic shape of Kapton material for spaceflight applications (Xu & Guan, 2012). Jet Propulsion Laboratory (NASA) designed an Inflatable membrane reflector using Polyvinylidene Fluoride (PVDF) having a parabolic shape for the application of high-precision surface control in space (Fang *et al.*, 2012).

To minimize the size of the satellite for space exploration applications, tiny CubeSats have been designed for S-Band; laboratory experiments and simulations have been done on inflatable antennas for CubeSats(Abdullah *et al.*, 2021). An inflatable antenna is made up of two parts: one is the reflective part that is metalized Mylar, and another one is transparent Mylar. A parabolic shape of the antenna has been designed by joining the edges of petals with Kapton tape and epoxy (Babuscia *et al.*, 2016). After much research on the inflatable antenna, a parabolic deployable mesh reflector antenna has been designed using a metal with a diameter of 1m and a focal length of 0.75m for deep space network telecommunication of X-Band and Ka-Band (Chahat *et al.*, 2016). An inflatable antenna of conical and planar shapes has been developed using Kapton, Mylar, and shape memory alloys for radio telescopes (Vertegaal *et al.*, 2021). Jet Propulsion Laboratory of California Institute of Technology (NASA) designed a parabolic inflatable antenna using Mylar for Radar interplanetary applications of gain 25 dBi (Babuscia *et al.*, 2021). The concept of inflatability has been growing because of its lightweight and high performance. Space Applications Centre - Indian Space Research designed an inflatable planar membrane reflector antenna via Kapton and neoprene-coated Kevlar fabric of a width of 1m and height of 0.250 m for solar cell arrays, solar sails and inflatable booms (Shinde & Upadhyay, 2021). Recently, an inflatable coplanar patch antenna has been developed using Kapton material with a gain of 11.8 dbi for space applications (Vertegaal *et al.*, 2021).

Membrane structures offer excellent deployable capabilities, making them highly suitable for various antenna applications (Liu *et al.*, 2017). Membranes are especially desirable for space applications because of their high strength-to-weight ratio, low weight, and ease of storing and deploying. ("Gossamer Spacecraft: Membrane And Inflatable Structures Technology For Space Applications," 2001). Figure 1 demonstrates the usage of several materials in the reflector membrane. Materials such as Mylar and Kapton were utilized more often, with a ratio of 38 percent and 28 percent, respectively.

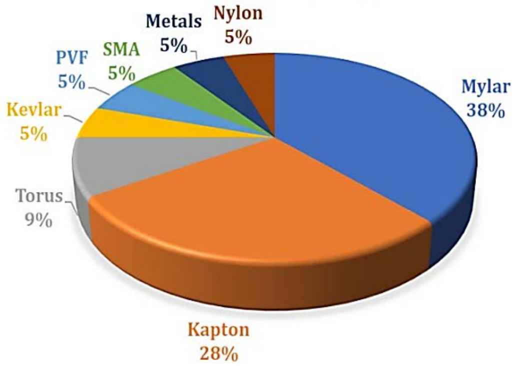


Figure 1: Representation of the reflector's material

The most common reflector antenna form is parabolic (as shown in Figure 2). It is owing to its capacity to produce very high levels of gain and directivity. The geometry of the reflector is critical to antenna performance. The bent antenna's performance was marginally better than the flat antenna's (Sankaralingam & Gupta, 2010). Figure 3 depicts the sizes of the antenna prototypes utilized in various studies ranging from 0.5 m to 14 m. In the trials, mainly antennas with a diameter of 1 m were used.

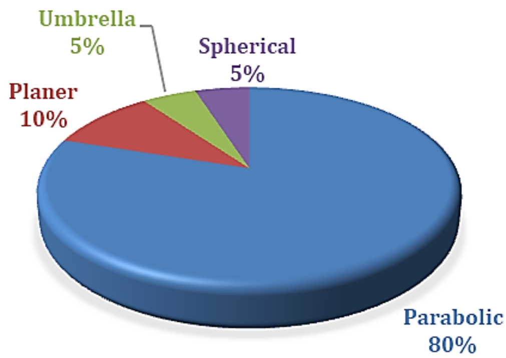


Figure 2: Representation of the reflector's shape

When it comes to inflating the membrane into a parabolic shape, it naturally takes a spherical shape. The parabolic shape deformed into a spherical shape (Im *et al.*, 2007), so the new concept of implementing the spherical reflector model has come. The spherical reflector antenna mainly consists of gores or sub-segments made of half transparent and the remaining half reflective membrane. A line feed is placed inside the membrane that deploys to the desired location (Babuscia *et al.*, 2017).

