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An overview of a deployable truss structure utilizing doubly slit cylindrical shells as integral composite hinges is presented along with a measurement system and results of deployment repeatability. The measurement system was developed and built as part of a project in the Space Scholars Program at the Air Force Research Laboratory at Kirtland AFB. Previous deployment repeatability tests of integral hinges at the University of Colorado focused on single members and not an entire truss structure. The largest translation accumulated over the course of the deployments was 363um and the largest rotation was 0.1°. The largest increment between deployments was 207um and 0.07°.

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Deployment Repeatability of a Truss Structure Utilizing Integral Composite Hinges

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An overview of a deployable truss structure utilizing doubly slit cylindrical shells as integral composite hinges is presented along with a measurement system and results of deployment repeatability. The measurement system was developed and built as part of a project in the Space Scholars Program at the Air Force Research Laboratory at Kirtland AFB. Previous deployment repeatability tests of integral hinges at the University of Colorado focused on single members and not an entire truss structure. The largest translation accumulated over the course of the deployments was 363µm and the largest rotation was 0.1º. The largest increment between deployments was 207µm and 0.07º.

Nomenclature

$\Delta x_{1\text{-}3}$	=	translational movement of the laser spot in the horizontal direction on the photodiode
$\Delta y_{1\text{-}3}$	=	translational movement of the laser spot in the vertical direction on the photodiode
d_{xyz}	=	translational movement of the laser original in one of the three principal axes
$l_{1\text{-}3}$	=	distance between photodiode faces
α	=	rotation of the laser origin about the X principal axis
β	=	rotation of the laser origin about the Y principal axis
θ	=	rotation of the laser origin about the Z principal axis

I. Introduction

SPACE observatories such as the Next Generation Space Telescope (NGST) are becoming increasingly focused on larger primary mirrors to provide the necessary light gathering ability to probe further and further into the universe[1]. These larger primary mirrors place a value upon the packaging space within launch vehicles and thus require intricate folding schemes. Deployable structures with a large unpacked surface area provide a quick and autonomous means of bringing a satellite to its operational stage. Available launch vehicles can be utilized to send the telescope into low earth orbit where it can unfold and begin its job without the assistance of robots or astronauts for construction.

The behavior of these structures must be studied to formulate sufficient control schemes. This normally involves optical sensing schemes to detect deformation in the structure from one deployment to the next. Previous work in deployment repeatability of integral hinges has measured only a single hinge. This work at the University of Colorado showed that the deployment repeatability was within 2.5µm axially and 9µm laterally[2]. It showed that

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there was significant deformation after the first deployment, but remained insignificant in following deployments. It also showed that there was a certain amount of creep which was directly related to the stowage time of the hinge. More work at the university concerned modeling the snap back phenomenon in the doubly slit cylindrical shells incorporated in the truss structure[3]. These shells were composed of a single composite tube that was cut on both sides down a portion of the length of the tube. This effectively created tape springs on the portion of the tube that was cut, allowing it to bend. This investigation was carried out to determine a suitable model that would help in designing structures under different loads during stowage and deployment.

The early work in modeling these shells was done at the University of Cambridge by Iqbal and Pellegrino[4,5]. Here bi-stable composite shells made of E-glass fibers in a polypropelene matrix were tested and mathematical models were formulated to explain their bi-stability. The bi-stability refers to these structures having equilibrium shapes like that of a tape measure or rolled up into a tube. Further work was carried out in ABAQUS to more accurately simulate the bending phenomena.

Mark Lake of NASA has studied problems associated with measuring deployment repeatability and its vital purpose in satellite performance[6]. He contended that knowledge of the deployment precision was crucial for developing low-cost and sufficient active control systems. Microlurch and the equilibrium zone were singled out as the two key factors affecting deployment repeatability. Microlurch, also referred to as creep, is a residual change in the shape of the structure after deployment. The equilibrium zone is a random final shape after deployment due to random microlurch of the structure. One of the challenges of measuring deployment repeatability down to microstrain levels was controlling environmental influences that were usually ignored in tests that did not require such high resolution. These include the effects of ambient light upon optical sensing schemes, temperature control, and vibration suppression.

