A ROBOTICALLY-ASSEMBLED 100-METER SPACE TELESCOPE

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The future of astronomy may rely on extremely large space telescopes in order to image Earth-sized exoplanets or study the first stars. In-Space Telescope Assembly Robotics (ISTAR) is a new paradigm for developing large telescopes while overcoming some of the most limiting constraints of current designs. The ISTAR project has developed a concept for an optical space telescope with a collecting area of nearly 8000 m$^2$, launched in pieces from the ground, and assembled by a dexterous robot in space. The proposed concept breaks the cost curve by using unique optical layouts, a high degree of modularity, bulk manufactured parts, lightweight structures, and formation flying. Preliminary analysis shows that the design meets high-level optical requirements to yield diffraction-limited images with a wavefront correction system.

This paper focuses on the concept and structural analysis of the telescope. Presented first is the optical scheme, which utilizes a spherical mirror 131 m vertex-to-vertex. Structural requirements are then derived from the limitations of the wavefront control system. The remainder of the paper details the concept of the primary mirror, the largest and most complex component, consisting of two layers: mirror segments and a supporting truss structure. Because the mirror is spherical, every mirror segment is identical, which facilitates a highly modular structure. The 6289 segments in the mirror layer are grouped into 331 mirror modules, each containing 19 segments and all associated actuators. Each mirror module is backed by a deployable truss module. The robot builds the mirror by deploying and connecting all truss modules first, then crawling on the resulting stiff surface to place each mirror module. The truss module provides stiffness and support to the mirror, and thus it must be designed to meet and maintain precision requirements under operational loads. The effect of the following loads on the structure are analyzed: fabrication and assembly errors, gravity gradients, thermal effects, and vibrations. A concept of the truss module that meets requirements is derived and presented.

I. INTRODUCTION

The bigger the telescope, the deeper we can probe, the fainter we can detect, the wider we can survey, and thus the better we can understand the universe. In 2018, the James Webb Space Telescope (JWST) is scheduled to become the largest ever built, and concepts for its even bigger successor are already being formulated. At just 6.5 m in aperture diameter, JWST is already too large to fit in a payload fairing in its final configuration, and must instead be assembled on Earth, folded for launch, and unfolded in space. The most innovative foldable concepts, like DARPA’s MOIRE and NASA’s
ATLAST, are sized at the 20 m range\(^2\). The achievable size of deployable telescopes is then strictly limited by the size of the payload fairing. While advances in lightweight and flexible materials can push this limit, folding up and deploying a telescope many times larger may not be realistic. The progression of space telescopes thus necessitates a new strategy.

One solution is In-Space Telescope Assembly Robotics (ISTAR). To reach larger scales, the telescope can be assembled in space, rather than on the ground, no longer limiting the aperture size by launch capacity. The ISTAR concept presented here outlines an architecture for a robotically-assembled optical space telescope that can reach up to the 100-m class. The architecture is entirely modular, enabling an expandable and evolvable system that can be suited to meet a range of missions and aperture sizes. This paper is focused on the development and feasibility of the 100-m class telescope to stretch the limits of the architecture. The complexity of constructing a large aperture is addressed through symmetry and modularity in the structure and use of robotic assembly. The concept is based on a set of precision requirements and correction methods using currently available technology. In this paper, the concept of the primary mirror, the largest component of the system, is described in detail, including component design and assembly plan. Preliminary structural and thermal analyses demonstrate that the precision requirements can be met.

II. TELESCOPE CONCEPT

II.1 Observatory Components

The ISTAR concept is a segmented, steerable, UV to near IR telescope robotically assembled in space. Fig. 1 shows the basic layout of the telescope and its four main components: the sunshade, primary mirror, Spherical Aberration Corrector (SAC) unit, and metrology system. Given the large size of the telescope, each of these components is structurally separate and formation flown. Each component is a self-contained unit with its own power, thermal control, and propulsion system that maintains formation.

The optical design borrows from that of the ground-based Hobby-Eberly Telescope (HET) and Southern African Large Telescope (SALT) by utilizing a spherical curvature primary mirror\(^4\).\(^5\). The primary mirror acts as a "precision light bucket", and is phased into a diffraction-limited telescope at the exit pupil inside the SAC using a technique described in Reference 6. One key advantage of this design is that the majority of the wavefront sensing and control (WFSC) and the only active deformable mirrors are offloaded from the primary mirror to the much smaller optics in the SAC. The primary mirror segments are identical, manufactured in bulk, and only require tip-tilt control, sharply reducing mirror fabrication costs, which is one of the most significant cost drivers in observatories. The SAC mirror segments have the same basic characteristics, but are deformable with \(\mu\)-level actuation range and correctable down to nm-level. The baseline mirror segments are drawn from currently available technology, and are assumed to have a hexagonal shape with vertex-to-vertex length of 1.35 m. Because the segments are hexagonal, the full primary mirror will also be approximately hexagonal. The primary mirror parameters are summarized in Table 1. The light-collecting area is equal to that of a 97.3-m filled circular aperture.

| Vertex-to-vertex length [m] | 131.88 |
| Light collecting area [m²] | 7444 |
| Radius of curvature [m] | 800 |
| Number of segments | 6289 |
| Segment vertex-to-vertex length [m] | 1.35 |
| Total areal density [kg/m²] | < 30 |
| Field of view [arc minutes] | 4.2x4.2 |

Table 1: Primary mirror (M1) parameters.

