Decentralized Control of a Segmented Reflector Testbed

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Abstract: - This paper outlines the ongoing research at the Structure, Pointing and Control Engineering (SPACE) Laboratory to achieve a decentralized control of a segmented reflector testbed. The main effort is concentrated on achieving the system's top-level requirements including figure maintenance of the primary mirror to within 1 micron RMS distortion with respect to a nominal shape of the primary mirror, and precision pointing with accuracy of 2 arc seconds using the decentralized control technique. Having the time realization of the system at hand will permit the implementation of such strict control requirements. Therefore this entails system identification methods to achieve such a realization.

Key-Words: - Precision Pointing, Large scale system, James Webb Space Telescope Large segmented space reflector, Attitude Control System, System Identification, Ray Tracing.

1 Introduction
Near-Future space-borne astronomical missions require increasing levels of optical performance and accuracy. The James Webb Space Telescope (JWST), with its large light-gathering mirror and superb resolution will be capable of detecting faint signals from the first billion years, the period when galaxies formed [1]. JWST will be capable of detecting radiation whose wavelength lies in the range of 0.6 to 20 mm.

Due to the size and weight limitations as well as the limitations associated with the launch vehicles, the future missions would employ segmented reflectors instead of monolithic ones that are cast from a single piece of glass. Although multiple-mirror designs have many advantages, a number of major difficulties are associated with this technique. Specifically, the ability to provide phasing of the separate beams is difficult. This problem requires special consideration in the optical design so that the individual focal planes can be properly aligned. The mirrors can be easily misaligned due to disturbances; therefore a controller is necessary for the shaping of the mirrors in order for the images to be reflected at the central panel. Another challenge in the integration of such advanced optical systems is the stringent requirements for the pointing of the telescope.

To address the issues and the difficulties mentioned above, The National Aeronautics and Space Administration (NASA) has provided funding to establish the Structures Pointing and Control Engineering (SPACE) Laboratory at California State University, Los Angeles. One of the major goals of this project is to design and fabricate a test-bed that resembles the dynamic behavior of a segmented space telescope.

This paper is organized as follows: Section 2 presents the system description of the SPACE testbed. Section 3 the system identification is described. Section 4 gives an overview of the system decentralization, while Section 5 gives an overview of precision pointing. Finally conclusions are given in Section 6.

2 Description of the System
The segmented telescope reflector test-bed 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 micron RMS distortion with respect to a nominal shape of the primary mirror, and precision pointing with accuracy of 2 arc seconds.

The SPACE test-bed shown in Fig. 1 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 having 101 cm in diameter. The six peripheral panels are actively controlled in the three degrees-of-freedom by 18 linear electromagnetic actuators (3 actuators per active panel), and the seventh panel is used as a reference.

In addition, a set of 18 edge sensors are used to provide measurements of relative displacement and angle of the panels (3 sensors per active panel). The test-bed’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 test-bed is supported on a triangular isolation platform made of aluminum honeycomb core with stainless steel top and bottom skin.
accomplished as shown in (1) by modeling the input-output relationships within the system as LTI ordinary $n^{th}$ order difference equations, whose coefficients are to be estimated.

Individual entries in Equation (1) represent the various JxK discrete-time transfer functions with corresponding numerators $N_j(\alpha)$ and denominator $d_l(\alpha)$. Estimation of the individual parameters requires solving a weighted nonlinear least-squares optimization problem which aims at reducing residuals between predicted models and actual frequency response data, namely

$$H(z) = \frac{1}{d(z)} \begin{bmatrix} N_{11}(z) & \cdots & N_{1K}(z) \\ \vdots & \ddots & \vdots \\ N_{J1}(z) & \cdots & N_{JK}(z) \end{bmatrix}$$  (1)

$$(\hat{\alpha}, \hat{\beta}) = \arg \min_{\alpha, \beta} \sum_{l=1}^{L} \left\| w_l \left[ \Gamma_l d_l(\alpha) - N_l(\beta) \right] \right\|^2$$  (2)

where $\alpha \in \mathbb{R}$, $\beta \in \mathbb{R}^{JxK}$. (3)

Here the transfer functions are evaluated at each frequency $l$, and weighted against the frequency response data $\Gamma_l$ at each experimental frequency by choosing proper windows or weights $w_l$. The goal is to obtain an estimate of the various coefficients $\alpha$ and $\beta$ that define each transfer function, thereby providing a linear relationship between each input and each output in the system.

Application of conventional identification techniques to this highly complex system would fail to yield proper data fitting. This is due to its high-order nature as well as the excessive number of inputs and outputs and subsequent amount of collected data [6]. To evade this problem, Bayard’s multi-band fitting approach is used, consisting of a sub-band decomposition compound curve fitting method that combines the effect of identified lower-order models to yield an estimate of the overall wideband system. This procedure makes it possible to relax the computational burden on the least-squares iteration algorithm and most importantly, it allows for parameter convergence and estimated model stability [7] [8]. (Fig. 3)

Traditional multi-sine experiments conducted in the system to obtain the necessary frequency response information will likely result in large amounts of data and long experimentation times. To greatly reduce data set size and experimentation times, alternative random and pseudo random sequences are designed and used as the persistently-exciting inputs to the system. Due to their particular frequency spectrum nature, these random sequences are able to excite frequencies of interest in the system in a single run, thereby reducing considerably the experimentation process time. This new procedure requires the design of data smoothing windows to improve the quality of the frequency response generated by Empirical Transfer Function

