NASA
Technical
Memorandum

NASA TM -100321

COST EFFECTIVE DEVELOPMENT OF A NATIONAL TEST BED

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February 1988

(NASA-TM-100321) COST EFFECTIVE DEVELOPMENT OF A NATIONAL TEST BED (NASA) 18 p CSCL 22B

N88-19585

Unclas
G3/18 0134283

National Aeronautics and
Space Administration

George C. Marshall Space Flight Center

MSFC - Form 3190 (Rev. May 1983)

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO. NASA TM-100321	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE Cost Effective Development of a National Test Bed		5. REPORT DATE February 1988
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) H. B. Waites, V. L. Jones,* and S. M. Seltzer*		8. PERFORMING ORGANIZATION REPORT #
9. PERFORMING ORGANIZATION NAME AND ADDRESS George C. Marshall Space Flight Center Marshall Space Flight Center, Alabhama 35812		10. WORK UNIT NO.
		11. CONTRACT OR GRANT NO.
		13. TYPE OF REPORT & PERIOD COVERED Technical Memorandum
12. SPONSORING AGENCY NAME AND ADDRESS National Aeronautics and Space Administration Washington, D.C. 20546		
		14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

Prepared by Structures and Dynamics Laboratory, Science and Engineering Directorate.

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16. ABSTRACT

For several years, the Marshall Space Flight Center has pursued the coordinated development of a Large Space Structures (LSS) National Test Bed for the investigation of numerous technical issues involved in the use of LSS in space. This paper describes the origins of this development, the current status of the various test facilities and the plans laid down for the next five years' activities. Particular emphasis on the control and structural interaction issues has been paid so far; however, immediately emerging are user applications (such as the proposed pinhole occulter facility). In the immediate future, such emerging technologies as smart robots and multibody interactions will be studied. These areas are covered in this report.

17. KEY WORDS Large Space Structures Dynamic Testing Verification Control Verification	18. DISTRIBUTION STATEMENT Unclassified – Unlimited

19. SECURITY CLASSIF. (of this report) Unclassified	20. SECURITY CLASSIF. (of this page) Unclassified	21. NO. OF PAGES 17	22. PRICE NTIS

MSFC - Form 3292 (May 1969)

For sale by National Technical Information Service, Springfield, Virginia 22151

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INTRODUCTION

The LSS GTF (Large Space Structure Ground Test Facility) is a facility which is being developed to investigate the controls and dynamics issues associated with LSS. The NASA/MSFC (Marshall Space Flight Center) initiated the LSS GTF to meet the desired objectives of complex space projects, by investigating the topics of control development and synthesis, dynamics verification, dynamic modeling, and hardware flight systems for space structures. The overall goal of the LSS GTF is to become a national test bed for investigations in dynamics and controls.

Spacecraft structures have become more complex and LSS requirements have become more stringent due to an increased use of space for Earth sciences, solar physics, astrophysics, material sciences, and defense. With the increase in spacecraft complexity, the experiments have become more ambitious and multifaceted (i.e., Space Station, Advanced Solar Observatory, etc.). Many of these missions require high performance from the LSS, such as extremely accurate pointing of optical elements and the attainment of vibration-free observation image planes. The LSS GTF provides the ground test capability necessary to experiment with large beams, LSS components, and even full-size LSS.

The LSS GTF has been developed over the past four years in a very cost-effective manner. The cost-efficiency has been "enabled" by using components from past projects and by assembling a team able to develop and operate the facility. The development of the LSS GTF required a multi-discipline team, since the LSS issues cover a wide range of technical disciplines. The team includes members expert in the areas of control, structures, optics, sensors and actuators, propulsion, computer hardware and software, electronics, and materials. The team members include MSFC, Control Dynamics, and DYNACS personnel.

OBJECTIVES

The goals of the LSS GTF are to automate as many LSS technical disciplines as possible and to integrate where possible, these disciplines into a user friendly analysis methodology. The LSS GTF is utilized to experimentally test and evaluate the dynamics and control of realistic space structures. The LSS GTF is a non-proprietary installation in which guest investigators are encouraged to implement and validate control and structural methodologies. The objectives of the LSS GTF are as follows:

1) Investigate control and dynamics issues on a single space structure. Develop a laboratory where control methodologies, dynamic modeling, and data reduction techniques can be evaluated.

2) Develop a laboratory for ground testing a possible flight experiment.

3) Develop and validate a computer tool which allows efficient simulation and analysis of connected flexible structures.

4) Investigate control and dynamics issues on complex multi-body structures. Study the disturbances induced by a robotic system on precision pointing experiments.

5) Investigate the use of novel sensors and effectors whose weights and geometries are relatively negligible compared to those of the flexible structure to be controlled. Examine the sensing and actuating capabilities of piezo-electric materials.

The expected outputs of the LSS GTF Team are as follows:

1) A national test bed capable of implementing and evaluating LSS control methodologies.

