CONTROL TECHNOLOGY DEVELOPMENT

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CONTROL TECHNOLOGY DEVELOPMENT OBJECTIVES

The main objectives of the control technology development task are given in the slide below. The first objective is to develop control design techniques based on flexible structural models, rather than simple rigid-body models. Since large space structures are distributed parameter systems, a new degree of freedom, that of sensor/actuator placement, may be exercised for improving control system performance. Another characteristic of large space structures is numerous oscillatory modes within the control bandwidth. Reduced-order controller design models must be developed which produce stable closed-loop systems when combined with the full-order system. Since the date of an actual large-space-structure flight is rapidly approaching, it is vitally important that theoretical developments are tested in actual hardware. Experimental verification is a vital counterpart of all current theoretical developments.

- TO DEVELOP DYNAMIC AND SHAPE CONTROL DESIGN APPROACHES BASED ON FLEXIBLE MODELS
- TO MAXIMIZE CONTROLLER PERFORMANCE BY JUDICIOUS SENSOR/ ACTUATOR PLACEMENT
- TO DEVELOP GENERALIZED MODEL REDUCTION TECHNIQUES
- TO DEMONSTRATE CONTROL TECHNOLOGY DEVELOPMENTS USING HARDWARE TEST FACILITY

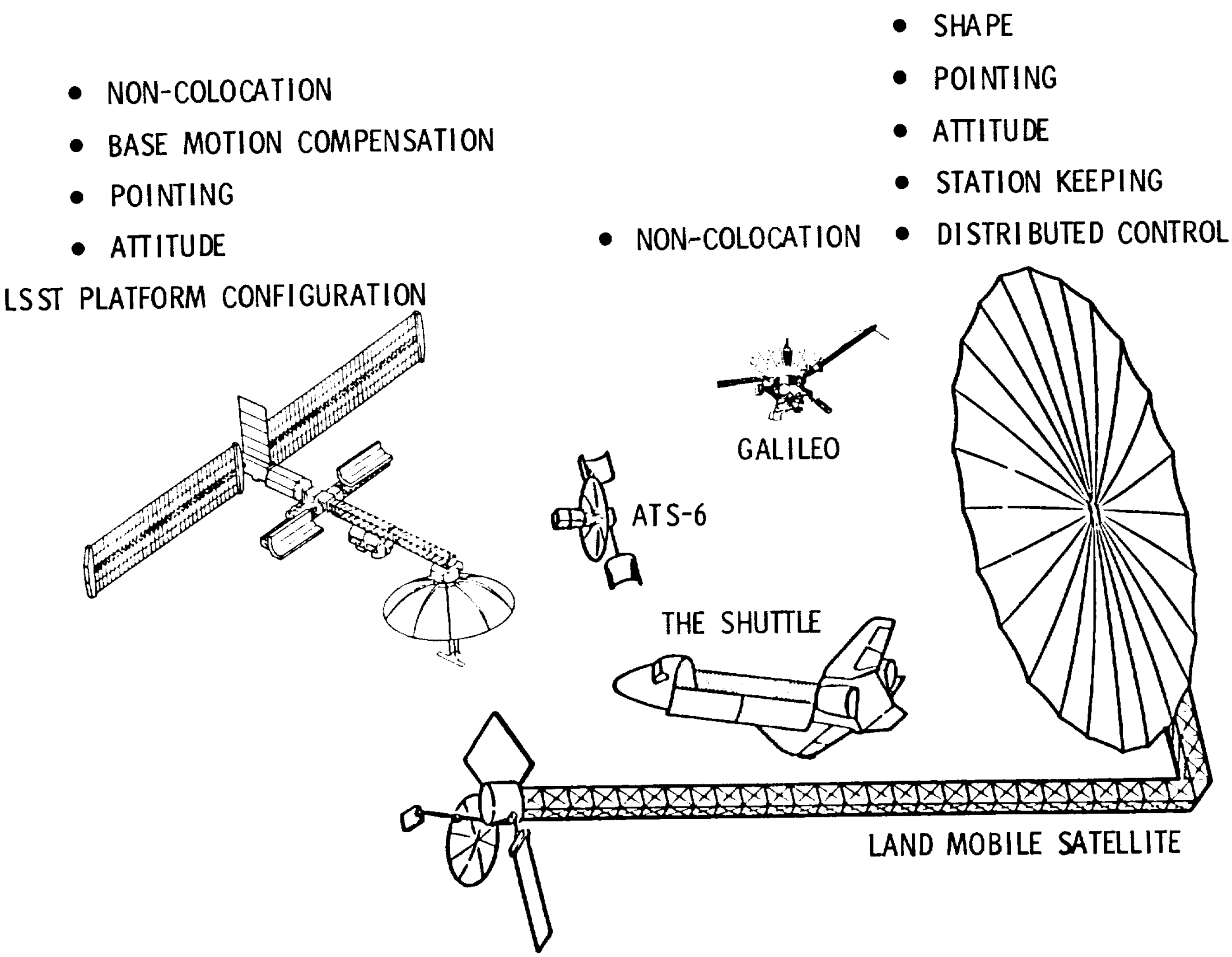
MAJOR ACHIEVEMENTS

