NASA Technical Memorandum 102763

ACTIVE DAMPING APPLICATIONS TO THE SHUTTLE RMS

M. G. Gilbert, M. A. Scott, and S. P. Kenny

January 1991

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23665

ACTIVE DAMPING APPLICATION TO THE SHUTTLE RMS

by

Michael G. Gilbert
Michael A. Scott
Sean P. Kenny

NASA Langley Research Center
Hampton, VA. 23665

Fourth NASA/DOD CSI Conference
Orlando, FL
November 5-7, 1990

ABSTRACT

Control-Structure Interaction (CSI) is a relatively new technology developed over the last 10 to 15 years for application to large flexible space vehicles. The central issue is recognition that high performance control systems necessary for good spacecraft performance may adversely interact with the dynamics of the spacecraft structure, a problem increasingly aggravated by the large size and reduced stiffness of modern spacecraft structural designs. CSI analysis and design methods have been developed to avoid interactions while maintaining spacecraft performance without exceeding structural capabilities, but they remain largely unvalidated by hardware experiments or demonstrations, particularly in-space flight demonstrations. One recent proposal for a low cost flight validation of CSI technology is to demonstrate active damping augmentation of the Space Shuttle Remote Manipulator System (RMS). This paper describes an analytical effort to define the potential for such an active damping augmentation demonstration to improve the structural dynamic response of the RMS following payload maneuvers. It is hoped that this study will lead to an actual inflight CSI test with the RMS using existing Shuttle hardware to the maximum extent possible. By using the existing hardware, the flight demonstration results may eventually be of direct benefit to actual Space Shuttle RMS operations, especially during the construction of Space Station Freedom.

A summary of the motivation for the proposed flight test is given along with the task relationships between NASA Langley Research Center, NASA Johnson Space Center, and Charles Stark Draper Laboratories. The current approach to the active damping augmentation feasibility study tasks are summarized, and results from the initial linear analyses are presented. The results form the basis of the preliminary conclusions that the RMS could be used for an in-flight active damping demonstration using the SPAS payload, and that the only additional hardware needed on the RMS would be a small number of feedback accelerometers. Plans for continued analyses and verification of results using a nonlinear simulation of the RMS, which includes nonlinear joint gearboxes and Space Shuttle computer hardware and software models, are given.

The Control-Structures Interaction (CSI) program at NASA Langley Research Center (LaRC) is dedicated to the development, application, and validation of new technologies for the control of large spacecraft systems which have significant structural flexibility. An important goal of this program is in-space flight tests to demonstrate quantitatively the benefits of CSI technology. One such proposed inflight demonstration is to actively augment the structural dynamic damping of the Space Shuttle Remote Manipulator System (RMS) arm, which currently exhibits low damping and long periods of oscillatory motion following routine operational maneuvers. This demonstration would provide a direct quantitative measure of the benefit of CSI technology as a part of the CSI program, while also measuring potential performance improvements in the current RMS which could ultimately have a significant impact on the assembly of Space Station Freedom (SSF).

This paper will describe an ongoing analysis effort at LaRC to determine the feasibility of providing active damping augmentation of the RMS following normal payload handling operations. The flight demonstration effort is motivated by a study completed by Charles Stark Draper Laboratory (CSDL) [1-2], which proposed using the Shuttle RMS for a CSI flight experiment. The flight experiment study proposed adding additional sensors to the arm, the installation of a flight experiment computer and hardware in the Shuttle cargo bay, and the use of an instrumented payload at the end of the arm to measure performance. However, the current flight demonstration feasibility study is restricted to the use of existing RMS hardware only if possible, and the minimal addition of new sensor hardware only if necessary. The use of an instrumented payload would be retained, but the flight experiment computer and hardware would be eliminated in favor of using the existing Shuttle General Purpose Computers (GPC's) for control law implementation. The demonstration feasibility study is considering active damping control laws for use in the time period following the end of arm-move commands and the beginning of the normal arm position-hold function, although active damping of arm motion following Shuttle thruster firings is also a possibility.