Previous work at the University of Colorado also studied the deployment repeatability of a 1.2m deployable truss structure which utilized mechanical hinges[7]. Here, Warren used revolute joints and one latch joint to create a truss structure which had a precision of 20μm. The structure exhibited a microlurch of 10μm and an equilibrium zone of 2μm.

II. Integral Hinge Optical Support Structure (IHOSS)

IHOSS is a deployable truss structure manufactured by Foster-Miller Inc. in Waltham, MA. The structure is designed to hold a mirror and has three anchor points specifically for that purpose. It measures approximately 2.9m

a) **b)** **c)**

Fig. 1 IHOSS in its various configurations: a) deployed, b) partially stowed, and c) completely folded

in length. IHOSS makes use of solid composite tubes in the part of the structure that can remain rigid. This includes the triangular anchor system for the mirror as well as parts of the truss beams that do not need to bend. These rigid components of the structure reduce the amount by which the structure can change shape between deployments. Doubly slit cylindrical shells (the integral hinges) are used in place of the rigid composite tubes where the structure needs to bend. This allows IHOSS to fold up roughly perpendicular from its deployed position.

IHOSS is housed inside its own room within AFRL at Kirtland AFB. The walls cover all sides of the structure except for a slit in the center of the roof for a tension cable. This room helps to eliminate the effects of ambient light upon optical sensing instruments and provides a more stable thermal environment. It sits upon a granite rock that is twelve feet square by two feet thick. The rock weighs over 66,640lbs and has an extremely low fundamental frequency. The rock is supported by air bags to further isolate it from vibrations.

III. Position Measurement System

An optical position sensing system was utilized to study the deployment repeatability of IHOSS. The sensors were manufactured by On-Trak Photonics and utilized a two-dimensional photodiode array. The sensors, coupled with an amplifier and display box also manufactured by On-Trak, have a stated accuracy to tenths of a micron (the claimed resolution is 250nm). Red laser diodes with a 650nm wavelength were used. One laser would point to each sensor and the sensor would give the centroid of the laser spot.

The drift noise of this system needed to be studied in order to realize the true accuracy of the system once it was implemented on IHOSS. Several drift tests were performed to see how stable the readings coming from the photodiode were when the laser was sitting as perfectly still as we could manage. Some tests produced a large amount of drift due to the setup. The best test was performed with the sensor adhered to the granite block and the laser clamped inside of a v-block which was adhered to the block as well. Hysol (Locktite 9309) epoxy was used as the adherent and Teflon tape was used to protect the surfaces.

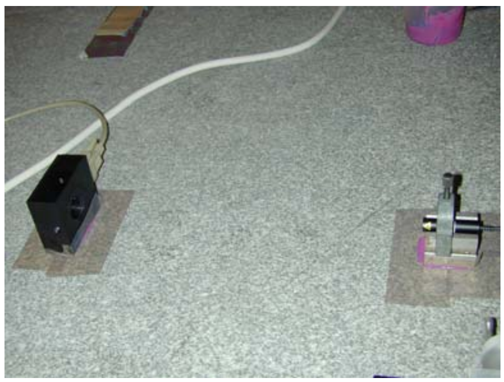

Fig. 2 Drift test with photodiode and laser adhered to granite block

Over a 24 hour period with a 90 second sampling rate, the data coming from the photodiode was found to have less than a 9μm standard deviation in the vertical direction and less than 5μm standard deviation in the horizontal direction.