3 System Identification

Estimation of the SPACE testbed model is attained through the use of an offline frequency domain identification approach, which makes use of collected frequency domain data. This data is provided by system excitation through the use of persistently exciting signals. A black-box parametrization of the MIMO system is
Estimates (ETFE).
To enhance the model estimation process, model order assessment techniques will be applied prior to identification. Having an approximate order at hand will facilitate the search of the n-th order frequency-dependent polynomials which best fit the experimental data.

\[ x = Ax + Bu \]
\[ y = Cx \]

with decomposition
\[ \dot{x}_i = A_i x_i + \sum A_{ij} x_j + B_{ij} u_i + B_{2j} d_i \]
\[ y_i = C_i x_i \]
and the isolated components are:
\[ \dot{x}_i = A_i x_i \]
where \( x_i = [\delta_i^T \; \delta_i^T] \)

In this case, a natural decentralization of the system is chosen by selecting one of the six peripheral segments of the primary mirror and its associated supporting structure as an isolated subsystem as shown in Fig. 4.

For control purposes the following state-space representation of the composite system is derived from (4) [5]:

\[ x = Ax + Bu \]
\[ y = Cx \]

where \( x_i = [\delta_i^T \; \delta_i^T] \)

Fig. 3. Least Square Algorithm

To conform with prevailing control methods, an equivalent state-space model is obtained from the estimated MIMO transfer function model. These validated state-space models will be used in the formulation of high resolution control design for this high-order, lightly-damped multivariable system.

4 Decentralized Control
The SPACE testbed consists of a large number of structural components as well as sensors and actuators leading to mathematical models that involve hundreds of states. On the other hand, controllers and processors are responsible of overall unit operation, interrogation of the measurement data and communication of the data. Consequently, the design of control laws based on the conventional centralized approach becomes exceedingly difficult with the number of calculations that can be made in each operation cycle [3]. In addition, it is vulnerable to a single point of failure and loss of computational and communicational abilities. As a result, the division of the control problem into a collective set of six smaller subsystems to control on a local level by set of decentralized controllers is a possible alternative to the centralized controller [4]. With decentralization, the control computation can be performed in parallel using the distributed control systems. Decentralization techniques are employed on the SPACE test-bed for the development of control laws to accomplish vibration suppression, precision pointing and reflector shape control.

The following equation of motion represents the structure model of the SPACE test-bed:

\[ M \ddot{\delta} + K \delta = B_1 u + B_2 d \]

Where \( M \) is the mass matrix, \( K \) is the stiffness matrix, \( \delta \) is a position coordinate vector, \( B_1 \) and \( B_2 \) are force amplitude matrices, \( u \) is a control-input vector and \( d \) is disturbance vector.

Fig. 4. Block Diagram of a Decentralized Control System

Therefore each subsystem is identified with three command inputs to the actuators and three outputs which are measured by the edge sensors. Local control algorithms are developed for each of the six isolated subsystems:

\[ \dot{x}_i = A_i x_i + B_{ij} u_i + B_{2j} d_i \]
\[ y_i = C_i x_i \]

Several control algorithms have been developed for the shaping of the primary mirrors, including classical and modern techniques using the decentralized method. Figure 4 the results derived when H-infinity control have been applied to segmented reflector [5].

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5 Precision Pointing
Over the years, the somewhat relaxed and straightforward demands on the control and measurement of the telescope orientation are changed to stringent demands of deterministic and random motion. The degree of precision increased the payloads demand into sub-arcsecond pointing accuracy.

A spacecraft like HST perform the telescope pointing using exclusively the spacecraft attitude determination and control system (ADCS). This requires a very stiff spacecraft and telescope structure, the use of precise gyroscopes, star trackers and/or fine guidance sensors, low-noise reaction wheels and a relatively high bandwidth attitude control system (ACS) [9].

Currently at the SPACE laboratory, our research is concentrated in the ACS area. In order to perform the simulation, the data from the ACS sensors and the overall system modeling and integration of the pointing simulation of the SPACE testbed are considered.

The system modeling in this paper is understood to be the process of analysis and assembly of an overall system model. The system contains the actual testbed, as well as controlled necessary to achieve shape maintenance and pointing.

For pointing control purposes the tools used at the SPACE laboratory are mainly MSC/NASTRAN™ and MATLAB™ to facilitate finite element modeling and numerical analysis and integration, respectively. With progressive research that has been performed at the SPACE laboratory over the past several years, custom made software packages have been developed to facilitate implementation of functions, such as the eigenvalue problem solution and modeshape animation. The functions have the ability to provide structural modeling capability for work at the conceptual and preliminary design levels. The main modeling tasks, which comprise our work, are as follows:

- Structural dynamics modeling
- Control Modeling: Attitude Control System
- Optical ray tracing analysis
- Assembly and analysis of overall system model

The main objective of this research is to develop and test an attitude control system for a three-axis stabilized spacecraft to view targets. First we define the system and orbital models used for a rigid body spacecraft (S/C) with momentum wheels.

To test the developed pointing algorithm on the SPACE testbed, we have to slew the entire structure. Due to structure limitations, the slewing of the testbed is not a feasible option. Thus we concentrate on designing an optical mechanism that allows the application of the pointing control laws to move the target instead of the testbed. For the analysis and design of this mechanism, we are developing an optical ray tracing program that will demonstrate the integration of the optical component on the SPACE testbed.

6 Conclusion
As most of the work in the shaping control has been completed using decentralized control techniques, we are currently developing an attitude control system, in addition to the control laws necessary for the pointing of the SPACE structure. On the other hand to demonstrate our pointing algorithms we are developing an optical ray-tracing program. Our preliminary results show that the decentralized techniques are used for both improved load balancing for any number of processors and tasks and allow the recovery from one or more processor failures.

References: