Lotus Mechanism: A Novel Concept for Primary Mirror Deployment

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***Abstract*—To cope up with the challenges of deep space exploration and communication it is mandatory to have telescopic reflectors of large diameters both on ground and in space. Current spacecrafts has constraints of its own in terms of available space to accommodate reflector of diameters more than 4m. This paper focuses on overcoming the challenges of available footprint area in the spacecraft by modifying the monolithic reflector by dividing it in segments. A new solution is proposed to "divide" and "rule" large sized telescopic reflectors in small segments and folding them to reduce overall size of the assembly; which will reduce the overall footprint area of the mirror.**

***Index Terms*—segmented mirror, mechanism, hinges, footprint area**

I. INTRODUCTION

Space exploration is gaining keen attention from scientists, engineers and astrologers for their research and future predictions. The future science goals of the Ultraviolet-Optical-Infrared (UVOIR) astronomy community include detailed study of the birth and evolution of distant galaxies and planetary systems [1]. Deep space antennas are becoming essential parts of upcoming space technology wherein large aperture of telescopic reflectors is an important parameter to look for. The maximum diameter of launching vehicles limits the diameter of a satellite to about 4m, but mirrors larger than this are required for earth observation, astronomy and communications [2].

The next generation of space-based imaging systems will push the limits of design methodologies, achieving performance that has previously been impossible [3]. Whether the goals are Earth imaging systems with better ground resolution and located in higher orbits, or astronomical telescopes looking back into time, the desired increase in optical resolution can be obtained through the use of larger primary apertures.

Development of segmented deployable mirror is one prevalent approach being considered to satisfy these conflicting requirements. Using the segmentation approach, the primary mirrors can be folded up and carried on launchers, and then they can be deployed to its full diameter in orbit [4]. Though the segmented mirrors give us a way to launch very large telescope mirrors into space and eliminate all problems/challenges in fabrication, handling and polishing of mirrors unlike in monolithic mirrors, they are not as simple as they look.

While these challenges are immense, they can be dealt through the use of lightweight, actuated, segmented primary mirrors. Instead of the traditional monolithic design, the primary aperture is made up of multiple smaller mirror segments which are easier to manufacture.

Though the segmented mirror approach looks to a viable solution, reducing the segmented mirror assembly is a real challenge, particularly the mechanism adopted to fold the segment assembly and yet maintain the alignment of segments to required degree of accuracy (typically in terms of nanometres)

The design and the approach adopted for deployment and folding of the segmented mirror has an important bearing on the functional performance and accuracy of the mirror. Also, the mechanism design shall be made to use minimum power to operate, occupy lowest volume and have less number of joints, links and simplest in design. There are many mechanisms available in the literature and have their pros and cons and are not suitable to operate in space bound applications.

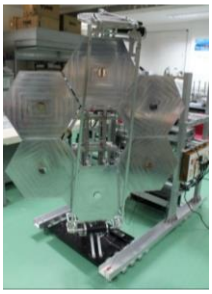

Figure 1. Vertically aligned segmented reflector [5].

II. EXISTING CCONCEPTS: CTATE OF ART

Inspired from James Webb Space Telescope, Dr. A.R. Srinivas developed a vertically aligned deployment mechanism for reflector diameter of 1.2 m [5] as shown in Fig. 1. Segment shape was optimized to hexagonal shape for obtaining more fill factor. Two segments connected with the central frame are kept rigid whereas

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remaining four segments attached on the sides are connected to the central frame with the help of a movable arm.

Mark S. Lake [6] showed that mechanical deployment is acceptable for NGST because an 8m mirror can be packaged in a 3m to 4m launch shroud using simple deployment kinematics, and a minimal number of deployment mechanisms (Fig. 2)

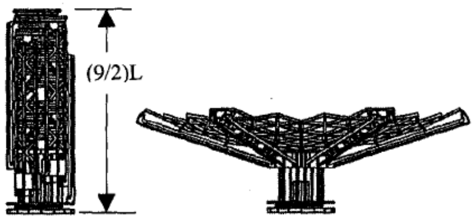

Figure 2. Package volume dimensions for starburst [6]

The current state-of-the-art in space telescope development is James Webb Space Telescope (JWST) (Fig. 3). JWST uses actuation of the rigid body motion of the mirror segments, and has an extensive modeling effort associated with its development [7]. Models for many subsystems, such as thermal, optics, and structures, are combined in order to calculate the performance of the system [8], [9]. JWST is a large aperture, space telescope designed to provide imaging and spectroscopy from 1 to 29 µm. The primary mirror is a segmented, 6.6 m diameter (inscribed circle) aperture and is mounted on a backplane structure which also serves as the mounting point for the deployable secondary mirror structure.