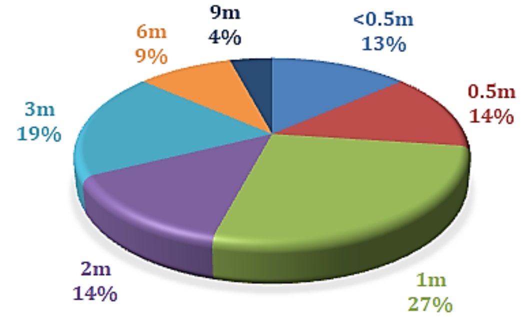


Figure 3: Diameter of the reflector

Stowing and deployability are essential considerations when designing space antennas. Based on this, Origami-inspired folding techniques are one approach to achieving stowability and deployability in space antennas (Natori *et al.*, 2013). In the context of space antennas, origami folding can create compact and lightweight structures that can be easily unfolded and deployed in space. One example of an origami-inspired space antenna is the Miura-Ori antenna. This involves a fold pattern involving a series of mountain and valley folds that allow the paper to be compressed and expanded (Pruett *et al.*, 2022).

Other origami-inspired folding techniques have also been developed for space applications, including the Yoshimura pattern (Cai *et al.*, 2016), which involves a series of diagonal folds, and the Hoberman sphere. This collapsible sphere can be used as a framework for antennas.

3. ADDITIVE MANUFACTURING

Additive manufacturing, also known as 3D printing, has the potential to revolutionize the way we design, build, and maintain space systems. Here are some ways in which additive manufacturing is already being used in space applications.

1. Manufacturing spare parts: the ability to produce parts on demand without the need for expensive tooling or long lead times. This makes it ideal for producing spare parts for space systems, where traditional manufacturing costs and time are prohibitively high (Helena *et al.*, 2020).
2. Reducing launch costs: AM technology can also help reduce the cost of launching payloads into space. By 3D printing parts and components in space, space engineers can reduce the mass and volume of payloads, allowing more to be launched simultaneously and reducing the cost per kilogram (Blakey-Milner *et al.*, 2021).
3. Design optimization: AM technology also allows for greater design flexibility and optimization (Najmon *et al.*, 2019). Engineers can create complex geometries that would be difficult or impossible to produce using traditional manufacturing methods and can iterate more quickly to optimize designs for specific applications.
4. Materials development: By developing and printing new materials for space applications, Space engineers can better understand how they perform in the unique environment of space and develop new materials with specific properties suited to space applications (Balaji *et al.*, 2022).
5. Overall, additive manufacturing has the potential to significantly improve the efficiency, cost, and performance of space systems, and we can expect to see increasing use of 3D printing in space applications in the coming years.

AM technology can potentially revolutionize the production of space antennas by allowing for more precise and efficient manufacturing processes. Producing complex geometries (Mohanavel *et al.*, 2021) and the ability to reduce the weight of the antenna by using lightweight materials such as composites. This can be especially important in space applications where every gram counts (Kamal & Rizza, 2019). However, the challenging part of AM technology is ensuring the reliability and durability of the printed parts in the harsh space environment, which includes exposure to radiation, extreme temperatures, and vacuum conditions. 3D printing is already being used to produce some space antennas, and this technology will likely become more prevalent as it continues to evolve and improve.

4. METHODOLOGY

A. Material Selections and Input Parameters

The most often used materials in 3D printing are ABS, PLA, TPU, etc. Since PLA (Polylactic Acid) belongs to the group of polymers with numerous characteristics that would aid in both deployability and sustainability, it also possesses qualities like its thermoplastic behavior and shape memory. Due to its simplicity of usage, low toxicity, and biodegradability (Rismalia *et al.*, 2019), PLA has grown to be a preferred material for 3D printing. Four alternative infill densities (20%/40%/60%/80%) were selected as input parameters for the tensile testing of the samples (Derise *et al.*, 2021). Table 1 illustrates the input printing parameters for sample preparations. Among infill patterns, the grid pattern stands out as the most frequently employed, and research conducted by (Yeoh *et al.*, 2020) demonstrates that the grid pattern outperforms zig-zag and concentric patterns in terms of providing greater tensile strength.

