Implementation of a Network Sensor Validation System for a Segmented Reflector Testbed

Eric Diaz, Jorge Espinosa, Gerardo Zarate, Khosrow Rad, and Helen Boussalis

***Abstract*—A large order flexible space structure, such as a segmented reflector space telescope, requires a high degree of precision and accuracy in order to maintain its nominal shape – the most critical aspect of forming clear images. The control of such a large complex multiple-input multiple-output (MIMO) system requires that its sensors be regularly checked against their calibration curves to detect deviations from the desired linear operating range. The Segmented Space Telescope Testbed at the Structures, Propulsion, and Control Engineering (SPACE) Laboratory at California State University, Los Angeles, utilizes a segmented primary mirror and a network of 42 sensors to mimic a parabolic mirror shape to high accuracy and precision. Regular validation of sensor linearity is crucial to system performance in order to achieve a high degree of precision. Individual verification of a larger number of sensors is both time consuming and prone to human error. Thus, a method for the rapid and autonomous validation of sensor linearity is being developed utilizing the Testbed's shaping controller and LabVIEW virtual instruments (VI) for sensor monitoring and hand calibration verification.**

***Index Terms*—sensor linearity; calibration; segmented telescope; LabVIEW**

I. INTRODUCTION

In order to extend our current ability to see further into space, it becomes necessary to increase the dimensions of the primary reflector in a space telescope. Current limitations on the manufacturing of a larger monolithic reflector, as well as limitations on allowable payload weight and size for current space launch vehicle technology necessitate an alternative design paradigm for a larger primary reflector. As successor to the Hubble Space Telescope (HST), The National Aeronautics and Space Administration's (NASA) Next Generation Space Telescope (NGST), the James Webb Space Telescope (JWST), employs a segmented primary mirror to overcome such difficulties. For the implementation of such a system, it is critical that the primary reflector's nominal paraboloid shape be maintained to a high degree of accuracy and precision.

In order to study the control of such large segmented systems, in 1994, NASA provided funding to establish the Structures, Pointing, and Control Engineering (SPACE) Laboratory at California State University, Los Angeles (CSULA). The goal of this project was to design and fabricate a Testbed that resembled the complex dynamic behavior of a segmented space telescope.

The NASA University Research Center (URC) SPACE Center team developed a telescope Testbed to emulate the performance of a Cassegrain telescope of 2.4 meter focal length with dynamics comparable to an actual space-borne system. It consists of a primary reflector made from seven hexagonal panels (6 peripheral and one center stationary), a secondary mirror and a lightweight flexible supporting truss. Each peripheral panel can be moved by three linear electromagnetic actuators. Each peripheral panel has three edge sensors to detect linear and angular displacements and the central stationary panel has six. The secondary mirror, a six-sided pyramidal mirror, is used to reflect light from the primary reflector to the focal plane.

To ensure the precision and accuracy required of the primary reflector conformation, it is necessary to regularly verify that the Testbed's sensors operating within the desired linear range. Calibration of a sensor firmly establishes the accuracy of the measuring device. Any deviations and nonlinearities from the desired gain result in deviations from the desired primary reflector shape.

In order to monitor the system's sensors in real-time as well as to expedite the process of verifying the response of the sensors, two LabVIEW virtual instruments that were previously developed were modified and merged to facilitate the process of checking the 42 sensors on the SPACE Testbed in conjunction with a shaping controller implemented on a digital signal processor (DSP).

II. DESCRIPTION OF THE SPACE TESTBED SYSTEM

The SPACE Testbed shown in Fig. 1 emulates a Cassegrain telescope of 2.4-meter focal length with performance comparable to an actual space-borne system. The system's top-level requirements include figure maintenance of the primary mirror to within 1 micrometer RMS distortion with respect to a nominal shape of the primary mirror, and precision pointing with accuracy of 2 arc seconds [4]. The SPACE Testbed consists of a primary mirror, a secondary mirror, and a lightweight flexible truss structure. The primary mirror (mounted on the support truss) consists of seven hexagonal panels each 101 cm in diameter. The six peripheral panels are actively controlled in the three

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degrees-of-freedom by 18 linear electromagnetic actuators (3 actuators per active panel), and a seventh center panel is used as a reference. In addition, a set of 24 edge position sensors are used to provide measurements of relative displacement and angle of the panels. The Testbed's active secondary mirror is a six sided pyramidal mirror, used to reflect the light from the primary mirror to the focal plane in the central plane and it is attached to the primary by a tripod. The entire Testbed is supported on a triangular isolation platform made of aluminum honeycomb core with stainless steel top and bottom skin.