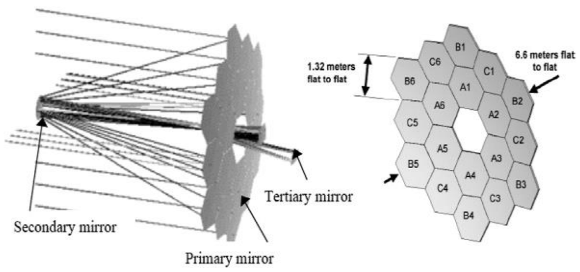

Figure 3. James web space telescope [7]

III. Design Approach

This section presents design criteria for kinematic linkages in developing deployable mechanisms of a reflector mirror. In order to calculate the number of degrees of freedom of one linkage that can be considered as rotational motion, Suh and Radcliffe [10] proposed a mobility criterion formula known as

$$f = 3\,(L - 1) - 2J_1 - J_2 \qquad (1)$$

f =Total degrees of freedom in linkage

L =Number of links

J_1 =Number of lower pairs which represent kinematic pairs with one degree freedom

J_2 =Number of higher pairs which represent kinematic pairs with two degree of freedom

The basic requirement of the mirror is that it should be rotated around one axis only. For 1 degree of system we will substitute the values and will decide the required number of links for one rotation of segment. Thus substituting f = 1, J1 = 1, and J2 = 0, we get L = 2. Hence we can use two links to rotate a segment out of which one will be stationary while other one will be rotating.

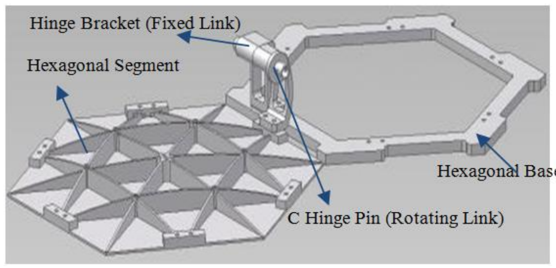

Figure 4. Folding mechanism of single segment

A. Modelling and Optimization

Modeling, simulation, optimization, and the design process are critical to the development and design of any complex system. Certain design factors like stiffness, rigidity, flexibility etc are kept under prime concern while designing a deployment mechanism. Primary concern is given to volume reduction of the overall unit to minimum. Trial and error approach is usually implemented to arrive at a particular design conclusion. Modeling software namely Autodesk Inventor was used to model the components and to understand the concept of mechanism virtually. Weight and size are the two factors which were given prime concern while design.

B. Material

Selection of material is an important aspect in any design process, because of cost associated with them. Apart from cost, materials selected should sustain varying thermal and static loads. Actuated Silicon Carbide (SiC) bears number of reason to be used as mirror material. SiC mirrors can be more quickly formed and some of the lengthy polishing process can be replaced with the actuation that reduces distortion.

Since SiC mirrors proves to be costly for demonstration purpose, we have manufactured segments from space qualified AL 6061 material. All other parts of the mechanism are also manufactured from AL 6061 because of its less areal density and good thermal properties to sustain fluctuation in thermal loads.

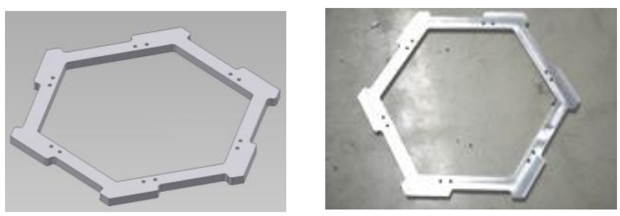

Figure 5. CAD model and actual image of hexagonal base frame

C. Hexagonal Base Frame

Six segments are connected with a rigid hexagonal base frame which acts as a stiff support for segments. Various links are used to connect the segments with the base frame so that segments can be folded and deployed at ease. Its size is restricted to 202 mm measured from one face to another face. Its thickness is kept to 6.5 mm. The central part of the hexagonal frame is scooped so as to accommodate receiver and to reduce its weight.