The chart below serves as an outline for the remainder of this presentation and lists the major achievements of the past year's work. Control-system design approaches based on distributed parameter (partial differential equation) systems have been developed. These control-system design approaches reduce control spill-over. Analogous techniques have been applied to the figure-control problem, with shape control of a large flexible reflector yielding excellent results from a computer simulation. Stanford University developed control system designs for the case sensors and actuators are separated by a flexible member, an inherently difficult-to-control configuration. Purdue University has fully exploited the possibility of optimizing sensor and actuator locations in terms of overall system performance. A detailed finite-element model of our hardware verification facility was developed, and detailed calibrations of the associated instrumentation were made. Multivariable frequency domain control design approaches were developed primarily for the large-space-platform application.

- DEVELOPED DISTRIBUTED CONTROL-SYSTEM DESIGN APPROACHES FOR CONTROL SPILLOVER REDUCTION
- SIMULATED A FULL-UP SHAPE ESTIMATION AND SHAPE CONTROL SYSTEM
- DEVELOPED NON-COLOCATED SENSOR/ACTUATOR CONTROL-SYSTEM DESIGN TECHNIQUES
- OPTIMIZED SENSOR/ACTUATOR PLACEMENT FOR IMPROVED PERFORMANCE
- DEVELOPED A DETAILED EXPERIMENTAL FACILITY MODEL, INTERACTIVE CONTROL SOFTWARE, AND INITIATED A TESTING PROGRAM
- DEVELOPED MULTIVARIABLE FREQUENCY DOMAIN CONTROL DESIGN TECHNIQUES FOR BASE MOTION COMPENSATION