The data acquisition system consists of a digital signal processor (DSP) (A Pentek 4285 with four Texas Instruments TMS320C40 processors) and Dual A/D and D/A converter package from Pentek. The data flow path originates at the sensors and transferred to the three DSPs. The DSPs generate output commands based on the control algorithm, which translate to forces for the segment actuators to achieve the desired alignment.

III. FIGURE MAINTENANCE CONTROLLER

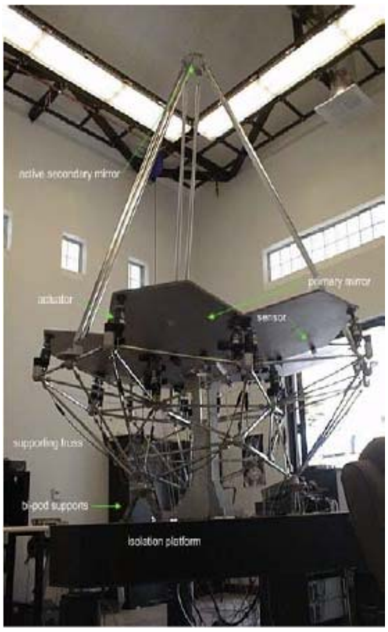


Fig. 1. SPACE Center Segmented Reflector testbed

Unlike a monolithic primary mirror, a segmented reflector, such as the JWST or the SPACE Testbed, requires an active control system to maintain the desired optical performance. Active control of the Testbed reflector panels was achieved using an H-infinity controller, Fig. 2, designed to suppress vibrations and provide figure maintenance and shape control of the primary mirror. Fig. 3 shows the closed loop response results, [9], using this control scheme under decentralized control.

It is evident that figure maintenance is achieved using the decentralized control scheme described in [4], [5], [10].

IV. CONTROLLER DESIGN

Fig. 6. SPACE Center Segmented Reflector testbed

Fig. 3. Closed loop response of the six Testbed panels to the Decentralized H-infinity controller, [9]

Consider the linear time-invariant system given by the following state equations,

$$\begin{aligned} \dot{x} &= Ax + \sum_{i=1}^{v} B_i u_i \\ y_i &= C_i x, \qquad i = 1,\cdots,N \end{aligned} \tag{1}$$

where $x \in \Re^{n}$, $u_i \in \Re^{m_i}$ and $y_i \in \Re^{p_i}$ represent the state, input and output respectively of the *i*th local control station. *A*, B_i and C_i are real, constant matrices. The results of the modal analysis are used to determine the matrices *A*, B_i and C_i that will describe the dynamics of the PPA structure.

For decentralized control, it is necessary to determine *n* local feedback control laws that will dynamically compensate for (Eq.1) in order to stabilize the control loop, generating the following feedback controllers:

$$\begin{aligned} \dot{z} &= F_i z_i + G_i y_i \\ u_i &= H_i z_i + K_i y_i + v_i, i = 1,\cdots,N \end{aligned} \tag{2}$$

Where $z_i \in \Re^{n_i}$ and $v_i \in \Re^{m_i}$ are the *i*-th subcontroller and local external input and F_i, G_i, H_i, and K_i are real, constant matrices. The standard two-block mixed-sensitivity H-infinity technique, [17], will be applied to accomplish a pointing accuracy of 2 arc seconds.

V. SENSOR DESCRIPTION

The sensors are inductive displacement sensors which take advantage of Faraday's Law of Induction. They are essentially inductive coils that form part of an alternating current (AC) bridge circuit. Fig.4 shows the interaction of the magnetic fields between the sensor and target material. An AC current is provided to the sensor. As a result of the alternating electric field, an alternating magnetic field is produced and radiates out toward the target materials. When target material enters this field, eddy currents are produced in the material as a result of the alternating magnetic field within the target and circulate within the conductive material. Opposing the induced current by the alternating magnetic field, an alternating current in the conductor will result in an alternating magnetic field within the conductor. This newly induced magnetic field will oppose the magnetic field produced by the sensor coil. The electronics that form part of the AC bridge circuit detect the changes in the sensor impedance and convert that to a corresponding change in voltage. A more in depth description of the sensor AC bridge circuit can be found in [16].

VI. LABVIEW SUBSYSTEM

The lengthy process of removing and replacing the sensors from the Testbed in order to assess their proper operation is fully described in [16]. Checking all 42 sensors by hand is a long and time consuming process that is subject to human error. To expedite the process, a LabVIEW VI was developed to speed up the process by automating the process of taking repeated measurements, performing the necessary calculations, and storing data. A description of the operation of the VI can be found in [16]. This VI still requires the removal of each sensor from the Testbed. In order to mitigate the error inherent in replacing sensors, as well as reducing time wasted in the removal of sensors that are in proper working order, the VI was extended and merged with another VI developed for the purpose of monitoring sensor noise on multiple sensors in real-time Fig.5, Fig.7, and Fig.8.

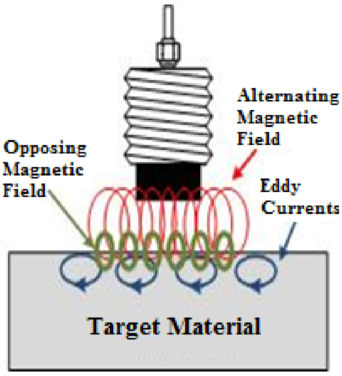


Fig. 4. Testbed sensor and induced eddy currents

The merged VI is capable of measuring and calculating the linearity of multiple sensors at once. The VI can only measure sensor output passively, therefore movement of the panels is achieved by using a modified controller running on the Testbed's DSP to change the shape the panels conform to. The Testbed's shaping control is achieved using an H-infinity controller with the system modeled as decentralized overlapping subsystems.

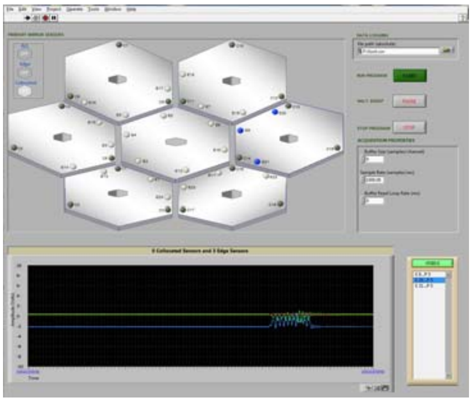


Fig. 5. Measuring sensor output for the right-most panel in real time

In order to automate the process, the modified controller changes the reference shape of the panels in order to make them translate in a single DOF, along the normal of each panel. As the panels are moved to each new reference plane, the DSP sends a trigger signal to the LabVIEW VI to indicate when sensor measurements are to be taken. Fig.6 depicts a block diagram of the process for a single cycle.

After the last measurements are taken at the final reference shape, LabVIEW calculates the sensor gain, stores the data, and displays the input-output curve for all the sensors being monitored.

VII. SUMMARY

The implementation of the Network Sensor Validation System will greatly improve performance of the Testbed. It will eliminate manual error from the calibration process of our inductive displacement sensors. Additionally, the Network Sensor Validation System will aid in efficiency when maintaining the functionality of the Testbed, allowing the existing shaping controller to aid in sensor validity. Allowing the calibration process to be managed by the shaping controller and LabVIEW will also aid in avoiding any mishaps that may occur while dismounting or remounting each sensor. The successful integration of the Network Senor Validation System will improve our overall System accuracy and efficiency.

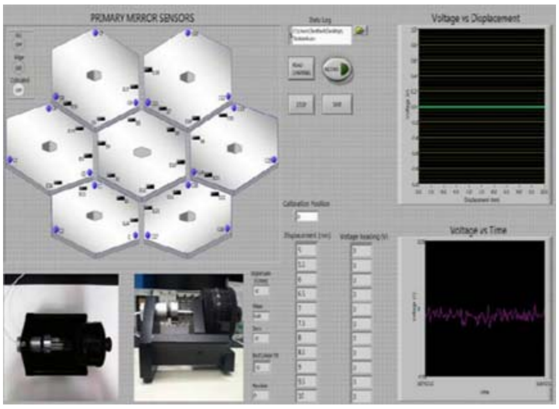
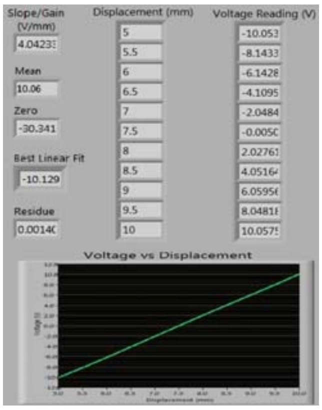


Fig. 7. LabVIEW Front Panel



Slope/Gain (V/mm): 4.0423
Mean: 10.06
Zero: -30.341
Best Linear Fit: -10.129
Residue: 0.0014

Displacement (mm)	Voltage Reading (V)
5	-10.053
5.5	-8.1433
6	-6.1428
6.5	-4.1095
7	-2.0484
7.5	-0.005
8	2.0276
8.5	4.0516
9	6.0595
9.5	8.0481
10	10.057

Fig. 8. Linear Regression Data(Left), Displacement Volts (Middle), Volts Vs. Displacements (Right)

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