ACTIVELY AUGMENT RMS DAMPING

Proposed inflight demonstration of CSI technology:

- Quantitative measurement of CSI technology benefits
- Improve current RMS operations
- Potential benefits for SSF assembly

Scaled-down version of CSDL experiment definition

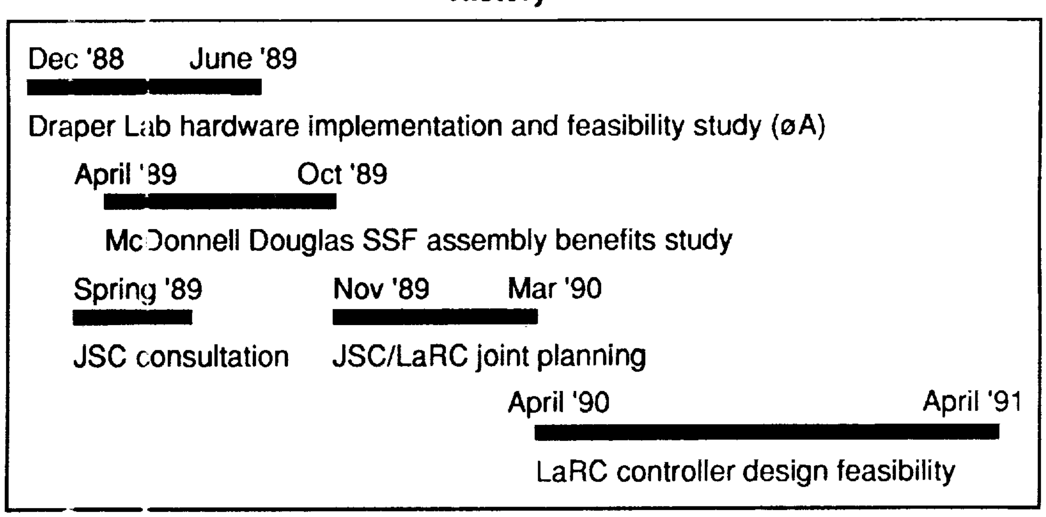
- Use existing hardware if possible, minimal additional hardware if necessary
- Actively damp between move command and position-hold functions, possibly after STS thruster firings
- Cast as development test to improve existing Shuttle hardware

RMS-BASED CSI FLIGHT DEMONSTRATION

The chart below summarizes the history of the proposed RMS CSI flight demonstration efforts. The original CSDL study [1-2] was completed in the period of December 1988 to June 1989. A study of CSI technology benefits for the assembly of Space Station Freedom was conducted by McDonnell Douglas Space Systems Co. from April to October 1989 [3]. This study determined that approximately 10 hours of cumulative time would be spent over 15 SSF-assembly Shuttle flights waiting for arm motions to damp down to ± 1 inch amplitudes following maneuvers with SSF components. The study also showed that a simple increase of two in the inherently small level of damping of the arm could reduce the cumulative settling time to 4 hours, a reduction in time approximately equal to the programed arm-operation time on a single assembly flight. This study became a prime motivator for the proposed flight demonstration. Also during 1989, LaRC consulted with the NASA Johnson Space Center (JSC) about a potential RMS-based flight demonstration, and following the McDonnell Douglas study results, a joint LaRC/JSC planning effort led to the current effort. The feasibility study has been ongoing since April 1990 and is scheduled to last until April 1991, at which time a decision to proceed to an actual flight test will be made.

RMS-BASED CSI FLIGHT DEMONSTRATION

History



LaRC / JSC BRIDGING PROGRAM

The joint LaRC-JSC RMS flight demonstration effort, referred to as a "bridging program", is divided into four tasks as shown below. The first two tasks, determination of feasibility using existing hardware and, if not feasible, the definition of the minimal set of additional needed hardware, is an LaRC activity. The third and fourth tasks, ground-based evaluations and the actual flight test, are JSC responsibilities. The decision to proceed with the flight demonstration will be made jointly. The Charles Stark Draper Laboratory, under contract to JSC, is and will be assisting with all tasks in the program.