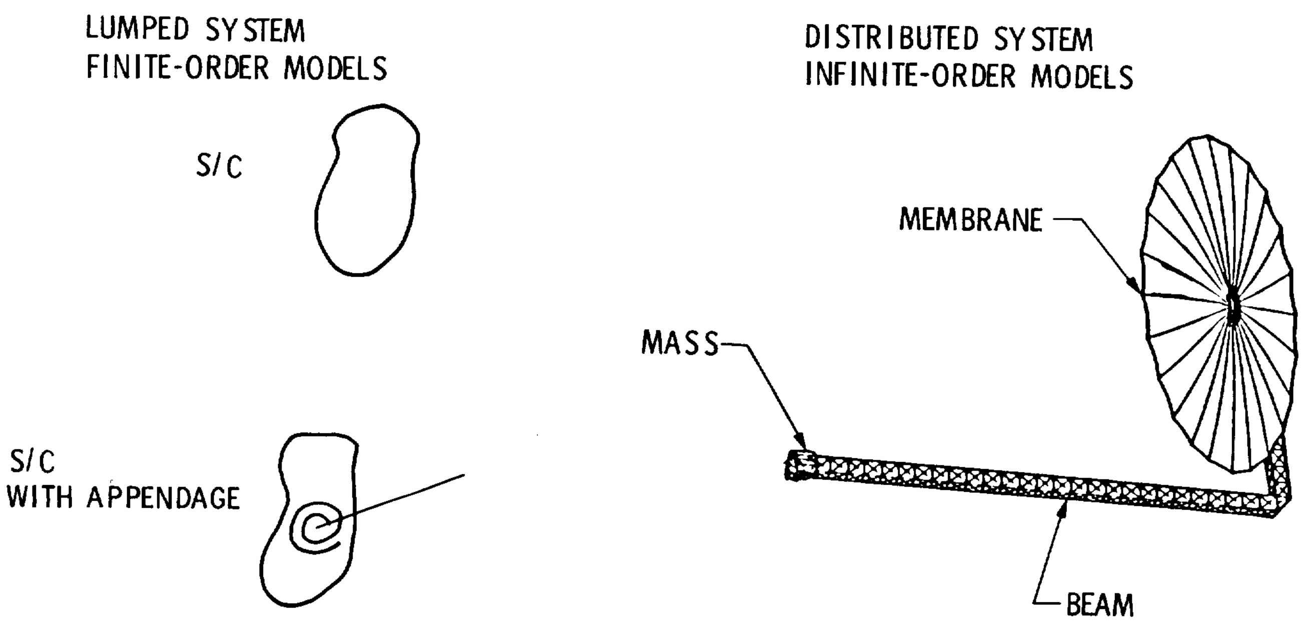
LARGE STRUCTURE CONTROL CONCEPT

Drawings of several spacecraft are shown below. Typical control objectives unique to large space structures are pointed out for some of these spacecraft. Although the control objectives of pointing control, attitude control, etc. may not at first seem to be unique to large space structures, the fact that these objectives are highly coupled with the structural vibrations resolves this discrepancy.



THE DISTRIBUTED-SYSTEM CONTROL PROBLEM

There are distinct and major differences between past, lumped-parameter systems and future distributed systems. A lumped system whether it consists of a single rigid body, or even a rigid body with a finite number of spring hinged appendages, possesses a finite number of structural modes. A continuously distributed parameter system made up of beams, membranes, tethers, etc. possesses an infinite number of modes. The control problem emerges as a result of the on-board controller ability to handle a finite-order model. Yet with the infinite-order systems, sensors still measure the unmodeled modes and actuators still affect the unmodeled modes. This can lead to instabilities when the control loop is closed.

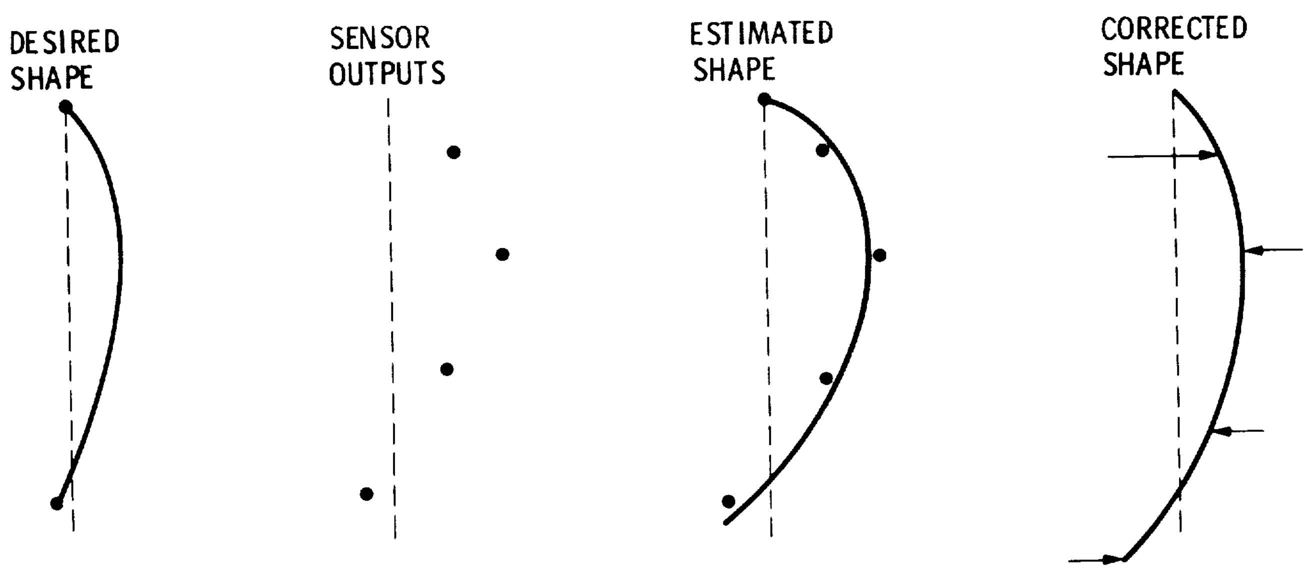


- EXISTING CONTROL-SYSTEM DESIGN PROCEDURES, WHEN APPLIED TO TRUNCATED DISTRIBUTED SYSTEMS MAY RESULT IN CLOSED-LOOP INSTABILITIES

