The Control and Structures Research Laboratory (CSRL): A Control-Oriented Test-Bed for Large Segmented Reflectors

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Abstract

Because of the weight and volume constraints of space-borne astronomical instruments, segmented reflectors have become the only practical choice for future astrophysical missions. While a monolithic reflector depends on the mechanical properties of its material to provide the dimensional stability required for good optical performance, a segmented reflector requires an active segment-alignment control system in order to make the reflecting surface have the optical performance of a monolithic unit. This paper describes an experimental test-bed that is being developed at the Control and Structures Research Laboratory (CSRL) at California State University, Los Angeles (CSULA). The CSRL test-bed is a 2.4 m focal length Cassegrain optical configuration consisting of a 2.66 m actively controlled segmented primary and an active secondary. The primary consists of six hexagonal panels surrounding a fixed central panel and supported by a light-weight flexible truss structure. The project has been funded by NASA to study the complex dynamic behavior of large segmented optical systems.

1 Introduction

To meet the needs of future astrophysics missions such as the Submillimeter Explorer (SMME), the Submillimiter Imager and Line Survey (SMILS) and the Large Deployable Reflector (LDR), the Precision Segmented Reflector Program (PSR) was initiated in 1988 as one of the major elements of NASA's Civil Space Technology Initiatives [1]. One of the main objectives of the PSR program is the development of technology for construction of large, space-based telescopes.

A monolithic reflector depends on the mechanical properties of its material to provide the dimensional stability required for good optical performance. A reflector built from segments relies on its support structure for stiffness and rigidity and an active control system to maintain alignment of segmented reflectors.

To study the complex dynamic behavior of large segmented optical systems, NASA has funded a five-year project to design and construct a test-bed in the Control and Structures Research Laboratory (CSRL) at the California State University, Los Angeles. the CSRL test-bed will serve as a generic experimental facility capable of performing experiments that simulate the complex dynamic behavior of a large segmented optical system. It will be used as an experimental facility for addressing in an integrated way, problems associated with structural dynamics, control of multi-input multi-output systems, optics, electronics, actuators and sensor design.

The CSRL project is in its third year of funding. An interdisciplinary team of faculty and students have developed mechanical design, flexible structural models, control algorithms, and system identification techniques for the test-bed. A consortium of four universities including California State University, Los Angles (CSULA), California State University, Long Beach (CSULB), University of Southern California (USC) and University of California, Berkeley (UCB) are collaborating in the development of the test-bed. The test-bed will be housed at the CSRL facility at CSULA.

2 Objectives of the CSRL Test-Bed

The prime objective of the CSRL test-bed is to provide an experimental tool to develop and validate methodologies and algorithms needed for active control of flexible segmented optical systems. The requirements include [2]:

2.1 Functionality: The test-bed is designed to perform the essential functions need for the various system missions including static and dynamic segment alignment, fine pointing and vibration suppression.

2.2 Performance: Performance of the test-bed is required to be of comparable quality of that of an actual system. The top-level performance requirements related to the CSRL control system were developed as follows:

- Figure maintenance to within 1 micron (RMS distortion) with respect to calibrated surface.
- Pointing accuracy of 2 arc seconds.
- An overall control bandwidth to produce robust control of modes affecting the mirror segments and motion of the secondary while reducing the slipover effects due to neglected modes and dynamics.
- A high level of disturbance rejection (100:1) and attenuation of vibration due to gravity, thermal and seismic effects and control structure interaction (CSI).

2.3 Dynamics And Control: The structure is designed to approximate the fundamental dynamic characteristics of a three-dimensional large structure, i.e. low-frequency modes, high modal density, and global mode shapes that properly reflect the coupling of the sub-elements of the structure.

2.4 Interdisciplinary Approach: The test-bed is designed to accommodate interdisciplinary experiments in validation of control algorithms, CSI, optics, electronics, actuators, sensors, and distributed multiprocessor design and implementation.

2.5 Decentralized Approach: The test-bed is designed to demonstrate physical and mathematical decentralization and accommodate development of control algorithms related to decentralized control technique.