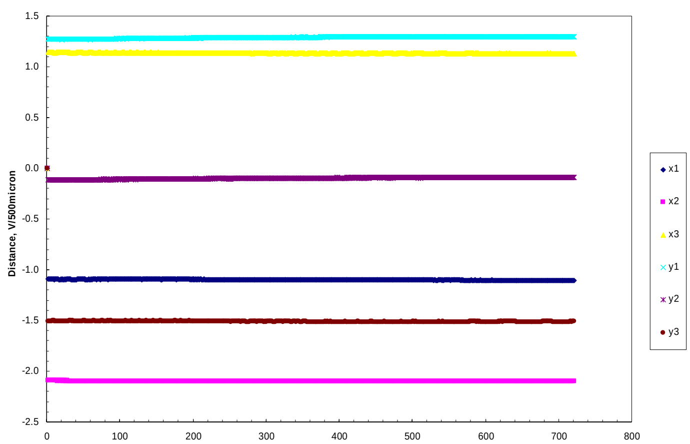

Fig. 3 Drift test of full measurement setup over 4 hours with <5μm standard deviation used to identify noise

Once this drift was determined, a final drift test was performed with the laser and sensor in the final test configuration (described in the next section). A test performed over 4 hours gave a standard deviation of no more than 5μm in any of the 6 sensor outputs. The outputs can be seen in figure 3. The low standard deviation of this setup was due partly to the fact that IHOSS had been deployed for a large amount of time and did not have any creep left. This made IHOSS an extremely stable platform.

IV. Measurement Setup

Fixtures had to be designed and fabricated in order to hold the lasers and sensors in place for the deployment measurement. A plate was designed to hold the sensors in place on a tripod. The plate held the sensors in a manner orthogonal to each other. The tripod provided the ability to raise and lower the plate to best center the laser spots. The lasers were held on the front anchor of IHOSS, as seen in figure 4a. The front anchor was chosen so that IHOSS itself would not strike any sensors or wires in the position sensing system during deployment.

a) **b)**

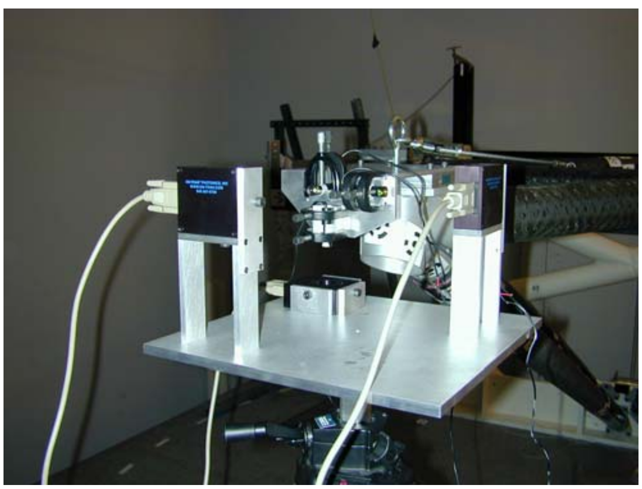

Fig. 4 The measurement setup, a) the lasers pointing to the sensors and b) one of the tripod legs adhered to the granite block with epoxy

The lasers hung off of the front anchor by a specially designed bracket. The bracket was bolted to the anchor and the lasers sat inside two v-blocks and one cylindrical block to point at the photodiodes in the three principal axes. Each laser was held to its block by two clamps.

In order to reduce any movement in the laser bracket, epoxy was used between contact surfaces in addition to bolting. The tripod legs were also adhered to the granite block with epoxy in order to keep them from sliding. Figure 4b shows one of the tripod legs adhered to the granite block. Teflon tape was used to protect the contact surfaces so that the tripod could be removed later. The contact surfaces of the laser bracket were not protected with tape since it did not need to be taken apart in the future.

V. Mathematics for Position Sensing

Each photodiode provided us with an X and Y value for position sensing. One could imagine a Cartesian plane over the surface of the photodiode, with the center of the diode being the origin. Using three photodiodes gives us six position values. We also had six unknowns pertaining to the translational movement of the front anchor of IHOSS and its rotation about those axes as seen in figure 5.