THE SHAPE CONTROL PROBLEM

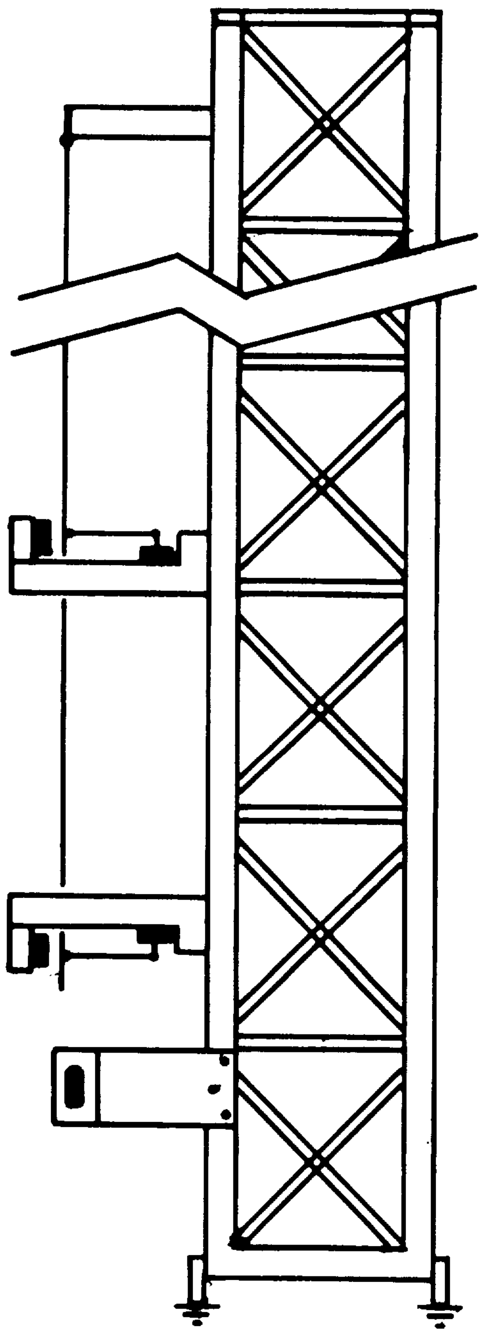
The shape control problem results from trying to estimate and control a continuous shape from a discrete set of sensors and actuators. The control process begins with the definition of a desired continuous shape. Discrete sensor measurements of the actual shape are combined with the structural model to yield a "best" estimated continuous shape. Subsequently, a set of controls are applied to return the shape as close as possible to the desired shape.

- CONTINUOUS STRUCTURE AND DESIRED CONTINUOUS SHAPE
- ONLY DISCRETE SENSOR OUTPUTS ARE AVAILABLE FOR RECONSTRUCTING ESTIMATED SHAPE
- ONLY DISCRETE ACTUATORS ARE AVAILABLE FOR CORRECTING THE SHAPE