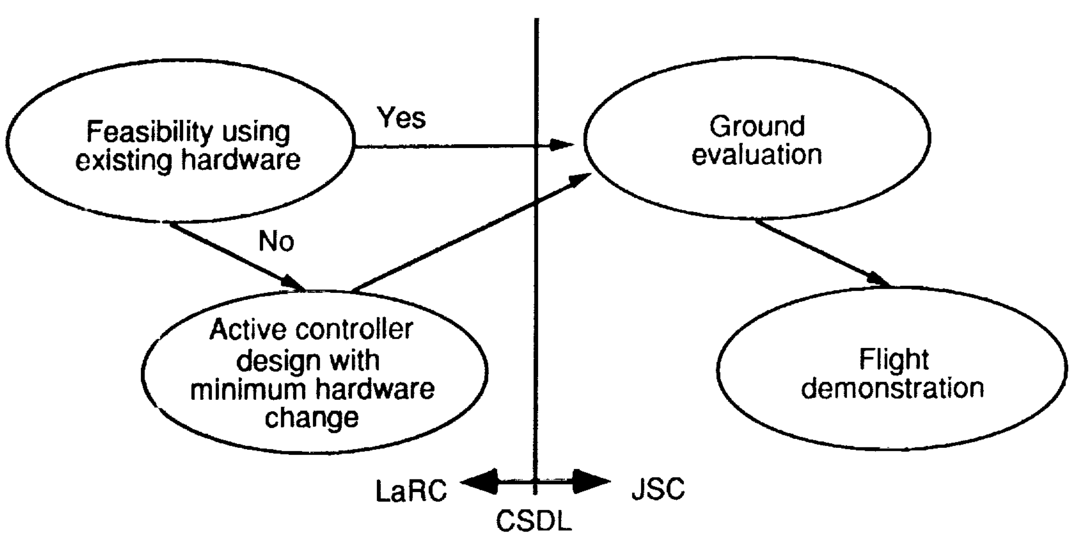
LaRC / JSC BRIDGING PROGRAM

TASK 1: Determine active damping control feasibility using EXISTING hardware

TASK 2: Active damping controller design with MINIMUM hardware changes

TASK 3: Ground evaluation of active damping control

TASK 4: On-Orbit Demonstration



FEASIBILITY STUDY APPROACH

Under the LaRC-JSC bridge program, the feasibility of actively augmenting the damping of the RMS arm will be determined by LaRC. The approach to this feasibility study is shown below. The first activity is to define payload and arm configuration combinations of interest which are consistent with the types of payloads expected during Space Station Freedom assembly. The second step is to examine RMS dynamics and operational characteristics using the Draper RMS Simulation (DRS) nonlinear simulation code [4]. This code was obtained for this study from CSDL through JSC and is used routinely for predicting arm dynamic motions in on-orbit RMS operations. The simulation includes models of the RMS structural dynamics, joint servos, motors, and gearboxes, and the software modules loaded in the Shuttle GPC for RMS control. The key activities for determining active damping augmentation feasibility involves the design and simulation of active damping control laws. For this purpose, two approaches to linear control design model development have been undertaken. One of these approaches is to use system identification methods on output data from the DRS to identify linear state-space models which closely match the DRS response for specific commanded arm movements. The other approach is to use a NASTRAN finite element model representation of the arm and calculate linear vibration modes for particular configurations and payloads. The mode frequencies and mode shapes are then used to obtain a linear state-space model for control design purposes. With a linear control design model, various active control law design concepts can be evaluated, as can the requirements for feedback sensors to measure arm motions. The final step is to simulate the active damping control laws in a modified version of the DRS to determine the effects of system nonlinearities and computer time delays.

FEASIBILITY STUDY APPROACH

Define payload/arm configurations of interest

Examine existing RMS capabilities and dynamic response

- Using nonlinear CSDL RMS simulation code (DRS)

