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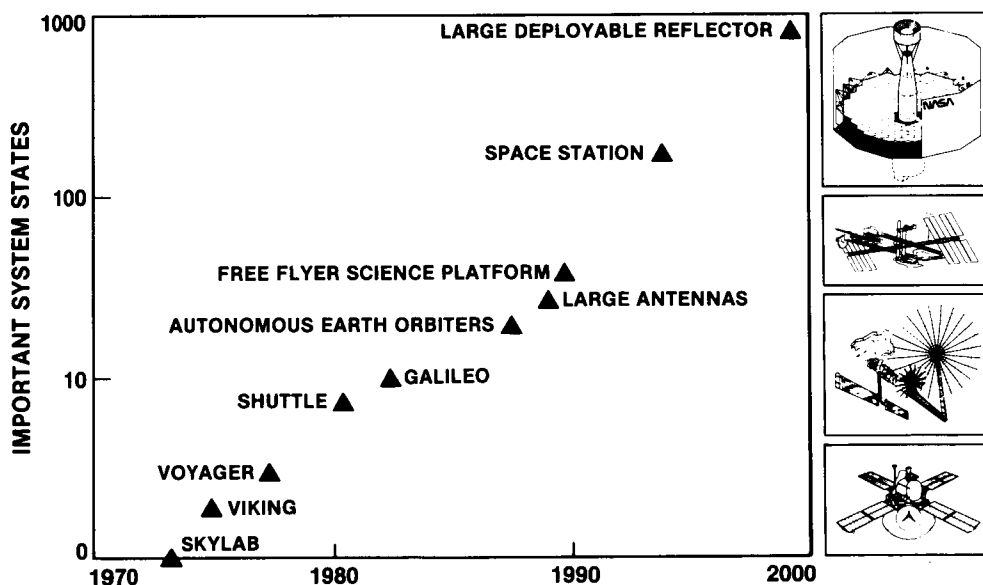
CONTROL TECHNOLOGY OVERVIEW IN CSI

J. B. Dahlgren and A. F. Tolivar
Jet Propulsion Laboratory
Pasadena, California

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CONTROL TECHNOLOGY EVOLUTION

The chart illustrates the evolution of some representative on-board control systems designs. While the chart is not intended to be all-inclusive it does represent major trends in spacecraft control systems. Typical of the first generation controllers flown was that of the Viking orbiter that estimates spacecraft angular velocities from celestial reference measurements. The estimator was a simple second-order analog system based on a linearized single-axis model for the vehicle dynamics. In Voyager a digital implementation became possible because of the introduction of a digital processor for reprogrammable implementation. In the second-generation systems, a more advanced class of estimator designs provides the capability for on-board attitude determination. The Shuttle and Galileo dual-spin spacecraft designs are typical of this generation. Future space systems requiring high dimensional advanced control/estimation designs including: large antenna systems with the need for static and dynamic shape determination; Space Station with the capability for relative position/attitude determination for intervehicle control, configuration tracking, and system identification to establish knowledge of poorly known vehicle dynamics; and advanced astrophysic missions such as the Large Deployable Reflector where the requirements for active vibration control and the precise maintenance of the overall figure of a multi-segmented aperture will involve sensing and control of perhaps 1000 degrees of freedom.



KEY CSI TECHNOLOGY NEEDS

There are a number of key technology needs requiring attention in the CSI development. These are shown in the table. Development of appropriate truncation criteria and techniques of finite element models for space structures is still immature, and therefore a crucial area in CSI technology continues to be the area of analytical modeling and model reduction. New structural concepts for space system application need to be pursued recognizing the goal of an optimal control system design, in addition to conventional goals such as lightweight, efficient packaging, and reliable and predictable deployment. System identification, where the structural and dynamic characteristics are inferred from observed response to known disturbances, provides for in-flight tuning of the controlled "plant" to achieve high control performance. Another important CSI area is in control law design methodology where control authority, parameter uncertainty, and robustness must be appropriately traded-off to provide a unified conceptual and theoretical architecture. For the case of simplified structures the control systems robustness may be measured by the typical "gain" and "phase" margins. These concepts are largely unusable for CSI designs and therefore new robustness criteria are required. The increased number of new types of sensors and actuators required for CSI control systems together with the need for in-flight characterization and relatively complex near real-time matrix calculations create a substantial computational requirement for new digital implementation approaches. Since CSI technology differs from conventional control-structure approaches new synthesis and design software tools are needed. Technology validation programs through ground and on-orbit testing are essential as part of the qualification/acceptance sequences for new CSI control strategies. The cost of large space systems will be significant and the implementation of CSI control technologies, as described, to these flight articles will require special attention to reliability and fault-tolerance.