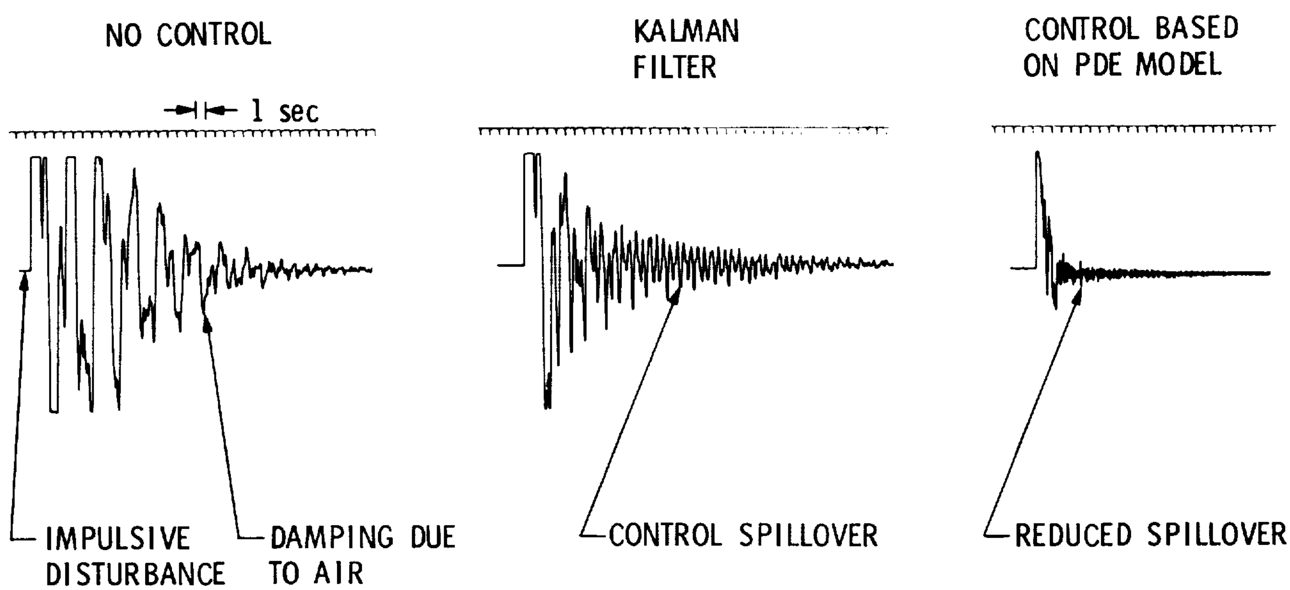


SCHEMATIC OF THE FLEXIBLE BEAM

Hardware verification of selected control concepts is performed in the JPL flexible-beam experimental facility. A schematic of this facility is shown below. It consists of a support tower, a pinned-free flexible beam hanging from the tower, and position sensors and force actuators located along the length of the beam. For evaluation of the distributed control system, an impulse is applied at the free end of the beam, and the resulting deflections at that point are observed. These results are shown on the following page.



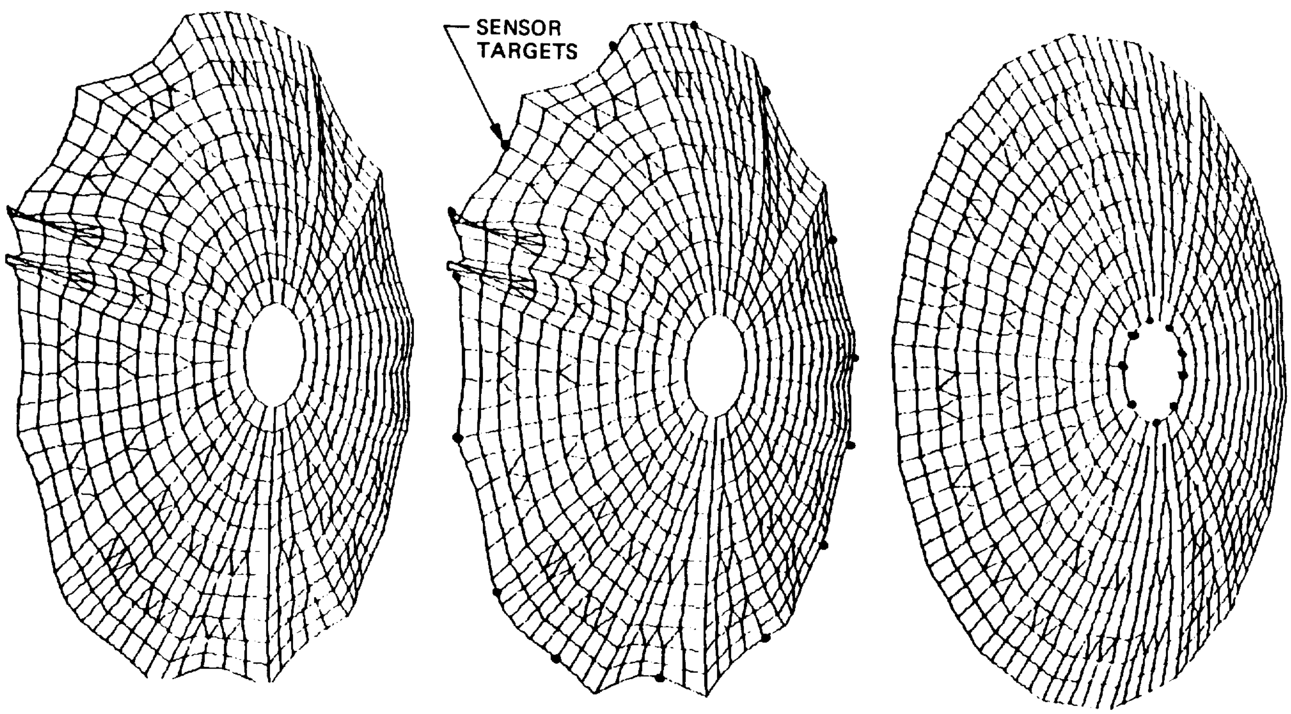
Control-system design approaches based on partial-differential-equation models have been verified on JPL's flexible-beam experimental facility (see previous page). The response of the free end of the flexible beam to an impulse applied at the free end is shown below. The first case is open loop. The damping is primarily due to the atmosphere. The second case shows the closed-loop response using a Kalman Filter controller based on the first three flexible modes. The rather persistent ringing occurs at the frequency of the first unmodeled mode, a classic case of spillover. The final chart shows the much improved response of the control system based on the partial-differential-equation model. The conclusion is that retaining the complete model throughout the control-system design process can greatly improve closed-loop performance.