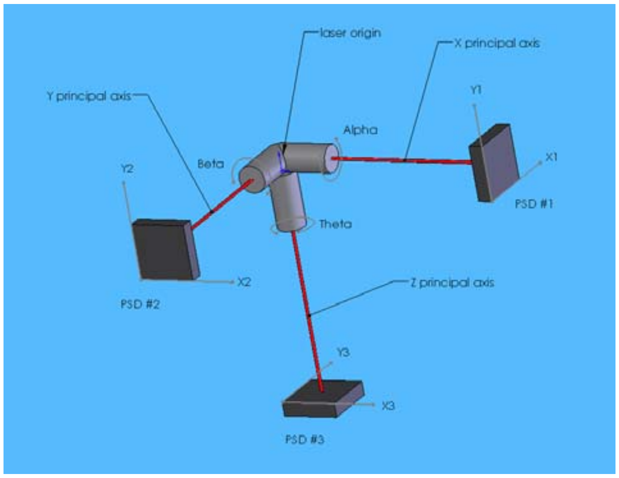

Fig. 5 Diagram of variables used in position measuring setup

$$\begin{aligned}
\Delta x_1 &= -d_y + \tan\theta * (l_1 - d_x) \\
\Delta y_1 &= -d_z + \tan\beta * (l_1 - d_x) \\
\Delta x_2 &= d_x + \tan\theta * (l_2 - d_y) \\
\Delta y_2 &= -d_z - \tan\alpha * (l_2 - d_y) \\
\Delta x_3 &= d_x + \tan\beta * (l_3 - d_z) \\
\Delta y_3 &= -d_y + \tan\alpha * (l_3 - d_z)
\end{aligned} \qquad (1)$$

The Δx and Δy values in (1) pertain to the relative readings from the photodiodes. The d_{xyz} values correspond to the translational movement of the laser origin. The α, β, and θ values correspond to the rotation of the laser origin about the three principal axes. The l_{123} values correspond to the distance between the photodiode faces. This was calculated by using calipers and the photodiode specifications from On-Trak.

The equations were formulated by considering which specific translational and rotational movements would affect the X and Y reading on each photodiode. Each measured value is a sum of a corresponding translational movement of the laser origin as well as a rotation. Thus each Δx or Δy measurement was broken down and matched to the corresponding movement of the laser origin and the rotation about the corresponding axis as described in (1).

One idea that was very important in developing these equations was the laser origin. The bracket holding the lasers in place was designed so that the lasers would back up to a single point. This origin served as the actual point of movement that was being calculated. It was assumed that the laser bracket was connected rigidly enough to IHOSS that it would also describe the movement of the front anchor.

VI. Results and Discussion

IHOSS was folded six times in order to obtain numbers for deployment repeatability. A drift test was performed before the first folding to determine the initial position numbers. In the first four folds, IHOSS was only raised approximately 45º. In the last two folds IHOSS was raised approximately 60º. After each of the deployments, data from the sensors was logged for at least four hours. After some of the deployments, data was logged for longer periods to try and examine creep or temperature cycles. Table 1 provides a list of the tests with their data logging times along with the largest two sigma standard deviation in any of the six sensor outputs. The largest 2α value is used in figure 6, although the average 2α value is only 18.05μm. We believe the high standard deviation in the fifth deployment came from the fact we folded IHOSS at a larger angle and thus bended the integral hinges to a greater degree. The final measurement values were arrived at by taking the average of the data over the entire testing period. The data for the first deployment was lost due to a software problem associated with the data acquisition hardware.