Develop linear dynamic models for control design

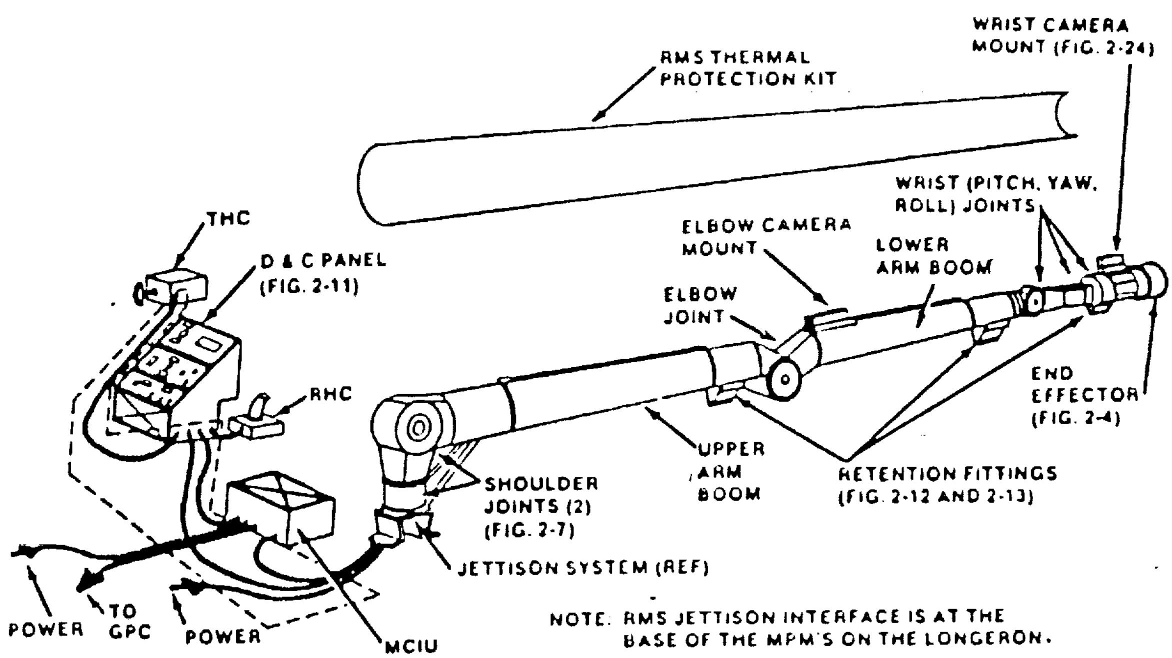
Synthesize active damping augmentation controller

Evaluate controller performance using DRS

REMOTE MANIPULATOR SYSTEM

The figure belows summarizes some of the design characteristics of the Space Shuttle Remote Manipulator System (RMS) arm [5]. The system is a six joint telerobotic system controlled from a panel located on the aft flight deck of the Space Shuttle. These six joints are directly analogous to the joints and freedoms of a human arm, defined as shoulder yaw and pitch, elbow pitch, and wrist pitch, yaw, and roll. An end effector for grappling payloads is mounted at the free end of the arm. From the control panel and translational and rotational hand controllers, commands to move the arm are processed by the Manipulator Control Interface Unit (MCIU) and the Shuttle GPC to provide electrical signals to drive the joint servo motors. Data in the form of angle position and motor shaft rate from an encoder and tachometer at each joint are returned to the MCIU and GPC for control purposes.