- CONTROLLER BASED ON PDE MODEL GREATLY REDUCES SPILLOVER

SHAPE CONTROL RESULTS

The figures below show the results of a shape estimation and control computer simulation. A known perturbation is first impressed upon the parabolic dish. This perturbation is a linear combination of the mode shapes for convenience. Eighteen sensor measurements are assumed along the periphery of the dish. From these discrete measurements, and a structural model, an estimated shape is computed. Note that it very closely matches the actual shape. Using nine actuators located at the hub of the dish, control forces are applied to return the dish as close as possible to the desired parabolic shape. The overall process yields excellent results.



ACTUAL SHAPE $U^{0} + 10\varphi_1 + 10\varphi_4 + 5\varphi_8 + 5\varphi_{10}$ ESTIMATED SHAPE CORRECTED SHAPE

CONTRACT ACTIVITIES

Stanford University has been studying control-system design techniques to overcome the destabilizing effects of sensor/actuator non-colocation. This problem is further complicated by uncertain knowledge of the flexibility separating the sensor and actuator. Adaptive control approaches using a phase-locked loop to track unknown or varying oscillation frequencies have been shown to be quite successful.

Purdue University is exploiting to full advantage the possibility of optimizing the sensor and actuator placement to achieve improved control performance. Purdue is also studying methods of reducing controller sensitivity to model errors. One very promising approach uses equivalent cost realizations to select good reduced-order controllers.