Table 1
Parameters selection for the samples

Input parameters	Value	Units
Filament Diameter	1.75	mm
Layer Height	0.2	mm
Print speed	70	mm/sec
Infill Density	20/40/60/80	%
Infill pattern	Grid	-
Nozzle Temperature	205	℃
Bed Temperature	55	℃
No. of top and bottom solid layers	3	-
No. of shell	2.5	-

B. Sample Preparations

This work chose four different infill densities, 20%, 40%, 60%, and 80%, and grid infill patterns for the sample preparation. For the tensile test, ASTM D638 type-V is followed. The samples were printed using RAISE3D E2 FDM setup. PLA filament (black in color) with a 1.75 mm diameter was used with 205˚C nozzle temperature and 55˚C bed temperature. To print the samples, the STL file of the CAD design must be sliced into layers and delivered to the printer in G-code format. The digital model is sliced using the IdeaMaker slicing program. Figure 4 shows the dimensions for the samples as per ASTM D638 Type-V. The grid infill patterns for the four infill densities are shown in Figure 5. The grid patterns print the layer with pathways intersecting at 90˚ and forming a 45˚ angle with the sample's axial axis.

C. Tensile Test

Tensile tests are carried out on the digital Hounsfield H50KS universal testing machine (UTM) with a 50KN load cell and a 1mm/min crosshead speed by ASTM standard criteria shown in Figure 6. Four samples are tested for each infill density, data is recorded in terms of load (N) versus elongation (mm), and the stress-stain curve is evaluated and analyzed from this data. Three significant properties, namely young modulus, yield strength, and ultimate strength, were investigated using the stress-strain curve. Each sample of the four distinct infill densities is weighed, and the average data from the four samples is considered. The specific strength (yield strength to sample weight ratio) determines the specific strength of each infill density. After optimizing the entire set of data, it was discovered that the 20% infill density's specific strength is higher. The shape stability of the 3D printed model must now be verified at a 20% infill density. Using SolidWorks, a CAD model of the reflector is created.

D. Cad Design

A spherical antenna reflector with a diameter (aperture length) of 80 mm has been created using SolidWorks. The desired focal-to-aperture length ratio falls within the range of 0.25 to 0.5 (Baars, 2003). Figure 7(a) depicts the upper part of the designed model of diameter 80 mm, while Figure 7(b) illustrates the lower section connected to the feed array antenna model, featuring dimensions of 15 mm in diameter, 5 mm in thickness, and a focal length of 40 mm. Figure 8 presents the complete assembly of the reflector model design.

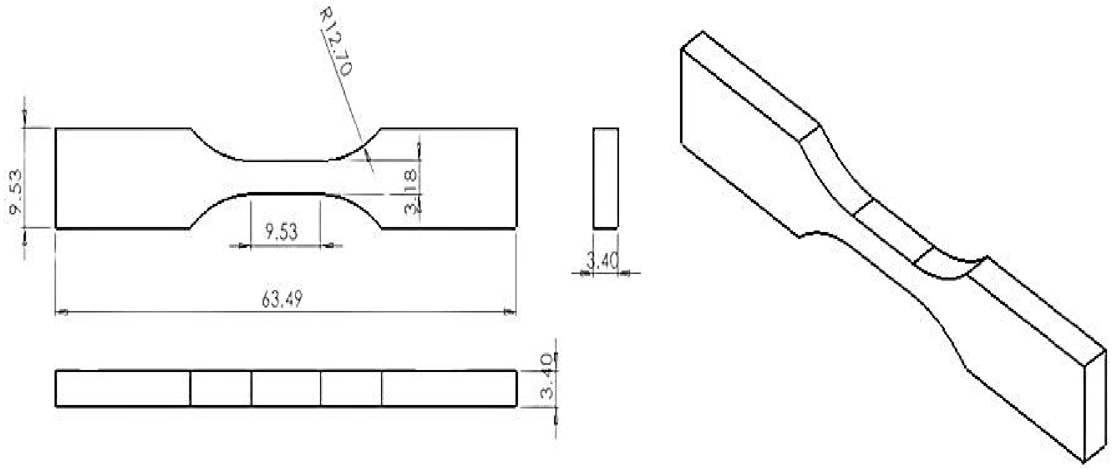


Figure 4: The dimensions of ASTM D638 Type-V (all dimensions are in mm)