2) An LSS ground test facility capable of applying and validating structural modeling techniques.

3) A facility in which real time testing procedures for space systems can be examined.

4) A multibody modeling computer analysis tool which is experimentally verified.

GROUND TEST FACILITIES

The current LSS GTF consists of the Single Structure Control (SSC) Laboratory. The GTF will be expanded to include the Pinhole Occulter Facility (POF), the Multi-Payload Pointing Mount (MPPM) Laboratory, and the Unobtrusive Sensor and Effector (USE) Laboratory. The Robot Enhancement Laboratory and a number of Thermal and Thermal/Vacuum Chambers will be incorporated into the overall LSS GTF. The POF design is proceeding presently, and initial testing is underway in the USE Laboratory. These future expansions are described in the section entitled Future LSS Activities.

Single Structure Control (SSC) Laboratory

The objectives of the SSC Lab are to apply and implement control design techniques on a realistic LSS, and to evaluate performance of LSS controllers. The control methodologies already implemented include the pole placement, FAMESS, HAC/LAC, and Positivity control algorithms. Comparison between these LSS control methodologies is presently nearing completion (see section on ACES Program). A model of the SSC test article has been developed and validated using modal testing and transfer function testing.

The SSC Laboratory (Fig. 1) is located at NASA/MSFC in a high bay building. The laboratory contains a flexible test structure, a Base Excitation Table (BET) for inducing prescribed vibrations and disturbances into the structure, a gimbal system for producing controller rotations of the test article, Linear Momentum Exchange Devices (LMEDs) for damping beam vibrations, a payload mounting plate, assorted sensors (accelerometers, rate gyroscopes) at several structure locations, an Image Motion Compensation (IMC) system for optical pointing, and a computer/telemetry system.

The evolution of the SSC laboratory over the past four years is depicted in Figure 2. Various sensors and actuators have been incorporated for different configurations. The basic test article has also been modified through the addition/replacement of tip appendages (i.e., cruciform, antenna structure).