3 CSRL System Description

Figure 1 shows a schematic illustration of major features of the test-bed, including primary and secondary mirrors, the actuators, the edge sensors, and the isolation platform.

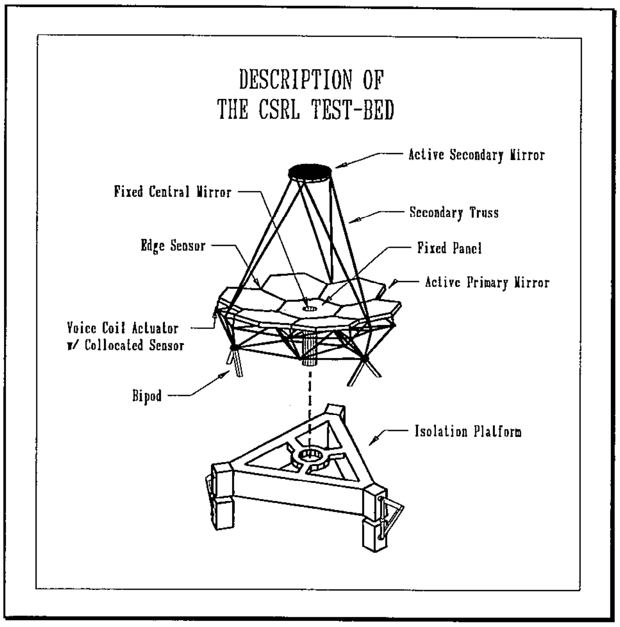

Figure 1

The active optical elements are the primary mirror segments which interact dynamically with the actuators, sensors and the supporting structure in an integrated way. The primary mirror is a 2.66 meters diameter dish supported on a lightweight, flexible truss structure. The optical system emulated that of a f/2.4 meters Cassegrain telescope. The major components of the CSRL test-bed are discussed below:

3.1 Structure: One of our most fundamental design goals has been a strong, light-weight truss structure whose structural-dynamic characteristics are representative of a large, flexible space borne system. These include low frequency modes, high modal density and global mode shapes that properly reflect the coupling of the sub-elements of the structure. A careful trade-off between the need for the structure to support itself in the 1-g laboratory environment versus the need to keep the frequency of the first mode as low as possible was achieved using multi-criteria optimization techniques and Pareto optimality concept [3].

The truss is made of thinwall stainless steel tubing in a unique geometric configuration to achieve highest strength with lowest mass.

3.2 Segmented Primary Mirror: the CSRL primary mirror is designed to emulate the critical properties of a real segmented mirror. These properties include segmentation geometry, inter-segment spacing, segment mass, inertia and stiffness, and optical focal ratio. The seven segment primary mirror consists of a ring of six actively controlled hexagonal segments surrounding a fixed center segment that acts as a reference.

Because the test-bed is control-system oriented, and because of difficulty and added expense of fabrication of actual optical-quality segments made from glass, the segments are fabricated from flat honeycomb aluminum plates. the active segments are attached to segment-positioning actuators via special three-degree-of freedom flexures. The relative displacement between the edges of adjacent segment is measured by an ensemble of 24 edge sensors. The edge sensors provide information about the segments' relative displacement as well as absolute displacements from the fixed center reference segment.

3.3 Segment-Positioning Actuators: We have designed and developed high performance segment-positioning actuators for precision control of the CSRL test-bed primary mirror. These actuators have extremely low noise level, are able to generate substantial force over a wide mechanical range and support the weight of a segment in a 1-g field. They have a bandwidth sufficient to accommodate the spectrum of expected disturbance and are able to support robust control of the system. To avoid friction specially designed disk flexures are used instead of conventional bearings. The actuators are fitted with collocated position sensors to increase system damping.

3.4 Active Secondary Mirror: The CSRL test-bed secondary reflector consists of an actively controlled mirror whose housing is supported by a tripod that is attached to the primary truss at three points. The mirror is suspended from its housing by means of isolation springs. The mirror is designed to provide two-axis, active beam-steering control. A closed-loop control system is being designed that is capable of aligning the secondary to the focal plane and removing all relative angular motion between the secondary and the reference central segment of the primary structure. The control system hardware consists of a number of reluctance actuators and position sensors.