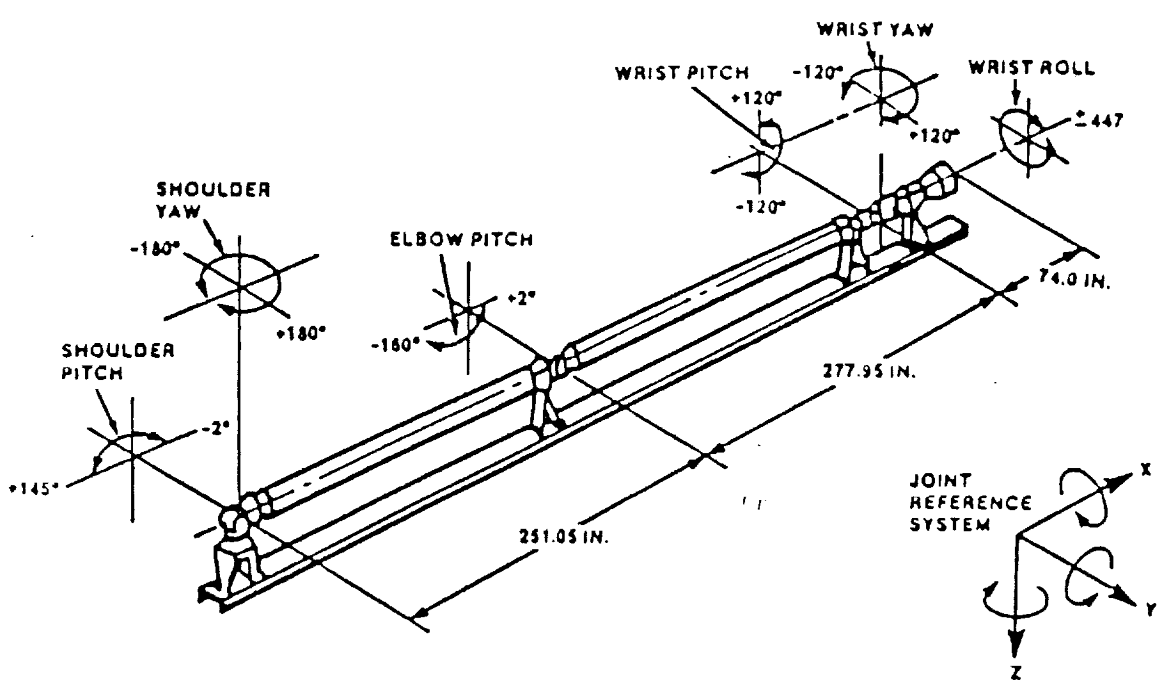
REMOTE MANIPULATOR SYSTEM



RMS DIMENSIONS AND JOINT LIMITS

The figure below defines the joint movement limits and dimensions of the RMS arm [5]. The arm is shown mounted in the Manipulator Positioning Mechanism (MPM), which is mounted via a swingout joint to the side wall of the Shuttle payload bay. The MPM is used to secure the RMS during launch and reentry of the Shuttle, and is positioned at an angle of 19.4° relative to the stowed condition during arm on-orbit operations. Also shown is the joint reference coordinate system.

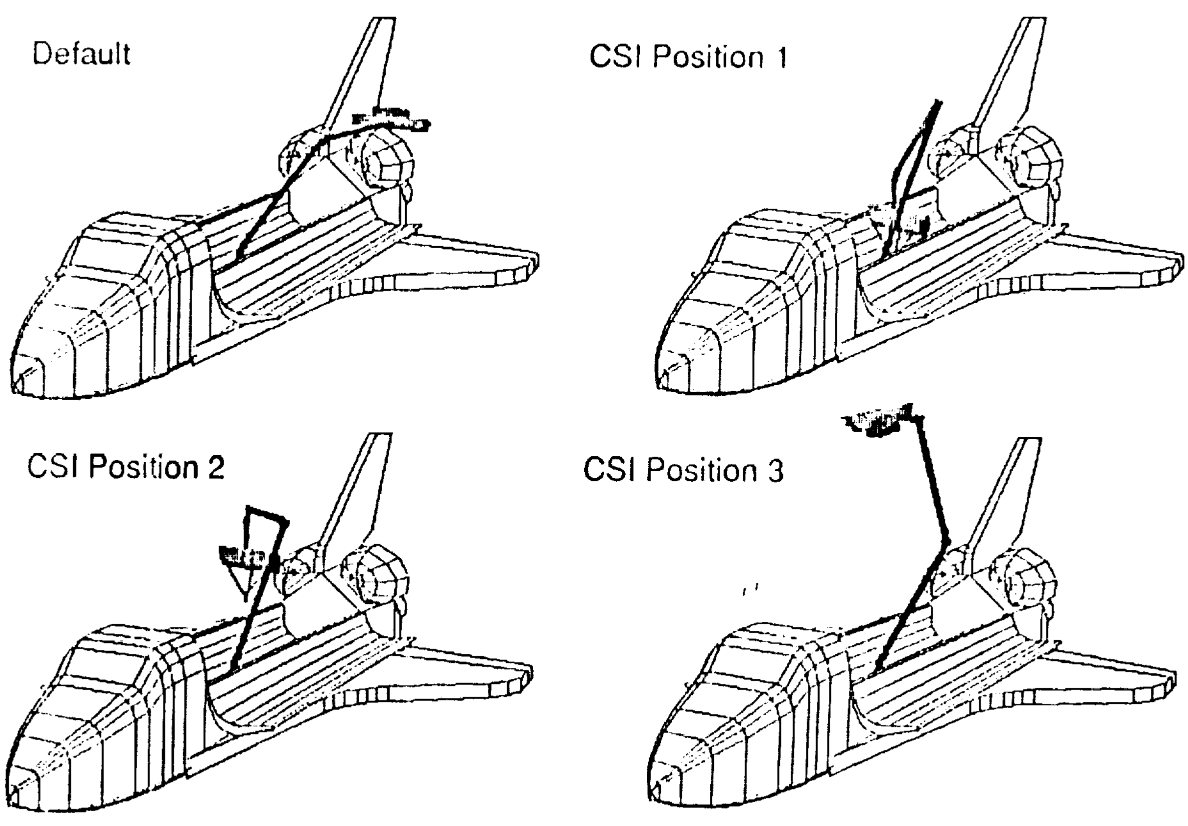
RMS DIMENSIONS AND JOINT LIMITS



RMS CONFIGURATIONS

Four standard RMS configurations have been adopted for the current feasibility study. These configurations are shown below with the SPAS free-flyer spacecraft as an attached payload. The first configuration is the default configuration of the DRS in the absence of any other specified configuration. The other 3 configurations are actual configurations used during the deployment of the SPAS satellite on a previous Shuttle mission. The first of these, CSI Position 1, is the position of the arm and payload just after release from the cargo bay attachments. CSI Position 2 is the position of the arm and payload after being lifted from Position 1 to a point which completely clears the sides of the cargo bay. CSI Position 3 is the actual deployment positioning at the time of the SPAS release. In the current study, these four configurations have been analyzed with several other payloads in addition to the SPAS.