D. Fixed Hinges

Hinge brackets serve the purpose of fixed support to the rotating links. An axle is placed in the hinge brackets such that the segment rotates around a fixed axis. Simple Z shaped brackets were designed and their heights were varied so as to rotate the segments around a fixed axis. Three types of hinge brackets are designed with only difference between them is of their heights. Their heights are 45 mm, 53 mm and 63 mm as shown in Fig. 6. Moreover material from the brackets was scooped so as to reduce its weight and increase its strength to resist bending.

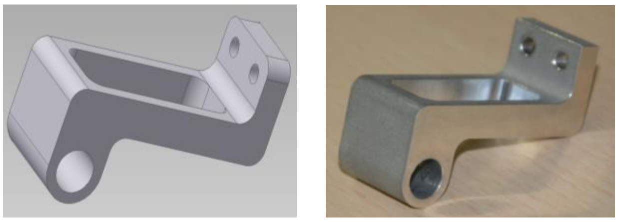

Figure 6. CAD model and actual image of hinge bracket

E. Rotating Hinges

To rotate the segments around a fixed axis a movable link is designed which helps in avoiding hitting segment with the base frame. Similar to hinge brackets these are also designed in three different sizes because these hinge pins must have same heights as of brackets. Segments will be attached to base of hinge pins and with the help of drive that segment is rotated. Certain designs were first proposed but by modifying them final design were selected which is shown in Fig. 7.

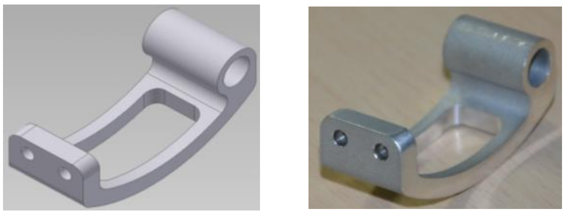

Figure 7. CAD model and actual image of C Shaped Hinge

F. Axle for Motor Shaft

To rotate a segment around a fixed axis motor drive is used. Hence to accommodate shaft of a DC motor, an axle is designed with I.D of 8 mm and O.D of 12 mm, such that it will grip the shaft and will transfer its rotary motion to C hinge pins. During manufacturing tolerances are maintained tightly and a tight fit in maintained so that motion is transferred effectively without any slip.

Figure 8. CAD model and actual image of Axle

G. Motor Torque

To fold a segment against gravitational force, a motor drive of sufficient torque carrying capacity should be selected.

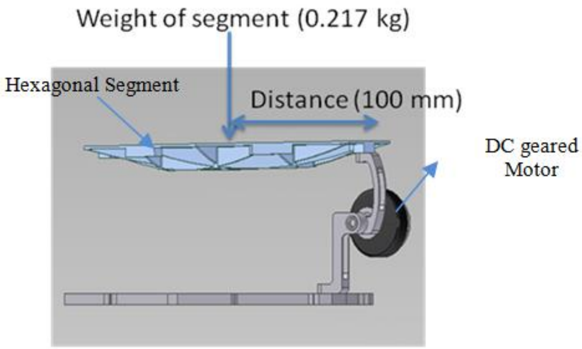

Figure 9. Calculation of motor torque

$$\text{Torque} = \text{Force (wt of segment) x radius (dist.)} \qquad (2)$$
$$= 2.2 \text{ N x } 0.1 \text{ m}$$
$$= 0.22 \text{ N m}$$

Hence torque required was evaluated according to formula and we selected a motor having capacity of transmitting torque of 1 Nm for safer side.

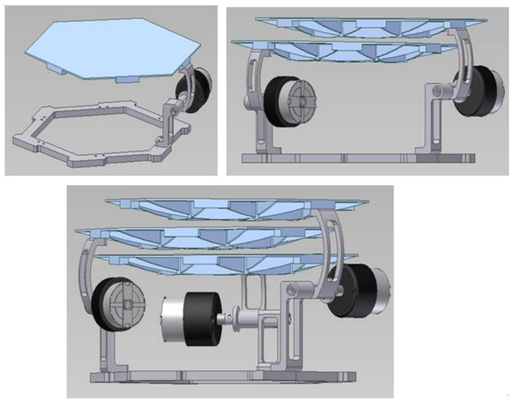

Figure 10. Sequence of folding segments

IV. FOLDING/DEPLOYING CONCEPT

Before packing the telescopic mirror in launching vehicle it is folded to its minimum volume possible in a pre-determined sequence. Since the folding concept of the proposed design is very similar to the Lotus Flower, this mechanism is named as “Lotus Mechanism”.

Firstly smallest hinge pin (in height) is rotated in counter clockwise direction around its axis by 185° from deployed to stowed condition. Similarly another hinge pins with increasing heights are rotated in counter clockwise direction around their respective axis such that all three segments will stack together one on another.

Thereafter, other alternate three leftover segments are similarly rotated in counter clockwise direction by 120° around their respective axis. Final assembly of all the folded segments at their respective predetermined position is shown in the figures (Fig. 11) below.

The mechanical simplicity of the deployable primary mirror implies a low development cost and risk as well as low risk of deployment failure. Specifically, vertical stowage of the deployable segments requires a packaging volume that is approximately twice as long as its diameter.

After folding all segments, three alternate segments which are stowed vertically bears an angle of 185° i.e. $\theta_1 = \theta_2 = \theta_3 = 185°$. Remaining three segments which are rested vertically bears an angle of 120° i.e. $\theta_4 = \theta_5 = \theta_6 = 120°$.

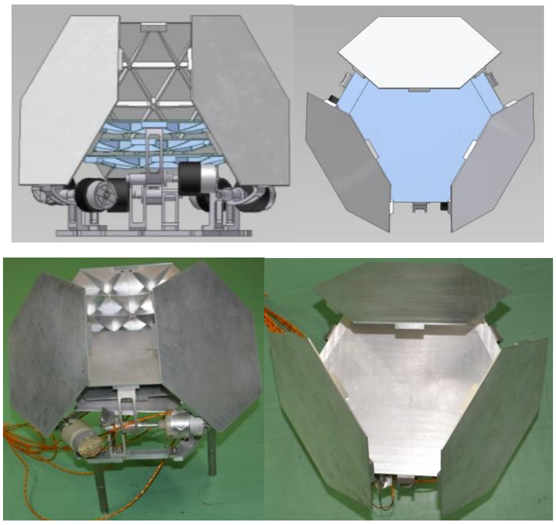

Figure 11. Different views of final assembly in folded condition

V. Reduction in Footprint Area

After folding the segments to their predetermined positions, overall foot print area should reduce marginally so that they can be accommodated in launch vehicle (consuming less space than monolithic mirror) with ease. Hence for the proposed mechanism calculation was carried out for the reduction in area which is explained below:

$$\Delta A = \left(A''(d)'' - A''(f)'' \right) \Big/ A''(d)'' \times 100\% \quad (3)$$

where ΔA = Reduction in area, %

A (d) = Area of Deployed Segments, mm^2

A (f) = Area of Folded Segments, mm^2

In designed mechanism, calculated area of folded and deployed segments is,

A (d) = 3.55×10^5 mm^2 and A (f) = 1.01×10^5 mm^2

As per Eq. (3), we get **71.54 %** reduction in total area of segments after folding. Several benefits are encountered because of segmenting and folding the segments which are enlisted below:

- It reduces the overall cost and weight of the mirror.
- There is also less risk in manufacturing smaller segments. If one of the segments is damaged, it can be easily replaced. If a monolithic mirror is damaged, the entire part needs to recast again.
- Fabrication of small segments is always easy compared to full size monolithic mirror.
- Total foot print area of the folded mirror is greatly reduced.

VI. Summmary and Conclusion

Lotus Mechanism is a project carried out to overcome the problem of launching space available for large sized telescopic mirror. In this paper we presented a simple mechanism to deploy segments, with an emphasis on design of hinges. Variation in inter-segmental gaps depends largely on accuracy of motor and the tolerances of hinges maintained during manufacturing.

Operation of motors is carried out manually by giving power to each motor individually at a time. Regardless of programming challenges there is scope ahead to automate the control of motors via programming, enhancing in accurate positioning of segments.

Major drawback of the Lotus mechanism is that it is very difficult to increase the number of segments because by doing so more and more complexity will be added to the system. Only way possible is to increase the size of individual segment rather than increasing number of segments till the launch vehicle is capable enough to accommodate.

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