STANFORD UNIVERSITY

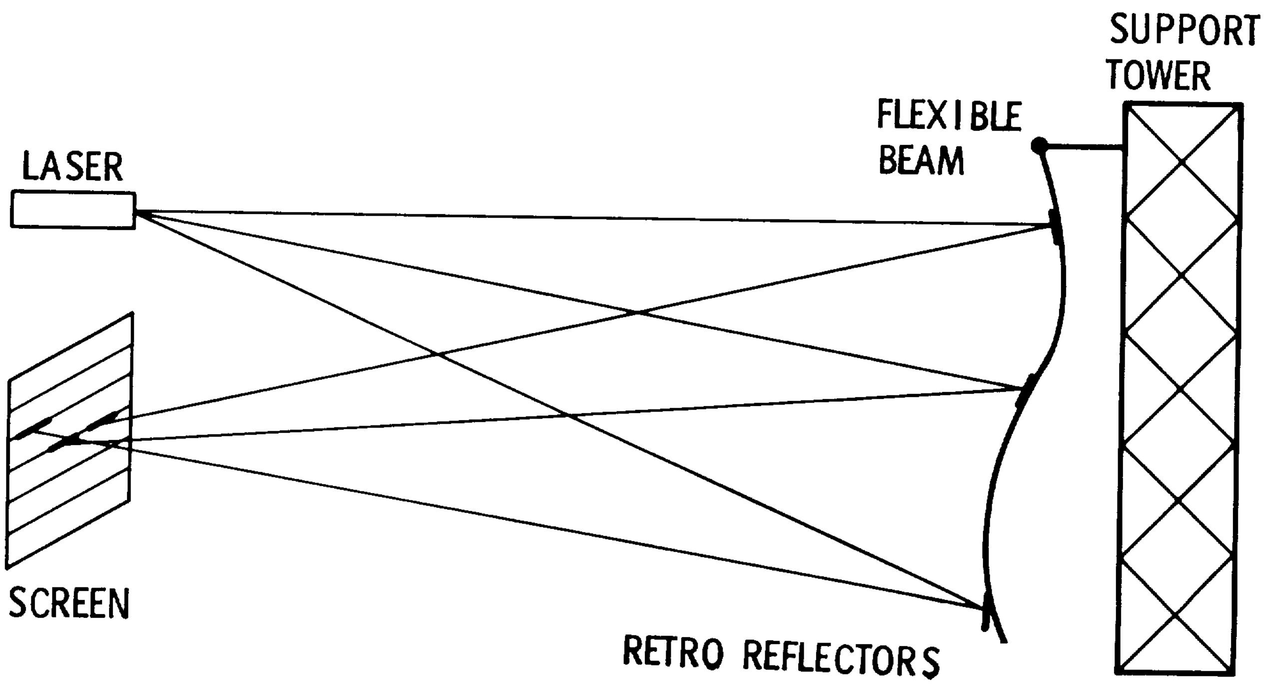
- SENSOR/ACTUATOR NON-COLOCATION
- ADAPTIVE CONTROL USING PLL

PURDUE UNIVERSITY

- OPTIMAL SENSOR/ACTUATOR PLACEMENT
- MODEL ERROR SENSITIVITY REDUCTION
- EQUIVALENT COST REALIZATIONS

HARDWARE VERIFICATION

A vitally important part of any theoretical control development for eventual spaceflight is hardware verification. Toward this end JPL has constructed a flexible-beam test facility for verifying many aspects of the control of large space structures. The facility has been augmented with a detailed finite-element model of the flexible beam, accurate calibrations of the sensors and actuators, a highly interactive software package for implementing various control systems, and a laser system for vivid visualization of the control-system objectives and performance. A movie demonstrating active shape control and active vibration suppression has been made which documents the excellent experimental results thus far obtained in these areas.



- SHAPE CONTROL
- DYNAMIC CONTROL

SUMMARY

The past year's work in the control of distributed parameter systems resulted in significant accomplishments. Prior to this year, all the results in this area had been based on partial-differential-equation models. These results have now been generalized to arbitrary finite-element models, with nice, closed-form analytical solutions resulting. It was also found that decentralized (or local) controllers are optimal in high-gain applications, i.e. in situations where the closed-loop dynamics are dominated by the feedback. The most impressive result in this area was the major reduction in control spillover obtained as a result of performing the design using a full-order model.

Shape estimation and control has been simulated on the computer using a finite element model of a large antenna. Excellent results were obtained. It was found that figure control performance is more often limited by the geometry of the sensor/actuator configuration than it was by the resolution of the sensor or the power of the actuator. In the laboratory, the continuous RMS shape error has been reduced to the theoretical limit, as governed by sensor/actuator geometry. It was also found that for economical design, there should be a specific balance between the number of shape sensors and the number of shape actuators.

CONTROL OF DISTRIBUTED SYSTEMS

- GENERALIZED PDE MODEL RESULTS TO FE MODELS
- OBTAINED CLOSED-FORM ANALYTICAL RESULTS
- DECENTRALIZED CONTROLLERS ARE OPTIMAL IN HIGH-GAIN APPLICATIONS
- OPERATOR TRUNCATION ALLEVIATES THE DESTABILIZING EFFECT OF MODEL TRUNCATION

SHAPE CONTROL

- SIMULATED STATIC SHAPE CONTROL OF A LARGE ANTENNA
- PERFORMANCE NOT ALWAYS CONTROL LIMITED, SOMETIMES GEOMETRY LIMITED
- RMS SHAPE ERROR REDUCED TO THEORETICAL LIMIT
- BALANCE MUST EXIST BETWEEN NUMBER OF SENSORS/ACTUATORS

SUMMARY (continued)

In the experimental validation area, a detailed facility model was made. This includes a finite element model of the beam in tension and an accurate calibration of the sensor/actuator scale factors. Interactive software has been developed for very fast implementation of a variety of control laws. Laser hardware, with beam-mounted retroreflectors, was installed for a vivid display of the beam's motion. Finally, as could only be found with actual hardware, nonlinearities, static friction, hysteresis, and unmodeled modes severely altered the control-system design process.