RMS CONFIGURATIONS



DYNAMIC RESPONSE ANALYSIS CASES

The table below summarizes, by operating mode, payload, and position, the dynamic response analysis cases which have been considered to date. The responses of the RMS to commanded movements in single joint operating mode and the four manual operating modes have been computed with the DRS using the various combinations of payloads and configurations as shown. Data from the single joint mode cases with the SPAS payload have been used extensively for single-input, single-output, linear system model identification purposes as will be discussed shortly. Data from the other cases have been used primarily for dynamic response characterization purposes, although it will also be used for multi-input, multi-output, linear system identification purposes as the study progresses.

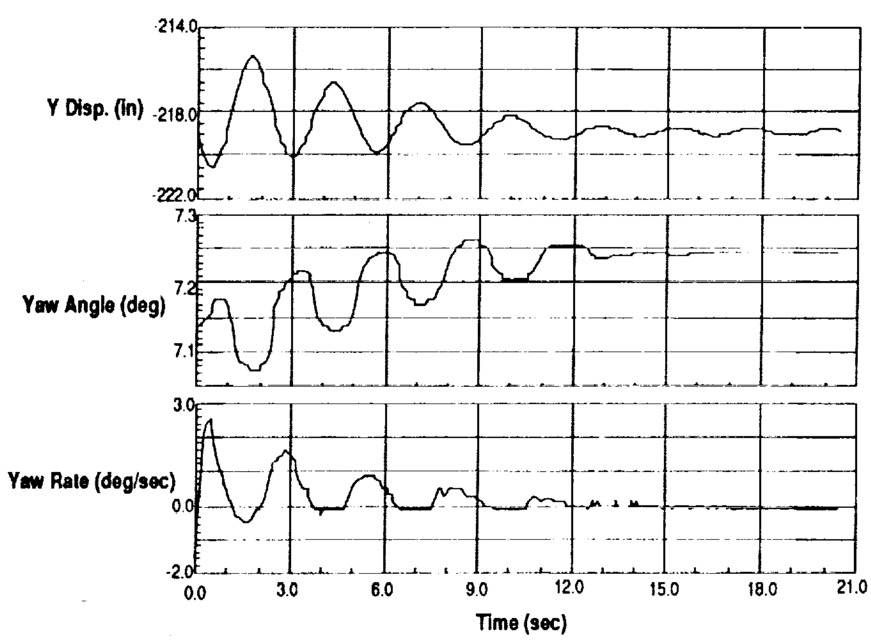
DYNAMIC RESPONSE ANALYSIS CASES

Operating Mode		Payload			Position			
		None	Spas	LDEF Class	Def.	1	2	3
Manual	Unloaded	X						X
	Loaded		X		X	X	X	X
	End Eff.		X					X
	Payload		X					X
Single Joint			X	X	X	X	X	X

TYPICAL RESPONSE AND SENSOR OUTPUTS

The time response data shown below are typical of the kind of RMS motions encountered during normal arm maneuvers. The data are the free responses following a 10-second rotation command to the shoulder yaw joint in single joint mode, with no payload and the other joints held approximately fixed by the RMS position-hold function. Shown are the lateral displacement of the free end of the arm, the shoulder yaw-joint angle encoder response, and the shoulder yaw-joint rate derived from the motor shaft tachometer. The peak-to-peak free oscillation of the arm after the command is about 5 inches, while the actual measured angle change during the same time is on the order of 0.1 degree. The discrete stepping of the encoder response is due to word length limitations in the Shuttle GPC, indicating that the signal is at the limit of useful resolution. The yaw-joint rate is on the order of 3.0 degrees/ second, and again has discrete stepping characteristics which is limiting the useful resolution of these data. These types of responses are typical for all configurations and payloads analyzed to date, and are an indication that the existing RMS sensors may not be completely adequate for active damping augmentation purposes.