4 Modeling and Structural Characteristics

A Finite Element Model for the CSRL was developed using MSC/NASTRAN [2]. The main concern in conducting the finite element analysis was to obtain the global modes affecting the primary mirror segments and the motion of the secondary mirror. The model includes the primary and secondary truss, the panels, joints and fittings, the actuators, the platform and the flexures. The model has a total of 3510 degrees of freedom.

The eigenvalue analysis of the system showed that the lowest natural frequency of the structure is at 10.3 Hz. Figure 2 shows the frequency histogram for the first 100 modes of the structure. The analysis of the mode shapes revealed that the first 13 modes are mainly due to the motion of the secondary. The first critical mode related to the motion of the primary segments is at 24.3 Hz.

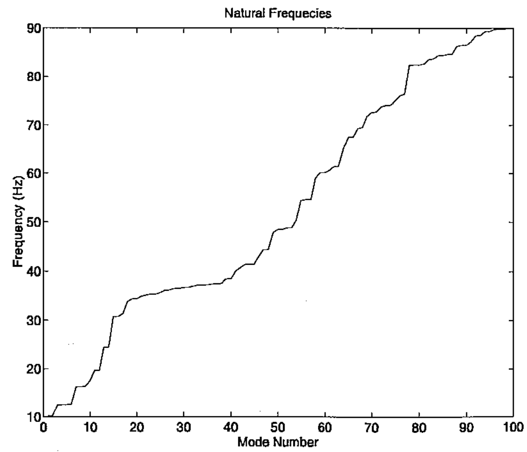

Figure 2

5 CSRL Control System Design

The CSRL control system objectives outlined in Section 2 will be accomplished using custom designed hardware and software which include an ensemble of sensors, actuators, electronics (including A/D, D/A converters, DSP boards, neural networks, control and system identification algorithm.

5.1 Edge Sensor System: The CSRL edge-sensor system consists of 24 position sensors mounted on the peripheries of the six actively controlled segments. The sensors (KDM-8200) are provided by Kaman Instrument Corp. They are low noise, high resolution (1 μm) inductive transducers with a dynamic range of 100,000. The sensors measure the relative displacements of the edges of adjacent panels. There is no measurement of the displacement of an individual segment with respect to the support structure. The figure maintenance is achieved through the measurement and control of the relative positions of the segments with respect to each other. The center segment, which is attached to the isolation platform, acts as the overall line of sight reference for the primary.

5.2 Actuators and Collocated Sensors: Eighteen voice-coil linear actuators mounted on specially designed platforms are used for figure maintenance and shape control. The actuators are manufactured by Northern Magnetic Crop. and have a maximum force output of 15 lb., a resolution of 0.1 μm, a stroke of ±2.5 mm and a bandwidth of about 100 Hz with a collocated position sensor. The position sensors used are the same as those fitted on panel edges and are used to provide an effective overall damping increase.

5.3 Computer Architecture: The drive electronics used in the CSRL test-bed is designed to process the analog outputs from sensors and interface them with the segment positioning actuators. The drive electronics is in charge of real-time processing and data acquisition. The computer and graphic set-up includes a DSP, a PC and two SUN stations. The DSP is the main computational unit and is responsible for real-time control processing, signal generation, and real-time directory memory. The DSP board is also used to analyze the data from the A/D converter and process a digital output code using the digital input signal to correct the position of panels [3].

The DSP and the SUN computers are used to monitor the CSRL experiments via the graphical display of the Kaman sensor reading, the actuator commands, and the mirror segments piston and tilt misalignment. The input/output unit is composed of two 32-channels 16-bit analog to digital and two 18-channel 16 bit digital to analog converters with a sampling rate of 200 kHz. Figure 3 illustrates schematically the CSRL test-bed overall computer architecture.