Structurally connected to the primary mirror is also the driving spacecraft and two solar panels similar to the ones used on the International Space Station, as determined by a preliminary power budget. The solar panels are connected to the spacecraft, which is located below the primary mirror in the center. The fully assembled unit is shown in Fig. 2.

Fig. 1: Diagram of ISTAR optical scheme.

Fig. 2: Fully assembled primary mirror with central spacecraft and solar panels.
The SAC is located halfway to the center of curvature of the primary mirror, for a separation distance of 400 m. It includes two 8.6-m clamshell aspheric mirrors, separated by 24.4 m. A ray trace diagram is shown in Fig. 4. Another major advantage of the spherical aperture is that the SAC can be moved relative to the primary mirror to observe a new target within a 7.16 deg field of regard without having to move the massive primary mirror. This enables rapid transition to a new observation without the overhead of time and fuel otherwise required to slew the primary mirror and wait for its dynamics to settle. The locus of motion of the SAC with respect to the primary mirror is a spherical surface of 400-m radius of curvature and 50-m diameter, as shown in Fig. 5. In the nominal position, the SAC is at the center and the entire primary mirror is visible. However, when it is moved to the limit of its range of motion, only about 40% of the primary can be seen, as shown in Fig. 3.

The metrology system is located at the center of curvature of the mirror. It contains a Zernike wavefront sensor and an Array Hetrodyne Interferometer to precisely measure the shape and phase of the primary mirror segments.

The sun shade design borrows from deployable solar sails such as Sunjammer, which is 38 m square and is scheduled to be launched in 2015. Four deployable masts extend from a central hub radially outward, carrying the corners of the sun shade to a full distance of 70 m, as shown in Fig. 6. The Shuttle Radar Topology Mission, launched in 2000, used a 60-m mast built by ATK. Thus, 70 m appears feasible with current technology. The shade membrane will be chosen based on thermal constraints described in Section IV.III.

II.II Primary Mirror Assembly Plan

The primary mirror is the largest component of the telescope and thus the focus of robotic assembly. A representation of the ISTAR robot needed to assemble the mirror is shown in Fig. 8. The robot will be commanded from Earth, but with significant on-board autonomy to minimize the bandwidth of communications to a human operator. The resulting supervised autonomy system will enable the Earth-based operator to specify high-level commands, while the robot performs all sensor-based motion and complex tasks autonomously.

Drawing upon the development of the Lemur and RoboSimian robots at JPL, the ISTAR robot is anticipated to have six appendages. During assembly, two of these appendages can be used for dexterous manipulation while the other appendages remain attached to the structure. All six appendages can be used to walk on the structure. Perception and dexterous manipulation
technologies that will be needed have been demonstrated in a laboratory environment at JPL\textsuperscript{11}. The robot is battery powered and can be charged from the primary mirror power grid.

The primary mirror consists of two layers: the mirror segments, which includes rigid body actuators and electronics, and a supporting truss structure. Because the primary mirror is spherical, all mirror segments are identical, which enables a highly modular structure. Groups of segments and their actuators are hexagonally packed into a cluster called a mirror module. Each mirror module is backed by a rigid plate which features structural and power connectors. Given the complexity and fragility of the segments and associated electronics, mirror modules are assembled on the ground by humans and launched as a package.

The truss layer is broken down into hexagonal truss modules, which are deployable structures sized to match one mirror module when fully deployed but can stow compactly for launch using internal hinges. An assembled mirror module and truss module are shown in Fig. 9. Each truss module is equipped with structural and power connectors located at the ends of each vertical member, with internal wiring throughout the members to transmit power. These connectors are structurally adjustable by the robot to ensure proper alignment between modules. The vertices of the main face of each module also features ball-like features which the robot can grasp while walking.

In space, the robot retrieves the first folded truss module from a central canister and deploys it so that the internal hinges lock. The robot then attaches the truss module at the connection points to a central hub that is rigidly mounted and wired to the spacecraft and solar panels. The robot then continues to assemble truss modules in concentric rings around the central hub. After each ring is assembled, a metrological measurement is made to check the assembly for adherence to alignment tolerances. The robot then uses this measurement to adjust the connectors and complete the ring. This pattern is repeated until the entire truss is built.

Once the truss is complete, the robot begins assembling mirror modules. The robot interfaces with the mirror module through the rigid plate, avoiding the sensitive mirror segments. In the same concentric ring pattern, the robot assembles mirror modules by attaching them to the underlying truss. Mirror modules are connected only to the truss, not to each other, to avoid
stress build-up. The module assembly process is summarized in Fig. 7.