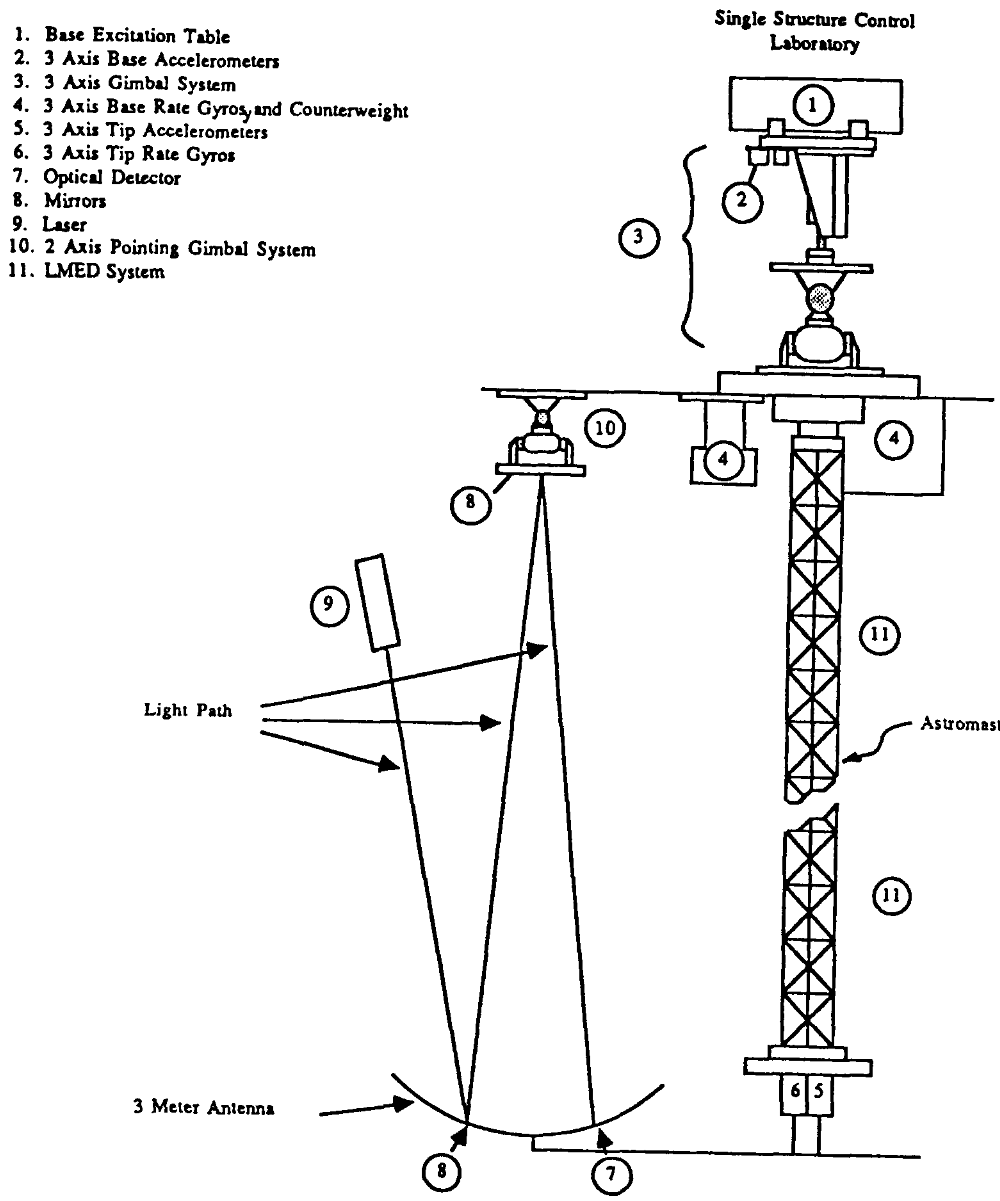

Figure 1. Single Structure Control (SSC) Laboratory.

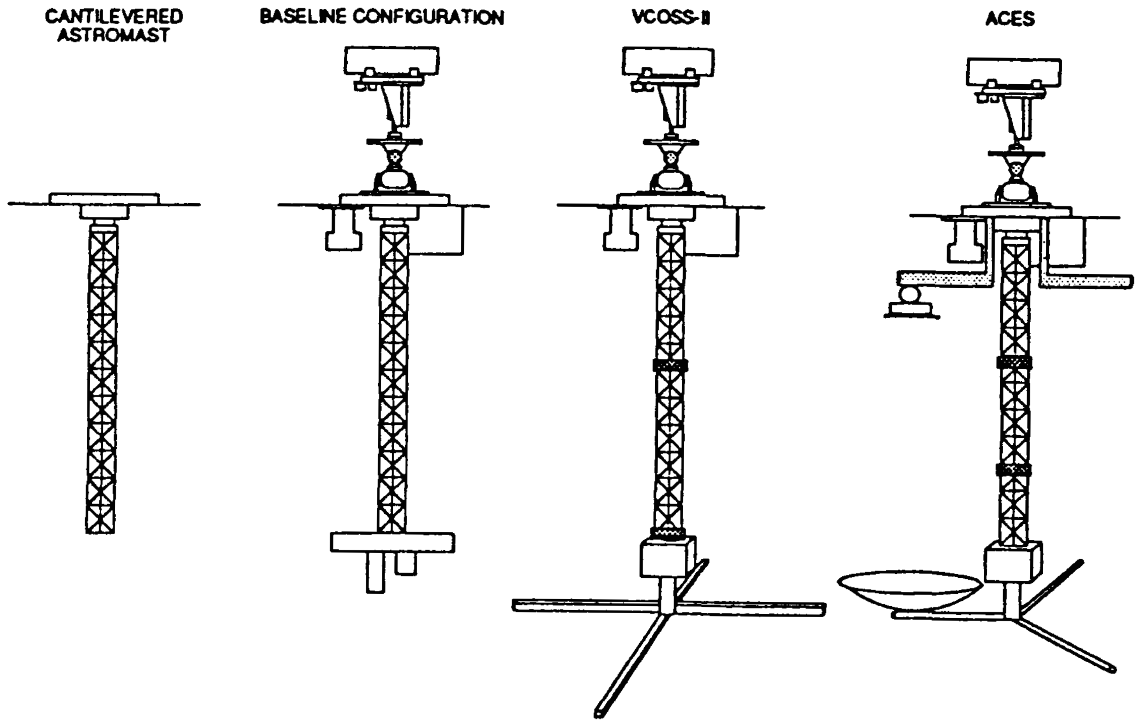

Figure 2. SSC Laboratory evolution.

COST EFFECTIVE DEVELOPMENT OF THE LSS GTF

The development of the LSS GTF has proceeded in a very cost-effective manner. This cost-efficiency stemmed from the following two factors:

1) Ability to obtain and update useful laboratory components from past projects.

2) Availability of LSS GTF Team members who are capable of developing, integrating, maintaining, updating, and operating all facility components.

The first factor is examined in Table 1, which compares the actual cost (to the LSS GTF Program) with the estimated (or actual) development cost of each component.

An experienced intra-structure of personnel was necessary to successfully develop and integrate the LSS GTF. The following discipline areas are presently assembled: controls, structural modeling, electronics, computer systems and programming, fabrication, sensors and actuators, optics, simulation, facility operation, propulsion, and program management. The vast experience assembled on the LSS GTF Team is indicated in Table 2. It should be emphasized that, even if one had $10 Million to invest in the LSS ground test facility components, it would be impossible to develop the facility without an established multidiscipline team having vast experience. The assembly and training of such a team would require another substantial investment. In addition, the actual implementation and development of the facility (i.e., hardware integration, software development, component modifications, interface definition, development, maintenance, etc.) would require an investment several times the initial component investment.