TYPICAL RESPONSE AND SENSOR OUTPUTS



LINEAR FLEXIBLE MODEL DEVELOPMENT

A NASTRAN finite element model developed by CSDL [6] has been adopted and subsequently modified for the purposes of linear control system design and dynamic simulation. The RMS is modeled in a spatially fixed arm configuration with the brakes on (i.e., the joints are locked). Preliminary studies will be conducted assuming the orbiter is fixed.

The model consists of 26 prismatic beam elements. Elements used in this model have been developed to represent extensional and torsional stiffness, as well as bending stiffness and transverse shear flexibility in two perpendicular directions. The joint housings, gear trains, and Shuttle and payload attach points are modeled by a total of 16 beam elements. Each joint assembly is represented by a pair of inboard and outboard beams. A total of seven joints, including the shoulder swing out, have been modeled. The upper and lower arm booms are discretized into 4 elements each. Longeron and payload grapple point stiffnesses are also modeled. At each joint, both cylindrical and rectangular coordinate systems are defined. This dual coordinate system scheme permits RMS configurations to be varied without explicitly calculating global frame nodal coordinates. New arm configurations may be defined by specifying only the appropriate joint angles, all nodal coordinate transformations are calculated internal to NASTRAN.

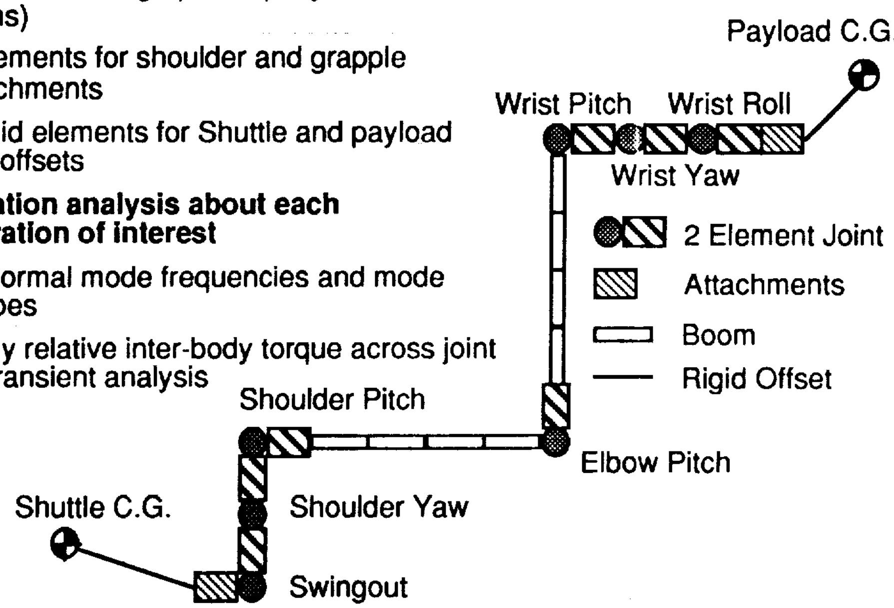
LINEAR FLEXIBLE MODEL DEVELOPMENT

NASTRAN finite element model of RMS

- 14 elements for joint/housing stiffness
- 8 elements for graphite epoxy booms (arms)
- 2 elements for shoulder and grapple attachments
- 2 rigid elements for Shuttle and payload c.g. offsets

Linear vibration analysis about each configuration of interest

- 10 normal mode frequencies and mode shapes
- Apply relative inter-body torque across joint for transient analysis