It is unlikely that truss modules will need to be serviced. However, mirror segments are sensitive and may encounter issues (e.g. meteoroid hits). Servicing of individual segments may be too complex for the robot, so instead the entire mirror module can be replaced. The connectors that attach the module to the truss will also be able to detach from the truss as needed.

II. III Mission Requirements

The wavefront sensing and control system has three levels of correction. First, as mentioned in the assembly concept, the truss will be robotically adjustable during construction. This corrects for fabrication and assembly errors. Second, the primary mirror segments are backed by rigid body actuators for removing quasistatic errors such as thermal loads. Finally, the active mirrors in the SAC remove any additional effects, including dynamic errors. The correction levels, defined below, are consistent with the current state-of-the-art.

- Robotic truss adjustment: 30 mm to 3 mm
- Rigid body actuators: 10 mm to μm -level
- Active mirrors: μm -level to nm-level
  - Also corrects up to 240 mm of change in radius of curvature

The telescope design must ensure that errors remain within the range of correction.

Along with the precision requirements, the following other functional requirements must be met:

- The telescope shall be functional no more than three minutes after a slew maneuver.
- The telescope shall operate at temperatures between 240 K and 300 K.
- The primary mirror shall have an areal density less than 30 kg/m². Since the mirror segments and actuators have a density of 25 kg/m², this leaves 5 kg/m² for the truss.
- Mirror segments shall have a gap of 100 ± 10 mm to facilitate the ball-like features that the robot uses to walk on the mirror surface.
- The telescope shall nominally operate in a geosynchronous orbit (GEO).

The ISTAR baseline to operate at GEO was chosen with the expectation the telescope would then also be suited for Lagrange point operation with few modifications, because the environment at GEO is more severe and thus produces more stringent design requirements.

The most customized parts of the architecture are the truss and mirror modules. Their design, described in the remainder of the paper, is based on these requirements.

III. MIRROR MODULE DESIGN

The mirror modules are all identical. Their geometry is based on the following key considerations:

- The module contains \( n \) identical, spherical mirror segments arranged according to a hexagonal tessellation.
- The value of \( n \) is chosen to be as large as possible to maximize launch capacity so that the modules can be stacked inside a payload fairing.
- The gaps between the mirror segments are 100 ± 10 mm to facilitate robotic mobility, as stated in Section II. III.
- The gap size between segments must vary to allow the hexagonal segments to lie on a spherical surface.

Fig. 10 shows three choices for \( n: 7, 19, \) and 37 segments. With the nominal 100-mm gap between segments, these designs yield maximum mirror module dimensions of 3.77 m, 6.28 m, and 8.81 m respectively. Since the proposed SLS launch vehicle will have a payload fairing with an outer diameter of 8.4 m, the \( n = 19 \) design was chosen\(^\text{12}\). With 6289 segments total, this design yields 331 mirror modules. Given their 25 kg/m² areal density, the total mass of the mirrors and actuators is then 145,300 kg.

The curvature of the mirror requires variable gap sizes between the mirror segments. The distribution of the gap size is a design parameter that has been studied in detail. An algorithm to place the segments on a spherical surface while imposing different constraints on the gap variations was developed\(^\text{13}\). A solution was obtained in which the gap sizes between mirror segments within a mirror module vary by no more than 1.7 μm, with the distribution being identical for all mirror modules. The gaps between one mirror module and another mirror module were also minimized with this solution, with values ranging from 98 mm to 101.3 mm. This result is well within the required tolerance of ± 10 mm.

The mirror modules will be assembled on the ground, incorporating the variable gap distribution that has been calculated. The variation in the larger gaps between
modules will be created by the robot using the adjustable connectors on the truss modules described in Section II. Note that the gaps between the modules increase linearly with depth through the truss thickness, and hence will be larger on the back side of the truss than on the front. However, because the radius of curvature is much larger than the depth of the truss, the difference is still well within the range of the adjustable connectors.

IV. TRUSS MODULE DESIGN

The truss geometry must facilitate a compact storage profile and a smooth deployment. A modified version of the Pactruss deployment scheme has been selected. Pactruss was developed by Aerospace Corporation specifically for large precision telescope structures. It was originally intended to provide an entirely deployable telescope backing structure, consisting of many triangular unit cells simultaneously unfolding. One flavor of the deployment scheme is shown in Fig. 11. This design was analyzed to show that it could maintain sub-micron precision under operational loads when fully deployed. However, there were issues in the deployment simulations controlling the order in which the many hinges were locked. The ISTAR concept removes this uncertainty because only one hexagonal unit cell is required for the truss module, greatly reducing the number of hinges that act simultaneously. The module and deployment scheme are shown in Fig. 12. The unit cell consists of 39 members: the 12 longerons that make the hexagonal face on each side (24 total), 7 verticals, 4 face diagonals, and 4 internal diagonals. The diagonals and 8 longerons are hinged in the center. In the compact state, the truss module folds like an umbrella, and thus the stowage footprint is determined by the hinge offsets and the outer diameter of the members.