TABLE 1. ACTUAL VERSUS DEVELOPMENT COST OF LSS GTF COMPONENTS

Component	Actual Cost ($K)	Development Cost ($K)
Beam	0.6	225.
Gimbal System (AGS)	0.4	2500.
Roll Motor	0.0	2.
Computer System Hardware	70.0	110.
Computer System Software	0.0	125.
Base Excitation Table (BET)	5.0	20.
Tip Gyros (KARS)	50.0	75.
Base Gyros (ATM)	0.0	50.
Accelerometers	0.0	50.
IMC System	17.0	2000.
LMEDs	7.0	150.
Linear Thrusters	28.0	130.
SAFE-I	0.0	4500.
Robot Arm	0.0	100.
Solar Optical Telescope	95.0	95.
Roll Tip Motor	7.0	7.
Sum	280.0	10,139.

TABLE 2. LSS GTF TEAM MEMBER EXPERIENCE

Discipline	Number of Members	Experience (Years)
Controls	6	80
Dynamic Testing	5	60
Structural Modeling	4	50
Computer Systems and Programming	5	55
Electronics	3	50
Simulation	6	55
Sensors and Actuators	7	100
Optics	3	50
Propulsion	2	20
Program Management	4	80

DYNAMIC MODELING

One of the more time consuming areas of LSS control verification is the development of the structural model. In many space projects, the data is presented to the control designer one substructure at a time. In addition, the substructure models are usually defined for a fixed substructure orientation. Most LSS have flexible substructures which change their orientation; this implies that a multitude of structural models are required to effect an LSS control verification. This scenario is not only time consuming, but it also contains many possible sources of error.

A user friendly computer analysis tool (CONTOPS) was developed to eliminate the aforementioned problems of time consumption and error generation. The tool works within the contraints of the system, such as model definition via substructures and different orientations. The significant features of the CONTOPS (Closed Tree Topology) are as follows:

1) Modular concept allows for rapid reconfiguration.

2) Models large angle rotations and angular rates for any module.

3) Allows for chain, tree, and ring topologies of flexible bodies.

4) A variety of control modules are available, including pole placement and quadratic minimum techniques.

5) Allows equality and inequality constraints between any two or more elements of the substructures.

The ring topology of flexible bodies is the latest feature that has been added to CONTOPS. The ring joints for each substructure have either equality or inequality constraints. The equality constraints consist of kinematic conditions. Inequality constraints are conditions such as:

1. Hard stops.

2. Coulomb dampers.

3. Velocity squared dampers.

4. Solid dampers.

5. Displacement squared springs.

The ring topology with joint constraints models and simulates many LSS, but future enhancements are required to upgrade the disturbance models, selection of critical structural modes, and the modeling of effectors with momentum. The enhancements for the nonlinear modeling and simulation program will be:

1. Gravity gradient model.

2. Atmospheric model.

3. Magnetic model.

4. Modal selection methods.

5. Momentum effector model.

6. Geometric stiffness.

With these additions, very complex structures can be modeled and simulated using various control options. The system model objectives, which were relative ease and reasonable times to model LSS, were achieved with the development and use of CONTOPS.

LSS CONTROL SYNTHESIS

The SSC Laboratory provides a realistic LSS on which LSS control methodologies can be experimentally implemented and evaluated. Several control techniques have been applied to each configuration.

The preliminary control technique demonstrated at the SSC on the cruciform configuration was a centralized pole placement technique. The cruciform configuration had 15 modes below 2.5 Hz and these modes had damping of 1.5 percent or less. The fundamental mode was at 0.5 Hz. An Orbiter thruster-like disturbance at the BET was applied to demonstrate the controller effectiveness. The open and closed loop rate gyro responses to the same stimuli are shown in Figure 3.

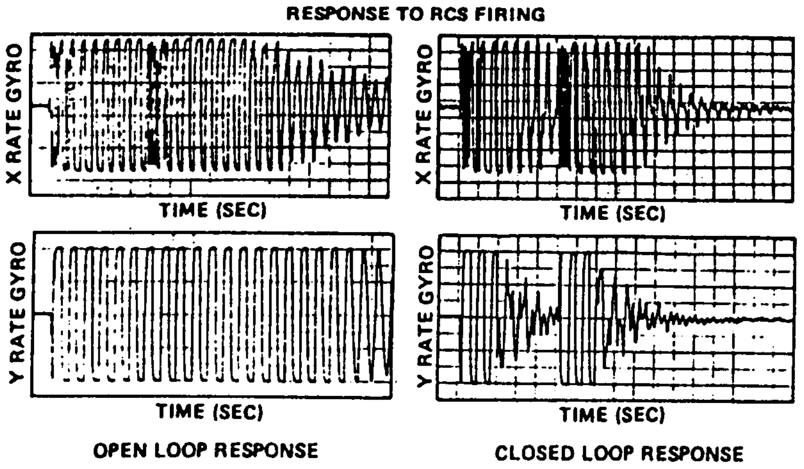

Figure 3. Open and closed loop responses at SSC Lab (cruciform configuration).