Table 1 Deployments with their corresponding data logging times and 2σ standard deviations

Deployments	Initial	Second	Third	Fourth	Fifth	Sixth
Length of Test	4 hours	48 hours	4 hours	4 hours	4 hours	12 hours
Largest 2σ (microns)	8.65	25.40	12.63	6.47	35.63	19.54

The biggest translational movement of the laser origin occurred in the left and right motion. From the initial measurements to the ones taken after the sixth deployment, IHOSS moved a total of 363μm to the left if one were looking straight at IHOSS. The largest rotation through all the deployments occurred with α, where a -0.1º rotation about the axis that runs left to right on the measurement system. This corresponds to IHOSS tilting its front anchor upwards. The single biggest incremental step in translation occurred between the fourth and fifth deployments. Here, IHOSS moved 207μm down towards the sensor plate. The largest angular step was -0.07º in the left to right axis. These numbers and the rest of the raw data can be seen in tables 2 and 3 with translational movements XYZ in microns and α,β,θ in degrees. Microsoft Excel's solver tool was used to solve the six equations. The sum of the squared errors from the solver is also presented with each measurement column to indicate the equations' proximity to zero. Figure 6 presents the accumulated translational movements of IHOSS from the initial measurements to the indicated deployment.

Table 2 Raw data indicating accumulated movements of IHOSS and the error sum from Microsoft Excel's solver tool for equations in (1)

Deployments	0 to 2	0 to 3	0 to 4	0 to 5	0 to 6
X	-225.92	-248.20	-356.75	-283.56	-363.37
Y	-62.20	46.57	-75.12	-15.53	-71.93
Z	-195.93	-154.82	6.60	-200.66	-47.56
α	-0.0019	-0.0256	-0.0936	-0.0555	-0.1044
β	-0.0290	-0.0152	0.0404	-0.0102	0.0322
θ	0.0399	0.0695	0.0771	0.0576	0.0834
$error^2$ sum	3.39E-21	1.08E-19	1.29E-26	3.68E-21	1.16E-23

Table 3 Raw data indicating incremental movements of IHOSS

Deployments	0 to 2	2 to 3	3 to 4	4 to 5	5 to 6
X	-225.92	-22.38	-108.60	73.23	-79.86
Y	-62.20	108.70	-121.67	59.67	-56.51
Z	-195.93	41.33	161.57	-206.73	153.23
α	-0.0019	-0.0238	-0.0680	0.0379	-0.0489
β	-0.0290	0.0139	0.0557	-0.0505	0.0425
θ	0.0399	0.0296	0.0077	-0.0195	0.0258
$error^2$ sum	3.39E-21	5.00E-21	5.80E-22	1.62E-24	2.18E-23

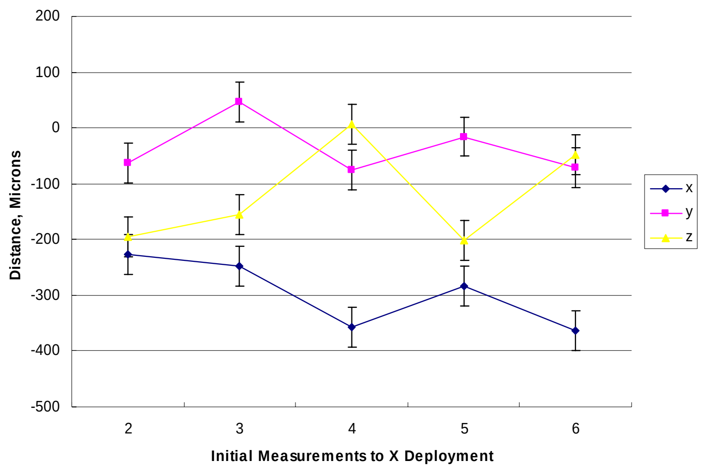

Fig. 6 Accumulated movements of IHOSS's front anchor in three principle axes

VII. Conclusion

It is unclear how much more movement to the left should be expected from further deployments. From the current results it is clear that a control mechanism that is capable of 0.5mm movement and ~0.11° rotation are needed to correct misalignments in a mirror supported by IHOSS. It is also clear that the structure tilts upwards more than any other rotation.

IHOSS is still a very stable and accurate structure capable of supporting large mirrors for space-based telescopes. Control mechanisms needed would be minimal in their actuation lengths and likely superior to ones needed in structures utilizing mechanical hinges.

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