The truss module dimensions are defined in Fig. 13. In order to reduce the number of redundant members, the truss modules are rotated with respect to the mirror modules, rather than hexagonally packed, as shown in Fig. 14. The value of the side length \( L \) must match this tesselation pattern, governed by the mirror module size. For \( n = 19 \) as chosen, \( L = 2.6 \text{ m} \).

M55J carbon fiber composite has been selected for the truss material, because of its high stiffness and low density. The truss depth, \( H \), and member cross-section properties, \( d_0 \) and \( t \), control the structural response to external loads, and thus must be chosen to ensure that all of the precision requirements for the primary mirror are met.

It is not known which source of shape error is in general the most demanding for a large space telescope. Thus, to determine the specific values of the design variables of the truss module, it is necessary to consider...
separately the requirements associated with each specific error source.

IV.I Fabrication and Assembly Errors

The fabrication and assembly errors must not exceed 30 mm (see Section II.III). The accuracy with which the truss can be built is currently unknown, as the joints, hinges, and connectors in the truss have yet to be designed, and the manipulation capabilities of the robot are not known in detail. Hence, assembly errors on the level of 10 mm, 1 mm, and 0.1 mm were considered to estimate the accuracy level needed to meet the 30 mm precision requirement. These errors were treated as length changes, $\delta l$, in the members of the truss to represent fabrication errors or slide in the hinges. A pin-jointed model of the truss was built in MATLAB. Each member was assigned a $\delta l$ value from a random uniform distribution with maximum amplitude given by the accuracy level. The resulting displacements were computed and this process was repeated 10 times for each accuracy level to obtain average and maximum values.

IV.II Gravity Gradient

Gravity gradients arise when one part of the telescope is closer to the Earth than another part. This effect is negligible for small telescopes, but becomes more significant for larger Earth-orbiting telescopes. Gravity gradients cause quasi-static errors in the mirror figure, and thus the resulting distortion magnitude cannot exceed 10 mm, as discussed in Section II.III.

The magnitude of the gravity gradient distortion on the primary mirror depends on its orientation with respect to the Earth. The maximum gravity gradient occurs when the mirror is oriented radially along the line of gravity, as shown left in Fig. 15, causing an axial distortion. However, the truss is much stiffer axially than in bending, and thus other orientations that have less of a gravity gradient may still have greater distortion.

In general, the distorting force on any node within the primary mirror comes from the difference between the gravitational force and the centrifugal force, which is set by the orbit. If the vector between the center of mass of the mirror and the center of the Earth is $r$, then the centrifugal force, $F_c$, on a node $i$ of mass $m_i$ is given by:

$$ F_c = \frac{\mu m_i r}{||r||^3} \quad [1] $$

Letting $u_i$ be the vector between the center of mass and the node $i$, the gravitational force, $F_g$, is given by:

$$ F_g = \frac{\mu m_i (r - u_i)}{||r - u_i||^3} \quad [2] $$

$F_{dat}$ is then the difference between these forces.

The distortions due to gravity gradient loads were computed from a finite element model of the primary mirror structure, consisting of pin-jointed elements and lumped masses distributed throughout the top surface to represent the mass of the mirrors and actuators. The nodes associated with the center module were fixed. The mass matrix for the entire model was computed and the mass associated with each node was used to calculate the gravity gradient loads. The depth and member cross-section were varied until an acceptable solution was found.

IV.III Thermal Analysis

The bulk thermal requirement is that the primary mirror must operate at $270 \pm 30$ K, as stated in Section II.III. However, one of the most detrimental thermal effects is a change in curvature of the primary mirror, which arises from a temperature difference through the mirror thickness, or from the mirror surface to the backside of the truss. The rigid body actuators, with a range of 10 mm, can correct for this type of error. In addition, the wavefront control in the eyepiece can counteract 240 mm of additional change in the radius of curvature from the nominal 800 m.

When the curvature changes, the sag of the mirror changes. The sag $x$ is the height difference between the mirror edge and mirror center, as shown in Fig. 16. The aperture diameter $D$ is defined in this picture as an arclength on the circle of radius $R$ that subtends angle $\phi$. This is to ensure that, as $R$ changes, the length of the mirror neutral axis stays constant. If $\phi$ is small (only about $3.5^\circ$ in the nominal case), the sag $x$ is approximately $(D/2)^2/(2R)$. The rigid body actuators can account for change in sag $dx$ of 10 mm. Given that the average diameter of the hexagon is about $D = 122$ m,
the maximum change in curvature $\Delta K$ that can be removed by the rigid body actuators is given by:

$$\Delta K = \Delta (1/R) = \frac{2d x}{(D/2)^2}$$

$$= 5.37 \times 10^{-6} \text{m}^{-1}$$

The wavefront correction system can account for an additional curvature change of $\Delta K = \Delta (1/R) = (1/800 \text{ m} - 1/800.240 \text{ m}) = 3.74 \times 10^{-7} \text{m}^{-1}$. Thus the total allowable curvature change is $\Delta K_{\text{max}} = 5.70 \times 10^{-7} \text{m}^{-1}$.

The curvature is then related to the temperature differential by the truss depth $H$ and material expansion coefficient $a_{\text{TRUSS}}$:

$$\Delta T_{\text{max}} = \frac{\Delta K_{\text{max}} H}{a_{\text{TRUSS}}}$$

Given $a_{\text{TRUSS}} = 1.1 \times 10^{-6} \degree \text{C}^{-1}$ for M55J carbon fiber composite and the curvature change obtained above, Equation [4] yields the maximum allowable temperature difference in terms of the truss depth, $\Delta T_{\text{max}} = 5.23 \cdot H \text{ °C}$.

In GEO, there are three distinct thermal environments, shown in Fig. 18. The temperature gradient in each case was estimated using energy balance on a simple thermal model. Fig. 17 shows a module of the truss, where surface 1 is the mirror surface and surface 2 is the back surface of the truss, consisting of a triangular tessellation of members with large gaps in between them.

In case 1, the telescope is pointed at the Earth with the Sun behind the sun shade. Surface 2 receives heat from the Sun that leaks through the sun shade. Surface 1 receives heat from the Earth’s surface radiation and albedo reflection from the Sun, as well as heat from the Sun that leaks through the sun shade and is not blocked by Surface 2. In addition, both surfaces exchange heat through radiation and conduction. By defining each of these inputs, the temperatures of both surfaces were found from the energy balance. The geometric parameters of the truss, the optical properties of the materials, and the fraction of heat blocked by the sun shade were varied until the temperatures were within 270 ± 30 K and the difference between the temperatures was less than the requirement. The full energy balance derivation can be found in Appendix A.

**IV.IV Dynamics**

It is assumed that, in order to passively reject vibrations and maintain the required dynamic precision of 1 $\mu$m, the fundamental frequency must be higher than the frequency of vibrations. One of the major sources of vibrations are reaction wheels. From Reference 16, the requirement on the fundamental frequency of the structure to reject reaction wheel disturbances is given by:

$$f_0 > \begin{cases} 
 f_c \sqrt{v_c} - 1, & v_c \geq 1 \\
 f_c, & v_c < 1 
\end{cases}$$

$$v_c = \frac{n_{\text{RWA}} U_s}{2 \zeta M_{\text{total}} \delta_{\text{max}}}$$

where $f_0$ is the telescope fundamental frequency, $f_c$ is the cut-off frequency of the isolation system, $n_{\text{RWA}}$ is the number of reaction wheels, $U_s$ is the static reaction wheel imbalance, $\zeta$ is the damping coefficient, $M_{\text{total}}$ is the total mass of the telescope and spacecraft, and $\delta_{\text{max}}$ is the maximum allowable deformation.

In the present case, $\delta_{\text{max}} = 1 \mu$m, and the damping coefficient was conservatively chosen as 0.005. Reference 16 states that a typical value for $U_s$ is $5 \times 10^{-6}$kg·m. It can be assumed that $v_c < 1$, and the fundamental frequency of the structure only needs to exceed the isolation cut-off frequency in order to maintain precision under reaction wheel imbalance loads. Isolation systems can achieve cut-off frequencies on the order of 0.1 Hz.17.
There are many other possible sources of vibrations on the spacecraft, such as the mirror actuators and joint settling. Control moment gyros may also be used instead of reaction wheels, which will have different vibration characteristics. Rather than addressing each source individually, it is practical to assume a spectrum of random vibrations. The minimum fundamental frequency to reject random disturbances is given by:

\[ f_0 > \frac{1}{2\pi} \left( \frac{G_0}{8\dot{\epsilon}_{\max}} \right)^{1/6} \]  

where \( G_0 \) is the RMS amplitude of the disturbance power spectral density over the bandwidth of their frequencies\(^\text{17}\). Assuming a 1\(\mu\)g amplitude and a 0-100 Hz bandwidth, \( G_0 = (9.8 \times 10^{-6} \text{m/s}^2) / 100 \text{ Hz} = 9.6 \times 10^{-13} \text{m}^2/\text{s}^3 \), which yields a minimum fundamental frequency of the telescope of 0.459 Hz.

Finally, one functional requirement is that the telescope shall be usable no more than three minutes after a slew maneuver. The exact response of the structure to a slew maneuver depends on the torque profile, the propulsion system, and other parameters not specified at this design stage. However, the settling time \( T_s \) required for structural distortions to fall below 2\% of the initial distortion amplitude can be estimated by considering a single-degree-of-freedom system: \( T_s = 3.9/\zeta \omega_0 \), where \( \omega_0 = 2\pi f_0 \). Again assuming \( \zeta = 0.005 \) and requiring that \( T_s < 3 \) minutes implies that the fundamental frequency must be larger than 0.69 Hz, which is the most stringent dynamic requirement.