- 1) ANALYTIC MODELING AND MODEL REDUCTION
- 2) STRUCTURAL CONCEPTS
- 3) SYSTEM IDENTIFICATION
- 4) CONTROL LAW DESIGN METHODOLOGY
- 5) ROBUSTNESS CRITERIA
- 6) SENSOR AND ACTUATOR DEVELOPMENT
- 7) DIGITAL IMPLEMENTATION TECHNOLOGY
- 8) SYNTHESIS AND DESIGN SOFTWARE TOOLS
- 9) GROUND TESTING
- 10) ON-ORBIT TESTING
- 11) RELIABILITY ISSUES (FAULT-TOLERANCE)

JPL CSI TECHNOLOGY DEVELOPMENT

The JPL technology development program related to CSI is directed at a range of space applications including space platforms, large antennas, and large segmented optics systems. Many of these advanced spacecraft may be characterized by tens of modes below 1 Hz with poor a priori knowledge of system dynamics, 20-100m apertures whose figure/alignment needs to be controlled with sub-millimeter accuracy, and spacecraft/payload pointing to stringent requirements. New and advanced control theories and methodologies are under development to cope with these challenges including system identification, adaptive control and unified modeling and design. These areas are covered in the following charts.

In the advanced hardware components area a sensor is under development which applies to a number of CSI areas. The objective for the sensor, given the name of SHAPES for Spatial High-Accuracy Position Encoding Sensor, is to provide high data rate, multipoint, 3-D position sensing to submillimeter accuracy which lends itself to performing dynamic measurements of large space structures.

Another important element in the program is the validation of these technologies through appropriate ground and flight experiment testing. Plans are in place to carry out an extensive ground test program of evolving control methodologies such as figure sensing/control, open and closed loop identification, active vibration control, and others. Appropriate flight experiment planning for many of these same technologies is also under way in support to the Control of Flexible Structures Programs (COFS) and the Antenna Technology Shuttle Experiment (ATSE).

- THEORY/METHODOLOGY
 - SYSTEM IDENTIFICATION
 - ADAPTIVE CONTROL
 - UNIFIED MODELING AND DESIGN
- ADVANCED HARDWARE COMPONENTS
 - SHAPES 3-D FIGURE SENSOR
- GROUND VALIDATION/TESTING
 - FIGURE SENSING/CONTROL
 - OPEN/CLOSED LOOP IDENTIFICATION
 - ACTIVE VIBRATION CONTROL
- FLIGHT EXPERIMENT PLANNING
 - CONTROL OF FLEXIBLE STRUCTURES PROGRAM
 - ANTENNA TECHNOLOGY SHUTTLE EXPERIMENT

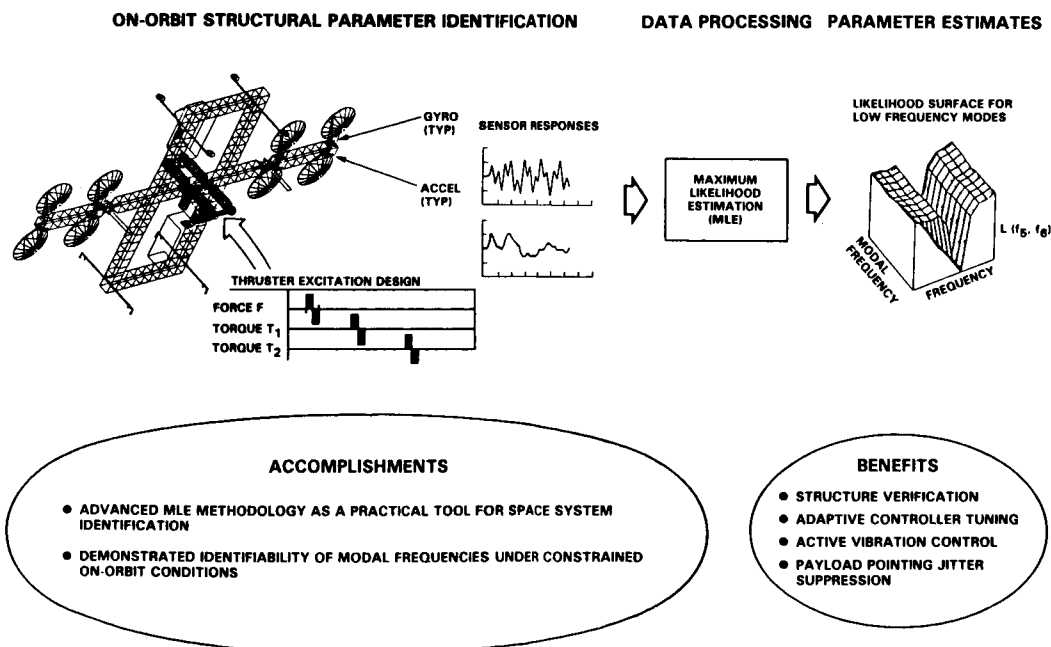
ON-ORBIT SYSTEM IDENTIFICATION

The identification of modal parameters provides information required for structure verification, controller tuning, active vibration control, payload pointing jitter suppression, and vehicle stabilization.

The objective of the On-orbit System Identification task is to develop methodology, techniques and algorithms required to perform in-flight control dynamics identification and characterization of key structural and environmental parameters. The technical approach is to develop and combine state-of-the-art linear and non-linear estimation techniques with realistic on-orbit experimentation and application procedures.

Accomplishments during FY'86 included the integration and evaluation of optimal excitation design techniques and Maximum Likelihood Estimation (MLE) methodology as a practical tool for system identification of Large Space Structures (LSS), and also demonstrated system identifiability of modal frequencies under constrained excitations and sensing. These results advance the methodology for on-orbit testing of LSS under operational constraints.

Future research plans include: Development of actuation and sensing strategies which extract parameter information efficiently (i.e., optimal design of experiment) given a constrained on-orbit configuration and testing environment; focus on the identification of parameters which directly support on-board controllers; and development of end-to-end methodology for synergistic use of frequency and time domain identification techniques.

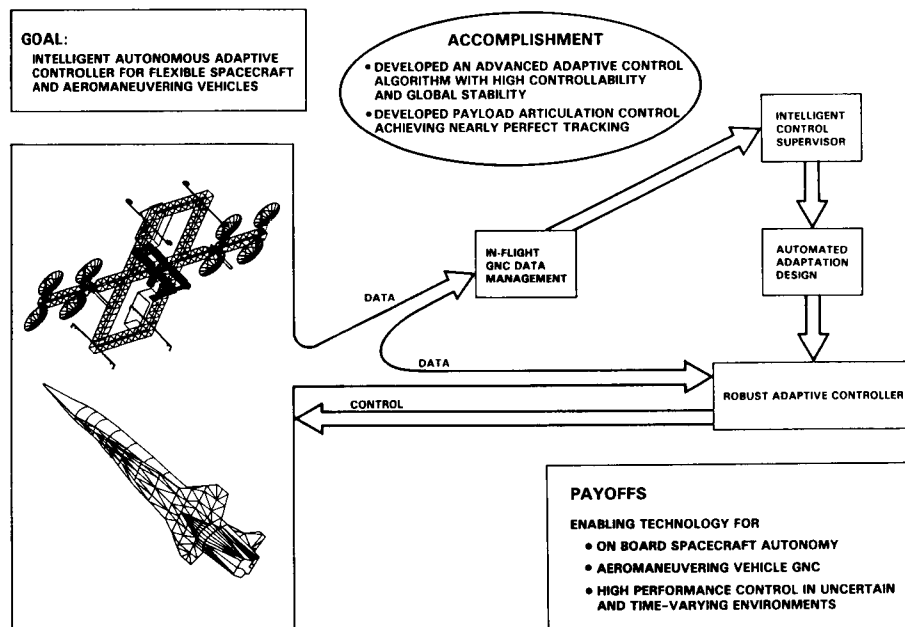


AUTONOMOUS ADAPTIVE CONTROL SUBSYSTEM DEVELOPMENT

The research objective of this task is to develop an autonomous adaptive control subsystem for application to emerging space systems, including future large flexible structures and aeromaneuvering vehicles. The overall approach is to develop and integrate high level intelligent control technology with state-of-the-art adaptive control techniques, resulting in a controller design which is robust to both gross system changes, such as large parameter changes, hardware failures, model-order variations, anomalies, operational disturbances and changes in mission objectives, as well as to local phenomena including drifting parameters, model uncertainties, and environmental disturbances. This concept will provide robust stabilization and control with enhanced performance for future space systems.

Accomplishments in FY 86 included development of the direct output gain weighting concept for providing increased control effectiveness in large multivariable adaptive control systems, sufficient conditions for global stability of the extended algorithm, and application of these techniques to high precision adaptive payload articulation/tracking control.

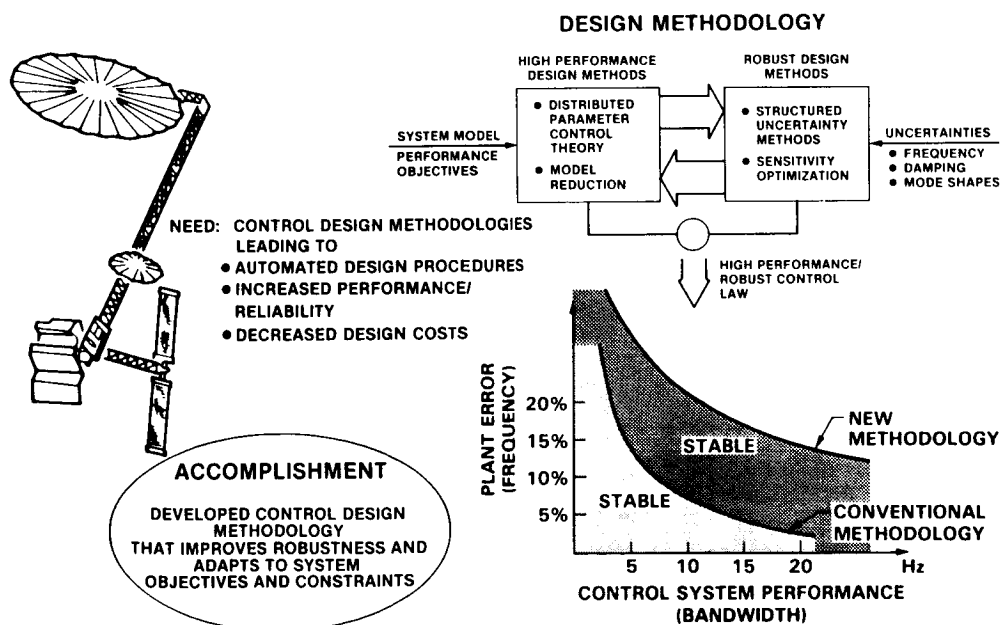
Future plans include the testing and experimental validation of these techniques in the JPL/RPL 3-D control technology experiment through a sequence of increasingly demanding demonstrations. The theoretical work during FY 87 will address several new and important areas: 1) the development of systematic algorithms for choosing design parameters for improved adaptive performance/robust controller, and 2) the introduction of intelligent control techniques to incorporate in-flight dynamics and performance knowledge with the appropriate design rules towards realization of a completely autonomous adaptive control subsystem.



UNIFIED CONTROL/STRUCTURE MODELING FOR CONTROL SYSTEM DESIGN

This task addresses the fundamental theoretical issues arising in the modeling of CSI systems where performance objectives require control systems which interact with the structure. The ultimate program goal is to develop a computer-aided design package for modeling and control design that incorporates elements from distributed parameter system theory, control-driven modeling, model reduction methodologies, and robust control design methods. This package will enable the designer to develop control systems that satisfy the multi-objective criteria that are imposed in an operational setting, e.g., accommodation of model truncation, parameter errors, actuator/sensor bandwidth limitations, finite computer memory size and computational overhead constraints.

Work to date has been very successful in designing reduced order compensators that are tuned to both the system model and performance objectives. Current work focuses on making these designs more robust while maintaining their excellent performance characteristics. The conventional approach to making a control system more robust with respect to parameter uncertainties follows a conservative path that ultimately sacrifices performance for robustness. Recent advances in robustness research have led to the development of design methods that simultaneously address the dual objectives of performance (control system bandwidth, settling time, etc.) and robustness, and that exploit the context in which uncertainties arise in physical systems. The derived control designs have been validated in simulations with a large-order flexible antenna model. The figure shows that the new methods lead to significantly greater regions of stability and reduced sensitivity to parameter errors, while simultaneously retaining control system performance. Future work will address the extension of the current results to discrete-time (digital) system design and their application to fine-resolution piecewise models for complicated simulated and physical structures.

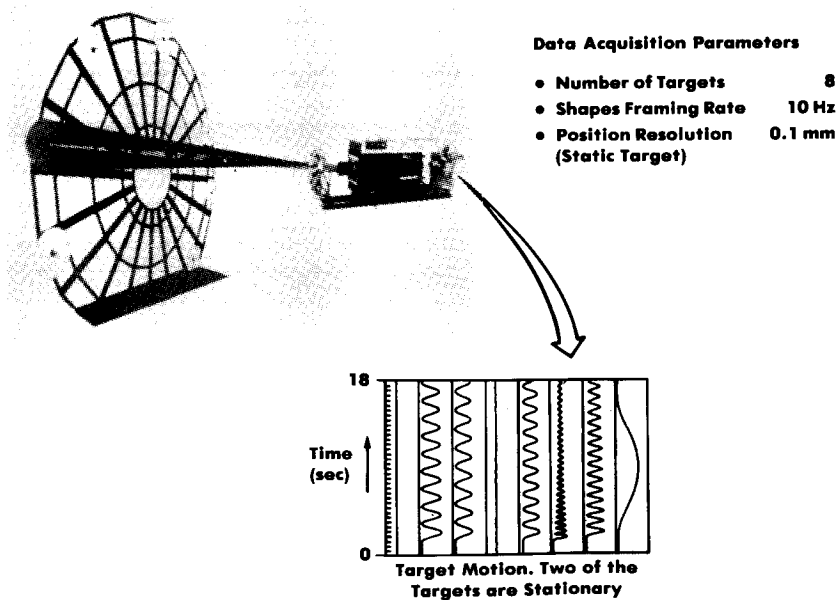


SHAPES: SPATIAL, HIGH-ACCURACY POSITION ENCODING SENSOR

The objective of the SHAPES task is to develop a control sensor for making 3-D simultaneous position measurements of multiple (50-100) targets with sub-millimeter accuracy and with sufficient data bandwidth for system identification, and shape and vibration control of large space structures. The technical approach is to develop and integrate angular and range measurement techniques based on multi-pulse time-of-flight ranging, fast semiconductor laser diodes, charge coupled device (CCD) imaging detectors, and picosecond resolution electro-optic signal-processing detectors.

A major accomplishment has been achieved the past year: the successful first-time demonstration of simultaneous optical ranging of 8 independent targets at an update rate of 10 measurements per second, with a measurement resolution of 10 microns (0.4/1000 in). These results have clearly demonstrated the viability of the multi-pulse, multi-target optical ranging concept. The next phase of the development will address the incorporation of angular measurement to obtain the full 3-D measurement capability.

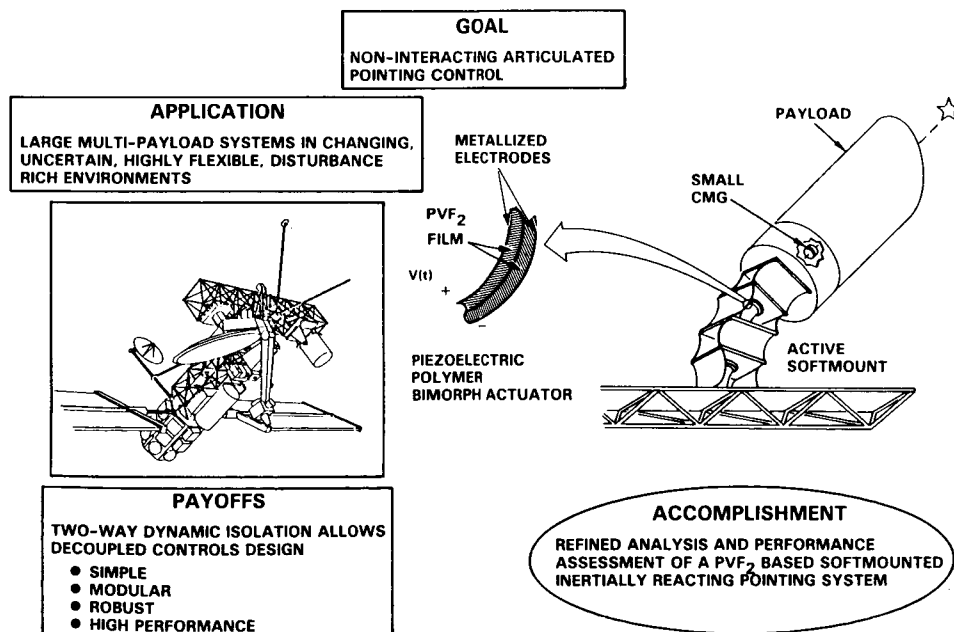
Currently, SHAPES is the only sensor to have demonstrated this simultaneous multi-target tracking capability, which is required for determining both static figure/alignment control, as well as dynamic in-flight characteristics of Large Antennas, Platforms and the Space Station (both during assembly and operational phases). In a typical application to space station and platforms, SHAPES can provide the sensing and instrumentation capability that will be needed during initial on-orbit tests and checkout. Such instrumentation will also be needed to support periodic diagnosis and verification during the station's operational lifetime. Specific applications include assembly, alignment, geometry certification, and measurement of in-orbit dynamics for structural verification and for updating control system gain. SHAPES can also be configured as a rendezvous and docking sensor with an acquisition range of 40 Km.