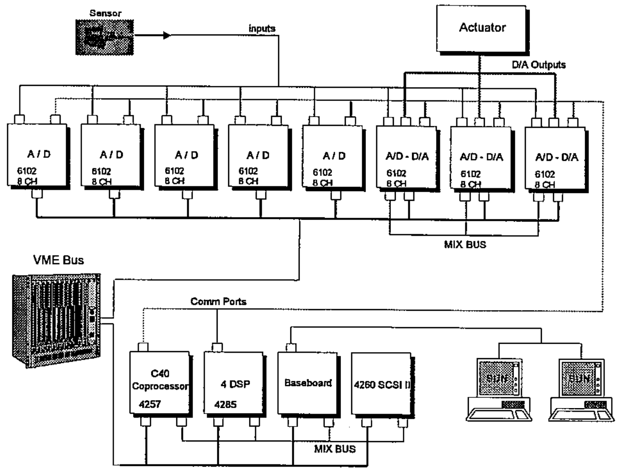

Figure 3

5.4 Control Algorithms and Simulation Studies:

Guyan reduction method was applied to the finite element model of the test-bed to obtain a state space representation for the development of control algorithms and simulation studies. The reduced model includes 42 nodes on the primary structure. There are 18 segment nodes, 3 per segment. Each node is constrained to have only a single degree of freedom resulting in a total of 42 degrees of freedom for the structure. The natural symmetry of the structure was exploited to decompose the system into smaller subsystems, each of lower order. Figure 4 illustrates conceptually the structure of the decentralized control scheme used in simulation studies.

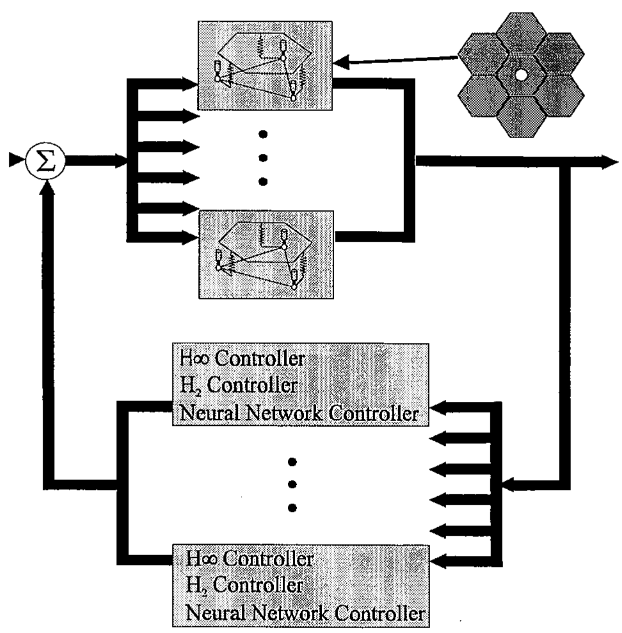

Figure 4

The control design was performed using H_2 (LQG) and H_∞ control. The control laws were developed at the local level and performance evaluations were performed utilizing PRO-MATLAB. Further, performance evaluations of three-subsystem structure were performed utilizing the control law of the isolated subsystems and the interaction among them [3], [4].

Figure 5 shows the simulation results of the application of H_∞ control law for disturbance rejection. The figure shows the comparison between the open-loop and the closed-loop time responses of a subsystem to a sinusoidal force. The controller is seen to reduce the disturbance by a large factor.

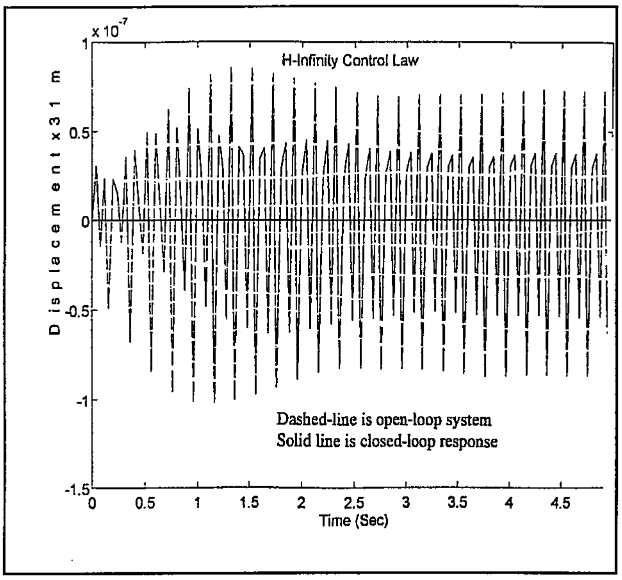

Figure 5

5.5 Neural Network Based Control: Two neural network architectures were developed and tested in simulation for the problem of disturbance rejection of the CSRL test-bed [3].