The fundamental frequency was estimated from the finite element model described in Section IV.II.

### IV.V. Analysis Results

After an iterative process that included each of the loading types outlined above, the design converged to the parameters presented in Table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truss side length, L [m]</td>
<td>2.6</td>
</tr>
<tr>
<td>Truss depth, H [m]</td>
<td>2.6</td>
</tr>
<tr>
<td>Member outer diameter, d_o [mm]</td>
<td>45</td>
</tr>
<tr>
<td>Member wall thickness, t [mm]</td>
<td>3</td>
</tr>
<tr>
<td>Truss areal density [kg/m²]</td>
<td>4.01</td>
</tr>
<tr>
<td>Truss mass [kg]</td>
<td>23352</td>
</tr>
<tr>
<td>Primary mirror mass [kg]</td>
<td>168690</td>
</tr>
</tbody>
</table>

**Table 2: Truss module design parameters**

Firstly, as described in Section II.III, the truss areal density is confined to less than 5 kg/m². This requirement is met with a margin of 1 kg/m², which may be allotted to the mass of the truss hinges and connectors. This design has a fundamental frequency of 1.0 Hz, which satisfies the dynamic requirements with a good margin. Despite the size of the telescope, the effect of gravity gradient was still negligible. The maximum distortion occurred when the mirror was oriented approximately 45 deg to the line of gravity (as roughly shown middle in Fig. 15), but this distortion did not exceed 46 nm.

Assembly errors on the level of 10 mm, 1 mm, and 0.1 mm were applied to the truss. The resulting distortions of the truss were computed to obtain the RMS and maximum distortion on the mirror surface in the direction normal to the curvature, as well as the RMS and maximum overall distortion, which are shown in Table 3. The maximum distortions indicate that the input error can be greatly amplified in the structure, in some cases by a factor of almost six, demonstrating the effect of error build-up. It follows that, in order to meet the maximum 30-mm requirement, the structure must be built to a precision of at least 5 mm.

<table>
<thead>
<tr>
<th>Error level</th>
<th>10</th>
<th>1</th>
<th>0.1</th>
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<tr>
<td>RMS Surface Distortion</td>
<td>92.51</td>
<td>0.91</td>
<td>0.12</td>
</tr>
<tr>
<td>Max Surface Distortion</td>
<td>55.70</td>
<td>1.56</td>
<td>0.69</td>
</tr>
<tr>
<td>RMS Total Distortion</td>
<td>9.73</td>
<td>0.96</td>
<td>0.12</td>
</tr>
<tr>
<td>Max Total Distortion</td>
<td>57.10</td>
<td>5.63</td>
<td>0.71</td>
</tr>
</tbody>
</table>

**Table 3: Results of fabrication error analysis. The units are all in millimeters.**

From Equation [4], given \( H = 2.6 \) meters, the maximum allowable temperature difference through the truss thickness is \( \Delta T = 13.59 \) K. The thermal analysis was performed using the parameters given in Table 4, where \( \alpha_i \) and \( \epsilon_i \) are the absorptivity and emissivity of surface \( i \) respectively, which can vary between the top and bottom of the surface (refer to Fig. 17).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar flux ( q_{solar} ) [W/m²]</td>
<td>1370</td>
</tr>
<tr>
<td>Earth surface heat flux ( q_{IR} ) [W/m²]</td>
<td>237</td>
</tr>
<tr>
<td>Earth albedo ( \alpha )</td>
<td>0.3</td>
</tr>
<tr>
<td>Orbit altitude ( A_{orbit} ) [m]</td>
<td>35786</td>
</tr>
<tr>
<td>Earth radius ( R_e ) [m]</td>
<td>63788</td>
</tr>
<tr>
<td>( \alpha_{1,top} ) (Polished aluminum)</td>
<td>0.02</td>
</tr>
<tr>
<td>( \alpha_{1,bottom} ) (Paint)</td>
<td>0.6</td>
</tr>
<tr>
<td>( \alpha_{2,top} ) = ( \alpha_{2,bottom} ) (CFC)</td>
<td>0.96</td>
</tr>
<tr>
<td>( \epsilon_{1,top} ) (Polished aluminum)</td>
<td>0.03</td>
</tr>
<tr>
<td>( \epsilon_{1,bottom} ) (Paint)</td>
<td>0.87</td>
</tr>
<tr>
<td>( \epsilon_{2,top} ) = ( \epsilon_{2,bottom} ) (CFC)</td>
<td>0.88</td>
</tr>
<tr>
<td>CFC thermal conductivity ( k ) [W/m K]</td>
<td>156</td>
</tr>
</tbody>
</table>

**Table 4: Parameters used in thermal analysis. CFC stands for carbon fiber composite, assumed to be roughly matte black.**

Note that the bottom of the mirror modules is coated with flat colored (red, green, or brown) paint to yield the desired optical properties, while the truss maintains the
optical and thermal properties associated with black carbon fiber composite. The resulting temperatures of \( T_1 \) and \( T_2 \) for the three different environmental cases are shown in Table 5.

<table>
<thead>
<tr>
<th>Case</th>
<th>( T_1 ) [K]</th>
<th>( T_2 ) [K]</th>
<th>( \Delta T ) [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>278.03</td>
<td>273.29</td>
<td>4.74</td>
</tr>
<tr>
<td>Case 2</td>
<td>277.96</td>
<td>273.26</td>
<td>4.70</td>
</tr>
<tr>
<td>Case 3</td>
<td>89.21</td>
<td>86.59</td>
<td>2.62</td>
</tr>
</tbody>
</table>

Table 5: Thermal analysis results.

The bulk temperature constraint of 270 ± 30 K is maintained in only two of the cases; the thermal analysis shows that the telescope will not be able to operate when it is eclipsed by the Earth. In GEO, eclipses only occur during 3 months of the year, lasting 72 minutes at maximum, so this is an acceptable mission constraint. When not eclipsed, a modest sun shade blockage factor of \( \gamma = 0.6 \) keeps the primary mirror within temperature bounds and with an acceptable gradient through the truss thickness to maintain precision requirements. The material of the sunshade will have to be chosen to obtain this blockage factor.

V. SUMMARY

This paper has outlined a solution for 100-m optical telescope that is robotically assembled. The concept breaks the cost curve by utilizing an optical design with a spherical primary mirror. The shape allows for the wavefront sensing and control system to be offloaded to an eyepiece, so that the primary mirror segments can be inactive and identical, sharply reducing the cost of the control system and mirror fabrication. The assembly process of the primary mirror efficiently balances deployable structures with robotic operations. The primary mirror is broken down into groups of mirror segments called mirror modules, backed by separate deployable truss modules. In orbit, the robot deploys and assembles the truss around a central hub connected to a spacecraft, then attaches the mirror modules to the truss. The mirror modules have been sized to fit in the proposed SLS payload fairing. The truss modules provide stiffness and support to the mirror surface. Preliminary structural and thermal analyses have been performed to design the truss module and demonstrate that it can provide precision levels within the range of the wavefront correction system to yield diffraction-limited images. Some important parameters of the telescope are summarized by Table 6.

The telescope presented here is currently in the concept stage. Results so far are promising, and work is ongoing to bring the concept to a higher level of maturity. This includes better characterization of the metrology, eyepiece, and sun shade, as well as continued development of the structural components and robotic assembly.

VI. ACKNOWLEDGEMENTS

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| Primary Mirror vertex-to-vertex (V2V) length [m] | 131.88 |
| Light collecting area [m²] | 7444 |
| Radius of curvature [m] | 800 |
| Field of view [arc min] | 4.2x4.2 |
| Field of regard [deg] | 17.6 |
| SAC to primary mirror distance [m] | 400 |
| SAC largest mirror dimension [m] | 8.6 |
| SAC clamshell mirror separation [m] | 24.4 |
| Number of primary mirror segments | 6289 |
| Number of mirror modules | 331 |
| Number of truss modules | 331 |
| Number of concentric rings | 10 |
| Mirror segment V2V length [m] | 1.35 |
| Truss module V2V length [m] | 5.2 |
| Mirror module V2V length [m] | 6.28 |
| Mirror segment aerial density [kg/m²] | 25 |
| Truss aerial density [kg/m²] | 4.01 |
| Sunshade diagonal dimension [m] | 140 |
| Operating temperature [K] | 240-300 |
| Sunshade blockage factor | 0.6 |
| Truss module mass [kg] | 70.54 |
| Mirror module mass [kg] | 439.0 |
| Truss member outer diameter [mm] | 45 |
| Truss member wall thickness [mm] | 3 |
| Truss module depth [m] | 2.6 |

Table 6: Important parameters of the ISTAR telescope concept.

APPENDIX A. THERMAL ENERGY BALANCE

The energy balance equations will be developed here for case 1, since all factors are present. Equations for case 2 and 3 can be derived by removing and rearranging the appropriate terms. In general, the balance for case 1 is as shown in Equation [7].

Surface 1:

\[
Q_{IR} + Q_a + \dot{Q}_{SS} - \dot{q}_{cond,1\rightarrow2} - \dot{q}_{rad,1\rightarrow2} - \dot{Q}_{out} = 0
\]

Surface 2:

\[
\dot{Q}_{SS} + \dot{q}_{cond,1\rightarrow2} + \dot{q}_{rad,1\rightarrow2} - \dot{Q}_{out} = 0
\]

Where:

\( Q_{IR} \) = heat from Earth internal radiation incident upon surface 1

\( Q_a \) = heat from Earth albedo reflection incident upon surface 1

\( \dot{q}_{cond,1\rightarrow2} \) = heat conducted from surface 1 to surface 2
\[ Q_{\text{rad,1-2}} = \text{heat radiated from surface 1 to surface 2} \]
\[ Q_{1,SS} = \text{heat from Sun leaking through the shade and incident upon surface 1} \]
\[ Q_{2,SS} = \text{heat from Sun leaking through the shade and incident upon surface 2} \]
\[ Q_{\text{L,out}} = \text{heat radiating from surface 1 to space} \]
\[ Q_{2,\text{out}} = \text{heat radiating from surface 2 to space} \]

Note that heat leaking through the sun shade can be incident upon surface 1 through the gaps between the truss members.

Each surface \( i \) has area \( A_i \), with top and bottom emissivity and absorptivity of \( \varepsilon_{\text{top},i}, \varepsilon_{\text{bottom},i}, \alpha_{\text{top},i} \), and \( \alpha_{\text{bottom},i} \). Respectively. The total area of the top surface \( A_1 \) is equal to the number of modules \( n_m \) multiplied by the area of one module with side length \( L \). The area of surface 2 is only the projected area of the truss members arranged in the triangular pattern shown left in Fig. 17. Each Module has 12 surface members with outer diameter \( d_o \) and length \( L \). \( A_1 \) and \( A_2 \) are given by:

\[ A_1 = n_m \frac{3\sqrt{3}}{2} L^2 \quad [8] \]
\[ A_2 = n_m (12d_0 L) \]

Given this geometry, the external heat fluxes are:

\[ Q_{1,IR} = q_{solar} A_1 \varepsilon_{\text{top},1} \sin^2 \rho \]
\[ Q_a = q_{solar} A_2 (1 - \varepsilon_{\text{bottom},2}) \alpha_{\text{bottom},2} \]
\[ Q_{1,SS} = (1 - \gamma) q_{\text{sol}} A_1 (A_1 - A_2) \varepsilon_{\text{bottom},1} \alpha_{\text{bottom},1} \quad [9] \]
\[ Q_{2,SS} = (1 - \gamma) q_{\text{sol}} A_2 \varepsilon_{\text{bottom},2} \alpha_{\text{bottom},2} \]
\[ Q_{\text{L,out}} = \sigma (\varepsilon_{\text{top},1} + \varepsilon_{\text{bottom},1}) T_1^4 \]
\[ Q_{2,\text{out}} = \sigma (\varepsilon_{\text{top},2} + \varepsilon_{\text{bottom},2}) T_2^4 \]

where \( q_{\text{sol}} \) and \( q_{\text{sol}} \) are the surface heat flux from the Earth and the heat flux from the Sun at 1 AU respectively, and \( \gamma \) is the fraction of solar heat that is blocked by the sun shade. The surface albedo of the Earth is \( a \) and \( \sin^2 \rho = R_E^2 / (R_E + A_{\text{orbit}})^2 \), where \( R_E \) is the radius of Earth and \( A_{\text{orbit}} \) is the altitude of the orbit. The Stefan-Boltzmann constant is \( \sigma \) and \( T_1 \) and \( T_2 \) are the temperatures of surfaces 1 and 2 respectively.

Conduction between the surfaces is carried through the 7 verticals of length \( H \) and 8 diagonals of length \( \sqrt{L^2 + H^2} \) in each module. The truss material has a conductivity \( k \) and the cross-sectional area of the members \( A \) is \( \pi / 4 (d_i^2 - d_e^2) \), where \( d_i \) is the inner diameter. Thus the total conduction term is given by:

\[ Q_{\text{cond,1-2}} = n_m k A (T_1 - T_2) \left( \frac{7}{H} \right) + \frac{8}{\sqrt{L^2 + H^2}} \quad [10] \]

The last term to define is the radiation between the two surfaces. Surface 2 can be treated as three arrays of parallel cylinders separated by \( s = \sqrt{3}/2 \) \( L \). The arrays are oriented at 30\(^\circ\) angles to each other to comprise the full triangular grid. It is assumed that the surfaces are large enough with respect to the individual cylinders to be treated as infinite. The view factor from an infinite plate to an infinite array of parallel cylinders is shown in Equation [11]:

\[ F_{1-2} = 1 - \left[ 1 - \left( \frac{d_o}{s} \right)^2 \right] \frac{1}{4} + \frac{d_o \tan^{-1}}{s \sqrt{s^2 - d_o^2}} \]

[11]

The total projected area of each array is \( 4n_d d_0 L \), because each module has four members of length \( L \) in each direction. The total radiative heat transfer from surface 1 to the six arrays in surface 2 is then given by:

\[ Q_{\text{rad,1-2}} = \frac{3 \sigma (T_1^4 - T_2^4)}{4n_m d_0 L \varepsilon_{\text{bottom},1} A_2} + \frac{1}{A_1 F_{1-2}} + \frac{1 - \varepsilon_{\text{bottom},1}}{A_1 \varepsilon_{\text{bottom},1}} \]

[12]

Substituting Equations [8]-[11] into Equation [7] yields the full energy balance for the system, which can be solved to obtain \( T_1 \) and \( T_2 \). The temperature difference \( T_1 - T_2 \) must then be compared to that in Equation [4] to ensure requirements are met.

REFERENCES