ADVANCED PRECISION POINTING TECHNOLOGY

The trend in payload pointing is toward combining multiple instruments on a common large basebody. Such large flexible base vehicles will present articulated payload pointing system designers with three significant challenges: an unprecedented level of dynamic disturbances, a set of extremely low frequency base vehicle structural modes (e.g. 0.1 Hz for Space Station/Space Platforms), and a system that is guaranteed to continually evolve as new instruments and other modules are added to the basebody and old instruments are removed or replaced. The first challenge represents a quantitative change over current systems; the latter represents a quantitative and qualitative change since for such systems it will be impossible to maintain the traditional separation between structural frequencies and pointing control bandwidth, and the control design cannot rely on fixed system dynamics.

These considerations motivate the development of a pointing concept that incorporates a mechanically soft (but actively controlled) interface between payload and base vehicle with primary pointing control authority resident on the payload in the form of a reaction wheel or control moment gyro. Such an approach provides two way isolation between payload and basebody and mitigates the problem of control bandwidth - structural frequency interaction. The concept under development is that of an active "softmount" incorporating the use of a piezoelectric polymer material (PVF₂) to implement the soft active interface. The principal accomplishment of FY '86 was a refined analysis of the conceptual design of such an active "softmounted" pointing system. Performance analysis of a planar model was performed, and a six DOF analytical model for a proof of concept analysis was developed. The next step is to complete the analytical proof of concept, with breadboard development and test to follow.



CONTROL TECHNOLOGY VALIDATION

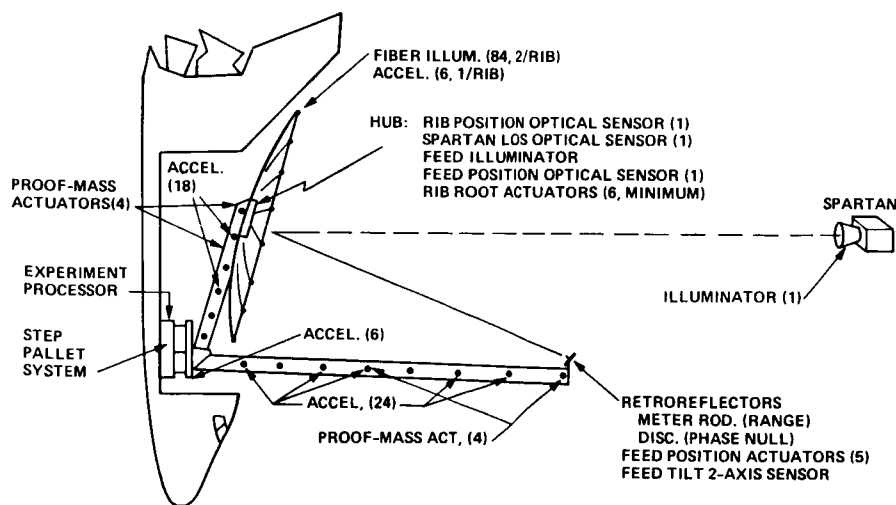
The objective of this program is to develop and conduct technology experiments to validate and demonstrate large space system static and dynamic control technologies in sensing, modeling, identification, and adaptive control, which are required for the control of future spacecraft, such as large antennas and space platforms. JPL is actively engaged in the development of these large space system control technologies including: figure sensing/control, dynamic identification, adaptive control, and unified control/modeling/ design. Ground validation of these technologies is crucial for establishing confidence and reducing risks in their future large space system applications. Evaluation of these fast developing control technologies through actual implementation on ground test is also essential to validate and compare the performance of different methodologies and algorithms, providing a valuable research tool to enable the further development of effective theories and solutions.