The first controller is a novel neural network controller (NNC) whose parameters are adjusted on-line [5], [6]. The control algorithm is simple and can be implemented in real time. Unlike other NNCs that are reported in the literature, the neural network controller developed for the CSRL test-bed requires relatively few neurons and its learning algorithm is faster than back-propagation. Stability analysis by a Lyapunov approach was used to determine the convergence properties of the algorithm. The stability is guaranteed with rather mild conditions and certain prior knowledge of the plant to be controlled.

The adaptive control developed consists of neural network placed in the feedback loop and an adaptation law to adjust the parameters of the network. The second controller is a feedforward two-layer neural network [3]. The network is trained off-line to emulate a dynamic compensator. The training is done by classical back-propagation.

6 System Identification

The system-identification process was required to serve a dual purpose: to identify the many closely packed low frequency vibration modes characteristic of a large flexible structure (see Figure 2); and to generate reliable, minimum-order state-space models of the structure with bounds on the estimated noise in the system. To accomplish these objectives, both time and frequency domain techniques are being investigated.

In the time domain, the classical Recursive Leas-Squares Filter type algorithms based on the usual autoregressive (AR) techniques (with/without external inputs, with/without moving averages) have been studied. Also, the Fast Transversal and Least-Square Adaptive Lattice Filters are currently being simulated [7]. The primary difficulty with these models has been model order size. Preliminary simulations yielded recursive models which had instabilities and thus were limited in their usefulness to the primary lower order modes. The optimum results obtained so far have been with reduced models of orders between 20—30.

Box-Jenkins and Output-Error models have provided better stability, but convergence to the finite element calculated modal values have been difficult. One possible reason could be that, so far, the system identification models have all been based on *simulated* input/output data from the MSC/NASTRAN model and without the benefit of actual input/output data (the physical structure is currently under construction). The NASTRAN model itself is an approximation of the modal behavior of the structure and the repeated transformations of this data from frequency to time domain and back again to frequency domain from the system identification estimated model is causing accumulation of numerical errors. However, as mentioned earlier, the underlying goal has been not to fit the system-id model to the simulated data, but rather to develop a set of usable algorithms to identify the parameters of the structure which can be used once the *real* input/output data is available.

In the frequency domain, initial progress with the traditional inverse discrete Fourier transform methods to generate Markov parameters have been limited because of the usual time aliasing distortions typical of this technique. However, recent advances made by researchers at NASA-Langley and NASA-JPL have provided some new techniques based on Eigensystem Realization Algorithms (ERA) such as the State Space from Frequency Data (SSFD) [8]. These general algorithms are currently being adapted for the CSRL test-bed and are being implemented on a MATLAB platform.

7 SUMMARY

This paper has described the experimental apparatus that is being developed at the Control and Structures Research Laboratory, at California State University, Los Angeles. The apparatus is a test-bed for research and development of technology related to the control of large, space-borne segmented optical systems. The CSRL test-bed has been designed to have dynamic characteristics similar to a large flexible structures and a control system whose performance is comparable to an astronomical-quality optical system. The control system architecture of the CSRL test-bed consists of an ensemble of sensors, actuators, and electronics which are used to achieve segment alignment and pointing. Decentralized control is being implemented by H_2 (LQG), H_∞ and neural network techniques using simulations and parameter values estimated by time and frequency domain system identification algorithms. The test-bed can be used as a generic research facility for validating a variety of control design methodologies as well as control and structures interaction.

Acknowledgments

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