The SSC Laboratory evolved into the VCOSS-II configuration from the cruciform configuration through the addition of the LMEDs (Linear Momentum Exchange Devices). The LMED provides a colocated sensor/actuator pair which applies a force and measures the resulting acceleration. Each LMED package contains two LMEDs having orthogonal axes, two accelerometers, and two LVDTs (Linear Variable Displacement Transducers). The two LMED packages are positioned at intermediate points along the Astromast, where these points were selected to maximize the actuation capability. A control loop was designed for the LMEDs and was able to significantly damp a mode at 5 Hz.

ACTIVE CONTROL EVALUATION OF SPACECRAFT (ACES) PROGRAM

The ACES program was a joint AFWAL (Air Force Wright Aeronautical Laboratories)/ MSFC venture which was implemented at the SSC Laboratory (ACES configuration) in 1986-1987. The purpose of the ACES program was to investigate the implementation of the three primary ACOSS (Active Control Of Space Structures) LSS control techniques: FAMESS (Filter Accommodated Model Error Sensitivity Suppression), HAC/LAC (High Authority Control/Low Authority Control), and Positivity.

The ACES configuration evolved by incorporating the IMC (Image Motion Compensation) system, the antenna system, and the arm system to the VCOSS-II configuration. The IMC system consists of the laser, two mirrors, a two-axis detector, a set of two-axis pointing gimbals, and electronics to interface both the detector and gimbals to the computer. The laser is fixed to the facility, the mirrors are located at the tip and base of the Astromast, and the detector is at the base of the antenna. The arms are located at the base of the mast. The pointing gimbals are attached to the tip of one of the flexible arms; the other arm acts as a counterweight. The arms are purposely very flexible to increase the complexity of the control problem. The antenna system consists of the antenna, the antenna arm, and the two counterweight legs appended to the tip of the Astromast. The ACES configuration contains many closely spaced, low frequency modes (43 modes under 8 Hz), which are lightly damped (<2 percent).

The goals of the controller are:

1) To reduce the IMC and LOS error due to three representative disturbances.

2) To ensure that the controller has a practical size (order).

3) To attempt to ensure that the controller is tolerant of model limitations.

The primary performance criterion is the RMS LOS error. The controllers' effectiveness as structural vibration suppressors was investigated. The ACES Program has recently been completed, and the final report is being written.

FUTURE LSS GTF ACTIVITIES

Future activities to be implemented in the LSS GTF include numerous programs, such as the ACES-II and ACES-III, COT (Control of Optical Train), and MMV (Multibody Modeling Verification) programs. Future laboratories to be developed include the POF (Pinhole Occulter Facility), MPPM (Multi-Payload Pointing Mount) lab, and the USE (Unobtrusive Sensors and Effectors) lab.

SSC Laboratory (ACES-II Program)

The SSC Laboratory will be used for the ACES-II program, which is a follow-on to the current ACES program. Additional promising candidate control techniques will be identified, implemented, and assessed. Several control techniques, such as Harris' MEOP (Maximum Entropy Optimal Projection), Control Dynamics' I-CAT (One Controller At a Time), the various H-infinity techniques, and Johnson's DAC (Disturbance Accommodating Control) will be among those techniques under consideration. The ACES-II program is to be performed in 1988.

SSC Laboratory (ACES-III Program)

This follow-on to the ACES programs will modify the SSC Laboratory through the incorporation of a tip roll gimbal motor and a set of bi-directional linear thrusters. Letters of Invitation will be sent to interested candidate Guest Investigators from industry, universities, and other Government installations. Guest Investigators will propose additional utilization and/or modification of the LSS GTF. Selected Guest Investigators will implement their proposed ideas within the ACES-III program. The ACES-III is scheduled for 1989.

Pinhole Occulter Facility (POF)

The POF will consist of several configurations; the Primitive POF (PPOF) is the first configuration and will be followed by the POF. The PPOF (Fig. 4) is presently under development and will consist of the vertical suspension of the 105 ft SAFE-I boom from a tripod air bearing. Two sets of AMEDs (Angular Momentum Exchange Devices) are being developed and a set of BLTs (Bi-directional Linear Thrusters) are being tested and developed for use as control actuators. The PPOF is planned to be operational in 1988. The POF configuration will be a modification of the PPOF by incorporating a set of control gimbals. Eventually, the POF will evolve to the omega-POF, through the application of USE technology to the boom.

Multi-Payload Pointing Mount (MPPM) Laboratory

The purpose of the MPPM Laboratory (Fig. 5) is to investigate the dynamic interaction between two or three pointing experiments that are mounted on the same structure and are operating simultaneously. Several configurations are to be examined, including components such as the SAFE-I boom, Solar Optical Telescope (SOT), and a Robot Arm.