The Control Technology Validation program is a joint activity with the Air Force Rocket Propulsion Laboratory. The approach is to define, develop, and conduct technology experiments in a 3-dimensional flexible test article. The test article resembles an antenna, with a horizontal dish of 7.2 meter diameter (consisting of 12 ribs attached to a rigid central hub) and a 3.6 meter long flexible boom hanging vertically downward from its center. The ribs are coupled together by two concentric rings of stretched wires under tension. To achieve the desired low frequencies (0.2 Hz), the ribs are very flexible and each is supported at two location by levitators. The sensing instrumentation includes a two-axis hub angle sensor, 28 rib displacement sensors, and an electro-optical sensor, SHAPES, which will provide 16 position measurements. Actuation is provided by a two-axis hub torquer and twelve rib root actuators, with one actuator acting on each rib. The experimental apparatus has been designed and fabricated and is being assembled. The first set of four experiments will be conducted during April-September, 1987.

FLIGHT EXPERIMENTS

Work in FY '86 included control experiment definition and planning activities with the COFS and ATSE programs. The chart illustrates an experiment configuration and approach to an ATSE in-orbit control experiment, whose objectives are:

- (1) Demonstrate active pointing and jitter and vibration control and antenna boresight pointing performance of 0.01 deg.
- (2) Demonstrate the capability to characterize the over-all system dynamics and disturbance environment based on in-orbit measurements.
- (3) Validate the methodology used to design the initial control system and the process of upgrading it in-flight based on in-orbit measurements.
- (4) Demonstrate in-orbit shape determination and control technology to measure the antenna shape (ribs, mesh and feed misalignments) to an accuracy of 0.3 mm rms (knowledge), and to control it with actuators (rib-root and feed) to an accuracy of 1.0 mm rms.
- (5) Update/refine analytical tools and prediction models with test data base.
- (6) Advanced control technology readiness to support operational systems such as MSAT second- and third-generation and orbiting VLBI/QUASAT missions.



SUMMARY

The paper has attempted to give a brief control technology overview in CSI by illustrating that many future NASA missions present significant challenges as represented by missions having a significantly increased number of important system states which may require control and identifying key CSI technology needs. Many of these technologies require extensive development and tests before commitment to space initiatives which may face serious design constraints if CSI-based design options are not available. The JPL CSI-related technology developments were discussed to illustrate that some of the identified control needs are being pursued.

Since experimental confirmation of the assumptions inherent in the CSI technology is critically important to establishing its readiness for space program applications, the area of ground and flight validation requires high priority. Valid real-time closed-loop hardware/software test beds as well as extensive simulation tools should be developed as part of any strong ground test validation program. In many cases the uncertainties in extrapolating ground test results to on-orbit environments will make on-orbit testing through flight experiments a prerequisite to technology readiness.

NASA has made some in-roads in developing some of the required near-term CSI technologies to a state-of-flight readiness by the focused R&D ongoing programs. However, much more remains to be done to recognize DOD needs and closely coordinate the overall activities. An expanded joint program between NASA, DOD, Industry, and universities must be encouraged and supported. This CSI focused conference has been useful in giving this effort a start. The NASA Civil Space Technology Initiative (CSTI) proposed for a FY 88 start and related programs could serve as a catalyst to accelerate further joint activities.

- FUTURE NASA MISSIONS PRESENT SIGNIFICANT CSI CHALLENGES
- MANY CRITICAL CSI TECHNOLOGIES STILL IN INFANCY - CONSIDERABLE DEVELOPMENT IS REQUIRED
- NEED A STRONG GROUND VALIDATION PROGRAM
- CSI BASED FLIGHT EXPERIMENTS MUST DEMONSTRATE TECHNOLOGY READINESS
- AN EXPANDED JOINT PROGRAM BETWEEN NASA/DOD/INDUSTRY/UNIVERSITIES MUST BE ENCOURAGED AND SUPPORTED