The area of platform control is discussed at length in a separate section.

Contractors have provided us with new insights into the control of systems where the sensor and actuator are separated by a flexible element. Phase-locked loops are employed to track changing or uncertain frequencies. Sensor and actuator placement is a new degree of freedom to be examined in the control-system design of distributed systems. Optimizing their location for improved control-system performance has been achieved under contract.

EXPERIMENTAL VALIDATION

- DEVELOPED A DETAILED FACILITY MODEL
- PRODUCED INTERACTIVE CONTROL-SYSTEM SOFTWARE
- SENSOR/ACTUATOR NONLINEARITIES, STATIC FRICTION, AND HYSTERESIS, NOT MODELED IN ADVANCE, SEVERELY ALTERED CONTROL DESIGN

PLATFORM CONTROL

- MULTIVARIABLE FREQUENCY DOMAIN DESIGN APPROACHES DEVELOPED

CONTRACT

- DEVELOPED NON-COLOCATED SENSOR/ACTUATOR DESIGN APPROACH
- OPTIMIZED SENSOR/ACTUATOR LOCATIONS FOR IMPROVED PERFORMANCE

FUTURE WORK

Further advances in control technology are required for successful application to large-space-structure control. A major thrust of future work will be to develop design techniques which can either adapt to changing or uncertain models or be insensitive to the model errors. In the past years, static shape control and vibration control have been independently demonstrated. Future work will be aimed at combining these distinct modes of operation. Control of distributed parameter systems based on continuum models will be investigated further to allow for generalized sensors (rate, acceleration, angular, strain etc.) and possibly generalized actuators. Shape control will be performed on more complex, multi-dimensional structures such as plate-like structures.

- IMPLEMENT MODEL ADAPTIVE AND INSENSITIVE CONTROL APPROACHES IN HARDWARE (FY 82)
- COMBINE STATIC SHAPE CONTROL WITH DYNAMIC CONTROL (FY 82)
- FORMULATE DISTRIBUTED CONTROL FOR GENERAL SENSOR/ACTUATOR TYPES (FY 82)
- SHAPE CONTROL FOR MULTIDIMENSIONAL CONFIGURATIONS (FY 83)

REFERENCES

A major output of a control technology development study is documentation. A partial list of publications from the past year is given below.

1. Weeks, C.: Shape Determination and Control for Large Space Structures. Jet Propulsion Laboratory Publication 81-71.

2. Edmunds, R.: Preliminary Control System Design for the Large Space Systems Technology (LSST) Reference Platform. Jet Propulsion Laboratory Publication 81-77.

3. Schaechter, D.B.: Estimation of Distributed Parameter Systems. AIAA Journal of Guidance and Control. 9/81.

4. Hamidi, M.: Optimal Control and Controller Location for Distributed Parameter Elastic Systems. IEEE 20th Conference on Decision and Control. 9/81.

5. Schaechter, D.B.: A Survey of Large Space Structure Control Approaches. IFAC, Kyoto, Japan. 4/81.

6. Rodriguez, G.: Model Error Estimation: S/C Control Applications of a Geometric Approach. IEEE, Workshop on Applications of Adaptive System Theory, New Haven, Conn. 5/81.

7. Hamidi, M.: On the Rigid Body Motion and Shape Distortion Evaluation for Large Flexible Spacecraft. Third VPI&SU/AIAA Symposium on Dynamics and Control of Large Flexible Spacecraft, 1981, pp. 191-202.

8. Rodriguez, G.: A Function Space Approach to Smoothing with Applications to Model Error Estimation for Flexible Spacecraft Control. IEEE Conference on Decision and Control, San Diego, CA. 7/81

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10. Eldred, D.: Experimental Demonstration of Static Shape Control. AIAA Guidance and Control Conference. 1/81.

11. Schaechter, D.B.: Distributed Control: Theory and Experiment. Purdue University Seminar. 4/81.

12. Schaechter, D.B.: Distributed Control of Large Space Structures. Jet Propulsion Laboratory Publication 81-15.