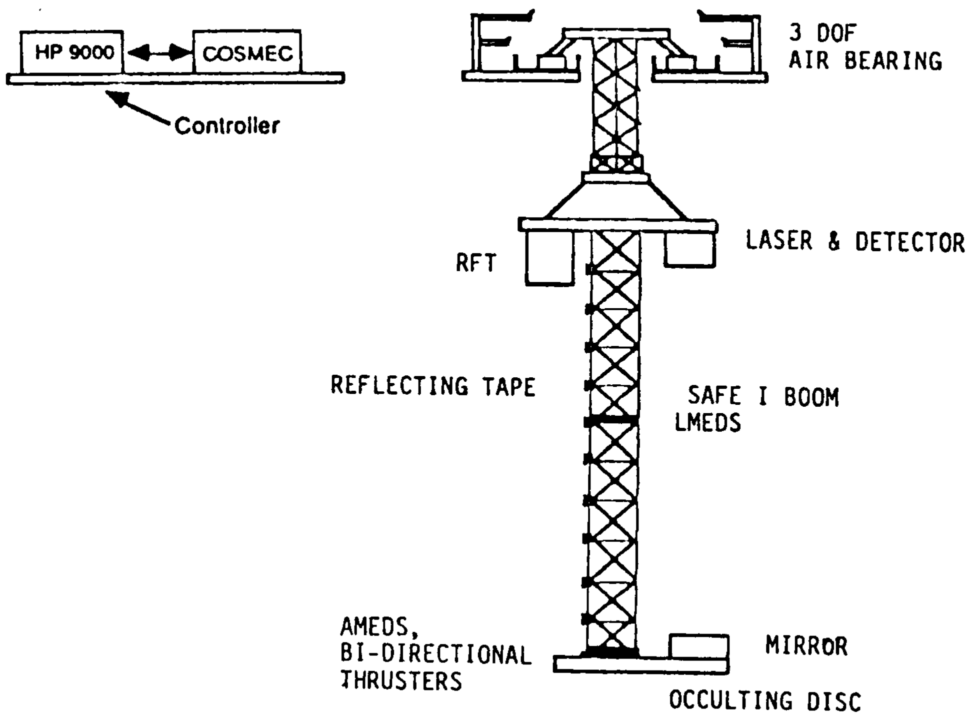

Figure 4. PPOF configuration.

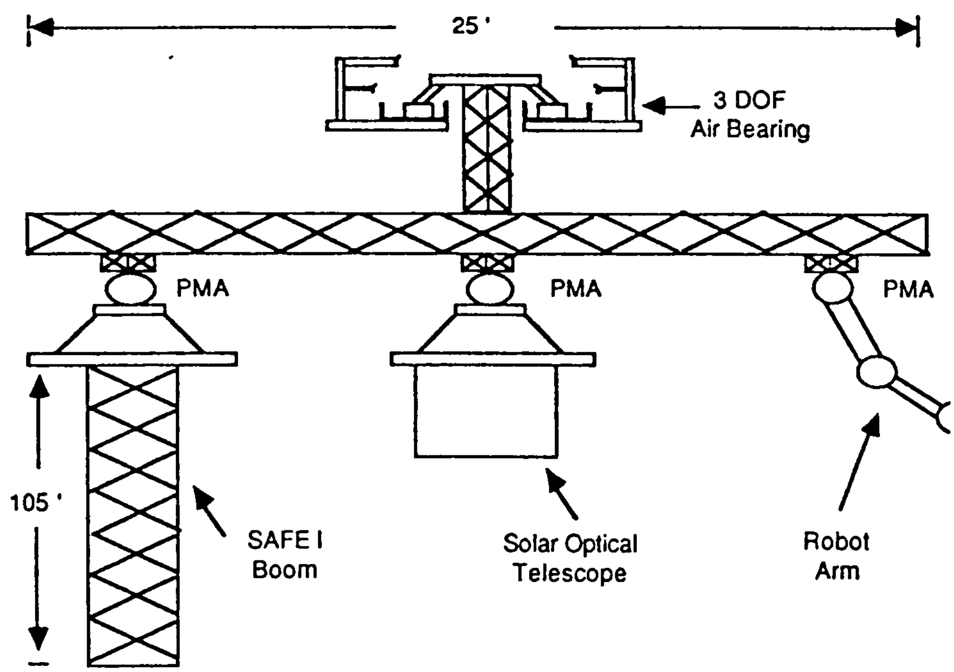

Figure 5. MPPM laboratory.

Unobtrusive Sensor and Effector (USE) Laboratory

The USE Laboratory is to investigate the use of sensors and actutors which are lightweight and have unobtrusive geometries. Testing of piezo-electric materials is presently underway; a small scale experiment has been developed which demonstrates the actuation capabilities of a piezo material. The experimental open and closed loop responses (Fig. 6) to an initial disturbance show the active damping capabilities induced by the piezo control loop. The USE lab will be expanded to accommodate the robot arm, which will be autmented with an end-effector having active fingers (to communicate with the piezo-electric sensors and effectors).