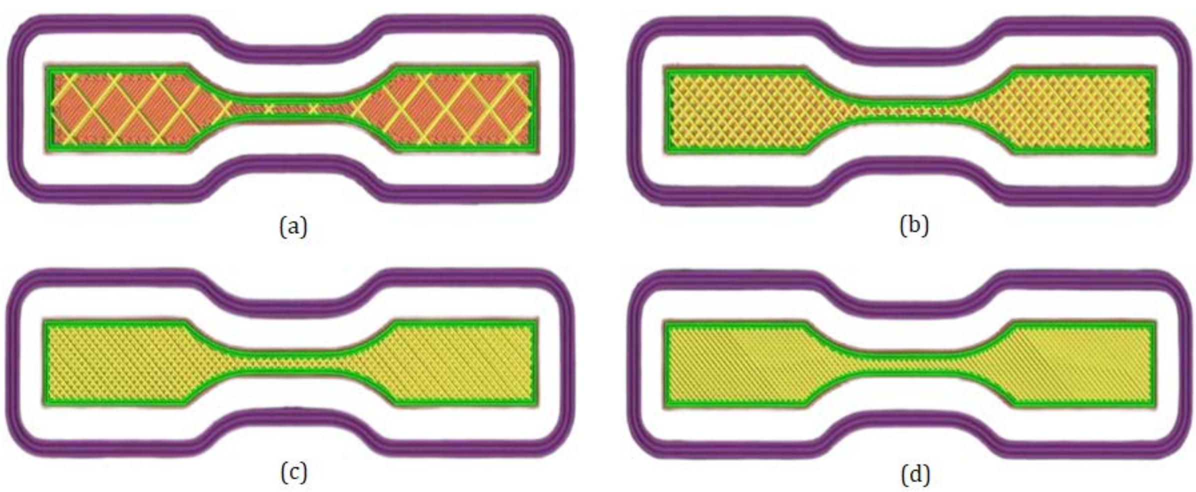


Figure 5: Infill densities (a) 20%, (b) 40%, (c) 60%, and (d) 80%

Figure 6: Sample testing on a UTM

(a) (b)

Figure 7: Spherical reflector model design, (a) Upper part and (b) lower part

Figure 8: Spherical reflector model assembly

E. 3D Printing of Model

The spherical reflector model is 3D printed using the Raise3d E2 Fused Deposition Modeling (FDM) technique. Figure 9 depicts the machine configuration, (a) and (b) show the 3D printing procedure and digital screen of the machine, respectively. To 3D print the model, two trials have been performed. In the first trial, 15% infill density is chosen. The feed array collapsed during printing; hence, the printed model failed to deliver the expected outcome. This is brought on by the basic design's insufficient central support for the feed plates. The 3D-printed portion of the first run and the failing components of the bottom structure are depicted in Figure 10 (a) and (b).

In the second trial, the design is modified, and the infill density is increased to 20%. The printed prototype showed promising results with an intact feed array and Vectran ties. The Upper and lower part of the spherical antenna was printed separately. Figures 11 (a) and (b) show the upper and lower parts, respectively. Figure 12 demonstrates the antenna assembly with the suitable fitting. This prototype displayed an increase in the accuracy and shape stability of the spherical reflector model.

(a) (b)

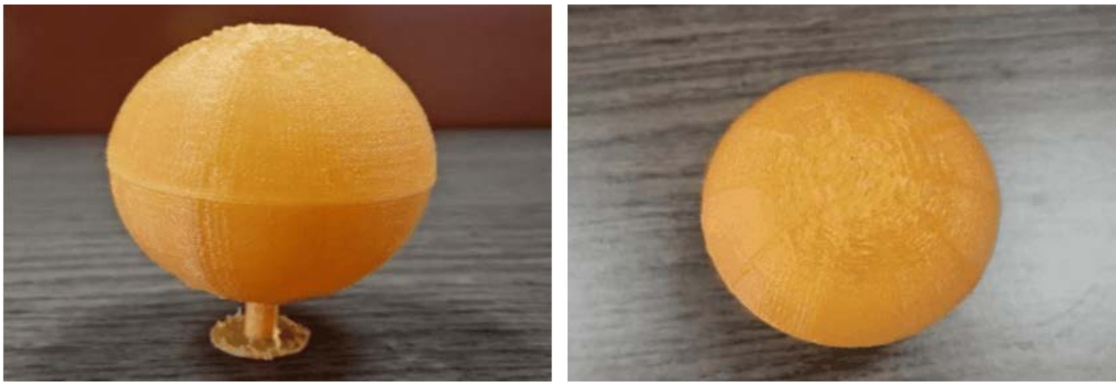
Figure 9: 3D printing of the reflector model on RAISE 3D E2 machine: (a) 3D printing of support structure, and (b) Digital screen of machine

(a) (b)

Figure 10: The failed part of the bottom structure of 3D printed spherical antenna (1st trial), (a) front view and (b) collapsed feed array

(a) (b)

Figure 11: (a) 3D printed upper part of the Reflector model and (b) 3D printed Lower part of the Reflector model with the feed array



(a) (b)

Figure 12: (a) Front view and (b) Top view of the 3D-printed spherical reflector model assembly

5. RESULTS AND DISCUSSION

A reflector antenna model has been created by using the FDM method. The primary goal of this study is to enhance specific strengths through the utilization of AM technology. To accomplish this objective, the infill pattern and structure volume are set as fixed parameters, while the infill density (20%, 40%, 60%, 80%) is considered as the variable parameter. Three significant properties—young modulus, yield strength, and ultimate strength—are extracted from the tensile testing of samples with four different infill densities. Table 2 lists the characteristics of the samples representing each of the four infill densities (measurement is based on the average of the four samples for each infill density). The tensile strength of the sample increases as the infill density does, as shown in Table 2. However, there is also an increase in weight, an essential consideration for aerospace applications.

As weight increases, the tensile strength-to-weight ratio decreases. However, lesser weight with adequate strength is preferred for space applications. In the first trial, 15% infill density was employed to lighten the weight; however, the feed array collapsed because of insufficient central support and lower strength. To improve the reflector model's strength in the second trial, the infill density was increased by 20%; however, this increased the model's weight, but the specific strength was increased. The reflector model is printed at a 20% infill density to achieve the stability of a spherical form, as shown in Figure 12. It was discovered that despite being lighter, it possesses sufficient strength.

Table 2
Properties of samples

Infill density (%)	Young modulus (GPa)	Yield strength (MPa)	Ultimate strength (MPa)	Weight (gm)	Specific strength (GPa/kg)
20	2.824	28.08	29.60	1.46	19.23
40	2.808	28.8	30.56	1.84	15.65
60	3.112	30.96	32.88	2.52	12.29
80	3.736	34.56	36.56	2.96	11.68

6. CONCLUSIONS

The current trend has proposed various reflector designs with different gain levels, RF factors, and foldability. The Kapton and Mylar are widely used materials in space applications because of their excellent thermal stability and mechanical strength. From the experimentation, it can be concluded that increasing the infill density enhances the mechanical strength, but at the same time, the structure's weight also increases. Specific strength (strength-to-weight ratio) should be high to make the structure robust and lightweight. Moreover, it was observed from the experimental evidence that at 20% infill density, it has the highest specific strength among all four different infill samples. However, printing the model at a lower infill density (at 15%), the structure was unable to sustain its spherical shape; meanwhile, the feed array also collapsed. For making the structure sound, the tensile specific strength criterion is not only sufficient to design a model but there is also a need for compressive specific strength to check the collapsibility of the structure.

Compared with traditional spacecraft structures, these 3D printed structures could have several advantages, such as reduced mass, low cost, and high gain-to-weight ratio. However, the 3D printed samples should be tested in space environment conditions. High-temperature tensile and high-temperature compression tests can be performed to check the strength at extreme temperature cycles.

More enhancements are required in implementing origami folding to the shape of a hybrid structure. Numerical methods can propose an optimization of the inflatable membrane reflector design. With the help of a polynomial series weighted by a set of shape parameters, initial geometry can be analyzed.

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