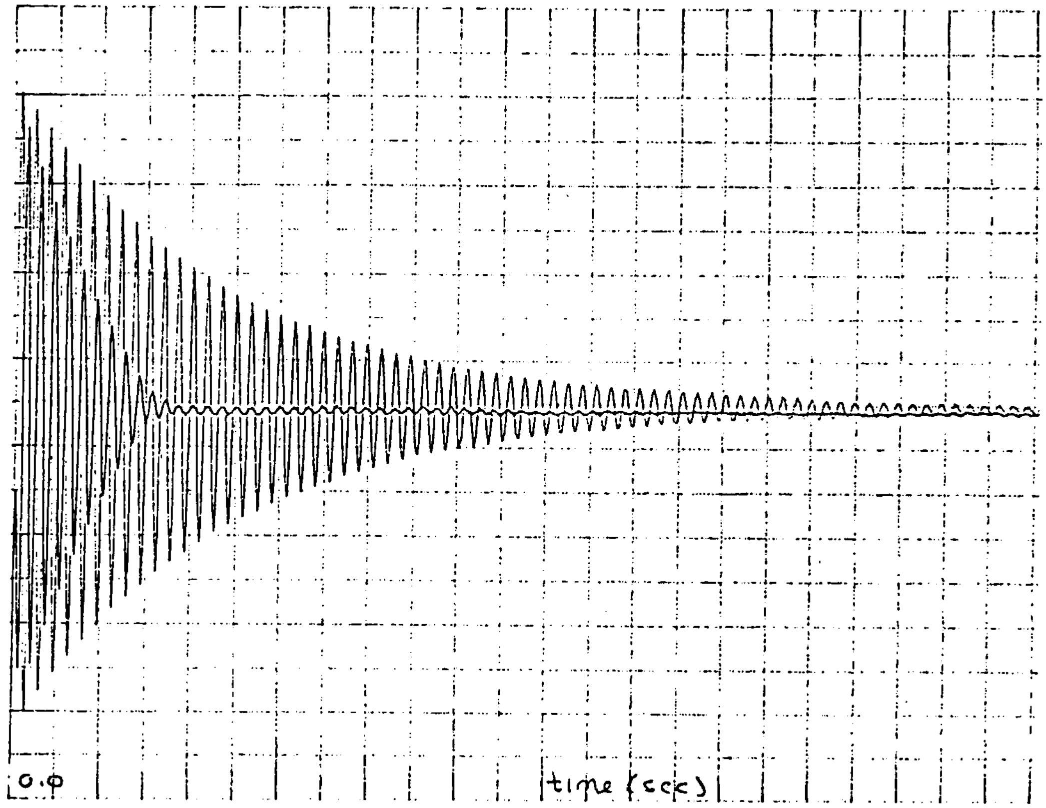

Figure 6. Piezo-electric actuation experimental open/closed loop responses.

Control of Optical Train (COT) Program

The COT program will be designed and developed for the purpose of investigating the dynamics of future programs which will utilize precisely pointed, stabilized, folded optics. Figure 7 shows the proposed experimental configuration of the COT.

Multibody Modeling Verification (MMV) Program

The main objectives of the MMV program are to improve the user friendly multibody modeling computer tool (CONTOPS) and to experimentally verify component modal synthesis

EXTENDED APERTURE
INTERFEROMETER EXPERIMENT

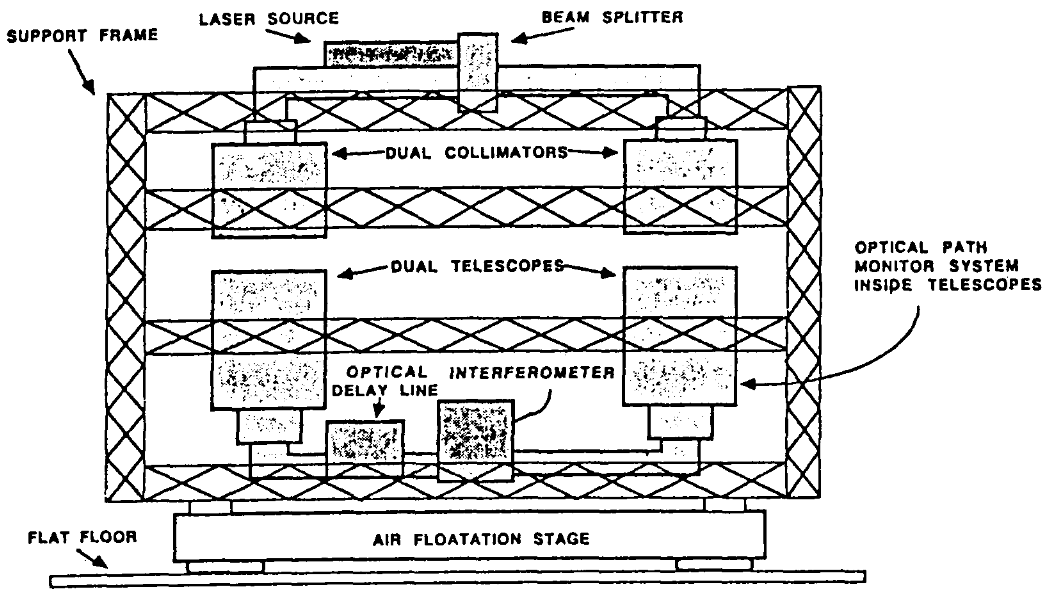

Figure 7. Control of Optical Train (COT) configuration.

methods. CONTOPS has the capability to effect component modal synthesis for a chain, tree, or ring topology of flexible bodies which can undergo large angular motions. The modal component synthesis methods are to be verified on a series of test articles. These test articles will be able to be reconfigured and will have the capability to experience large angular and translational displacements. One of the test articles is shown in Figure 8 in several of its configurations.

CONCLUSION

The NASA/MSFC LSS GTF is one of the most complete LSS ground test facilities in the United States. The topics of control development and synthesis, dynamics verification, dynamic modeling, and hardware flight systems for space structures are being addressed. The present and future activities will enable the LSS GTF to become a national test bed for investigations in dynamics and controls.

The SSC Laboratory has been successfully developed and several significant experimental LSS programs have been completed. The SSC Laboratory contains a structure which is representative of LSS, with many lightly damped, closely spaced, low frequency modes. The ACES program is the first direct experimental comparison of the ACOSS LSS control methodologies.

The future activities include many investigations which will validate present control and dynamics methodologies and which will hopefully lead to the development of promising technologies. The application of unobtrusive sensors and effectors is presently underway; a small scale piezo-electric material experiment has been developed. The design and development of the Primitive Pinhole Occulter Facility is also currently proceeding. The multibody modeling computer tool (CONTOPS) is being improved. A plan is being developed for a facility in which validation of multibody modeling algorithms will be effected. Eventually, the complex control problems dealing with multi-payload pointing experiments will also be addressed.

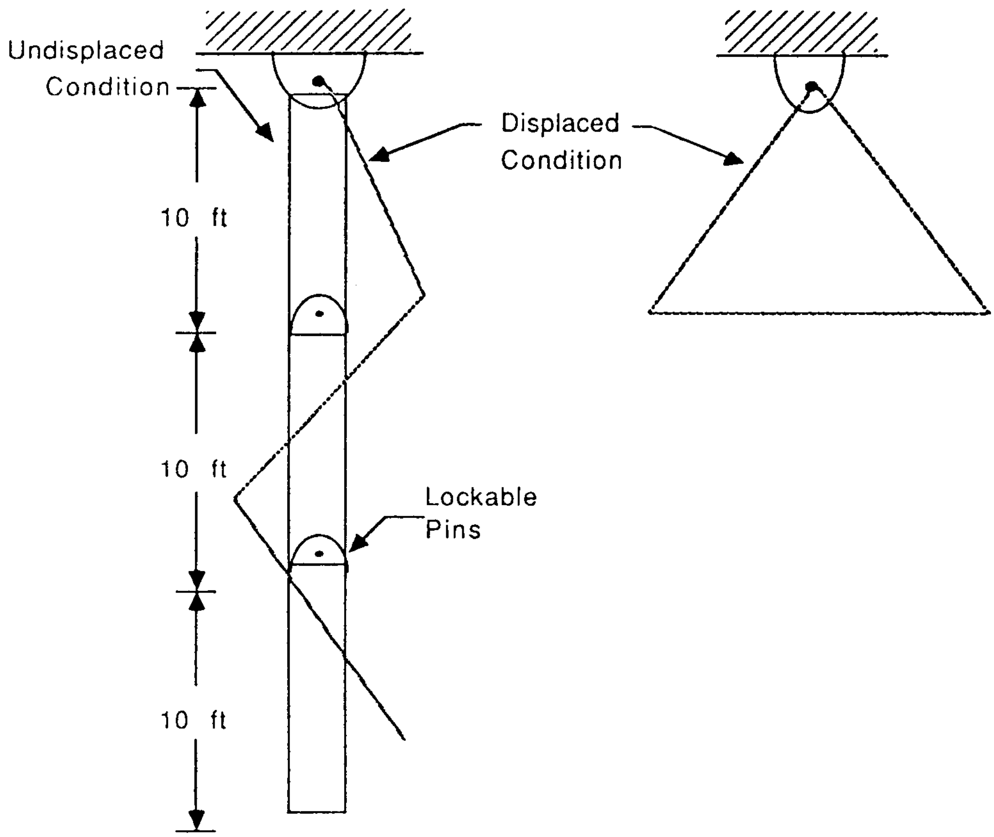

Figure 8. Multibody modeling verification test article.

APPROVAL

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The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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