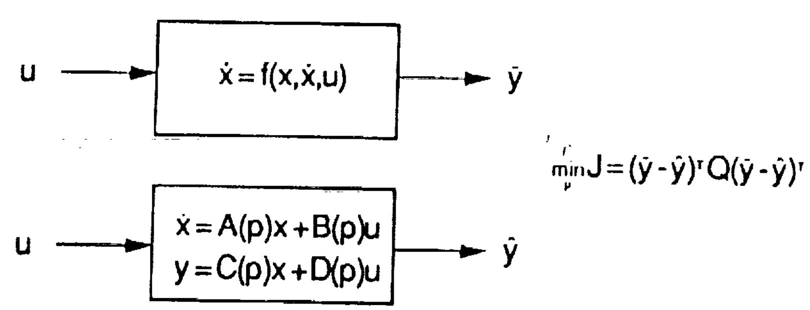
LINEAR SYSTEM IDENTIFICATION APPROACH

For the purpose of evaluating active damping augmentation controller feasibility, linear, single-input, single-output state-space control law design models of the RMS have been derived from DRS response data using linear system identification methods. The data have been obtained for single joint mode cases with the SPAS payload using the desired joint rate command as the input signal, and either the joint tachometer or a linear acceleration measurement at the tip of the arm as the output signal. For a given model order, usually 6 to 10 states corresponding to 3 to 5 vibration modes, frequency and damping parameters were selected to make the model best match the DRS response data in a least-squares sense. Following the least-squares parameter selection, an iterative Maximum Likelihood method was used to further refine the model parameters. These models are then used to evaluate the effects on RMS damping arising from feedback of the tachometer or acceleration signals through simple gain loop closures. In all cases, the system identification process has been greatly complicated by the highly nonlinear characteristics of the actual joint hardware. System identification methods for multi-input, multi-output models which correspond to the manual mode operations of the arm are currently being evaluated, with the Eigenvalue Realization Algorithm (ERA) [7] showing potential for this class of problem.

LINEAR SYSTEM IDENTIFICATION APPROACH

Linear system identification approach:

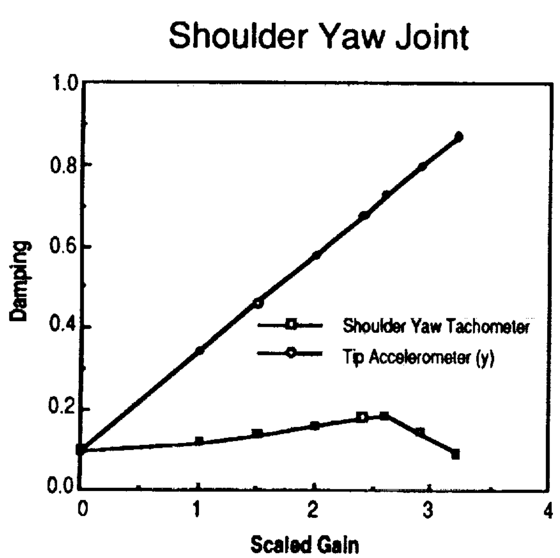
- Single-input, single-output state-space models
- Using Least-Squares and Maximum Likelihood methods
- 3-5 structural modes
- Joint rate command inputs, joint tachometer or tip acceleration output
- Complicated by highly nonlinear joint dynamics
- ERA method for multi-input, multi-output

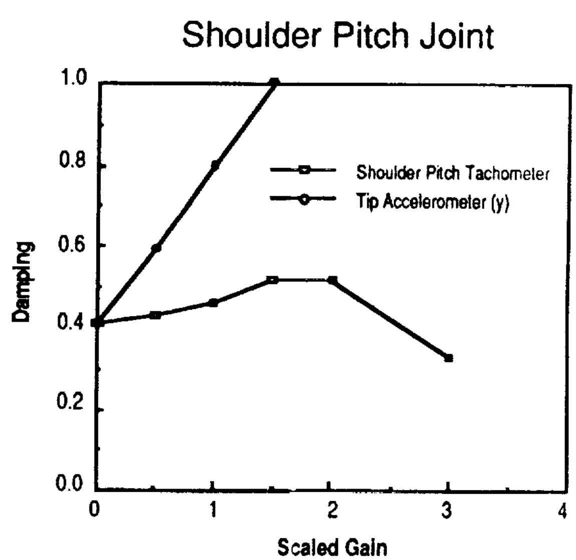


Using the single-input, single-output (SISO), linear state-space models derived from system identification, simple gain feedbacks of tachometer or acceleration signals to the joint rate command for single joint mode cases have been completed. Results are shown in terms of RMS damping improvement as a function of a scaled gain parameter, which normalizes the actual feedback gain by the overall loop gain. For CSI Position 1 with the SPAS payload, results are shown below for the shoulder-yaw and shoulder-pitch joints. The initial damping values for zero gain for the two joints are different because the joints excite and are able to control different structural modes. For both joints, feedback of the tachometer signal initially resulted in a small increase in RMS damping. Feedback of the acceleration signal in both cases showed larger achievable increases in damping. While the trends for the two joints are the same, the differences of the results in terms of which mode is being influenced illustrate the high configurational dependence of RMS dynamics.

SISO ACTIVE DAMPING AUGMENTATION RESULTS

Position 1



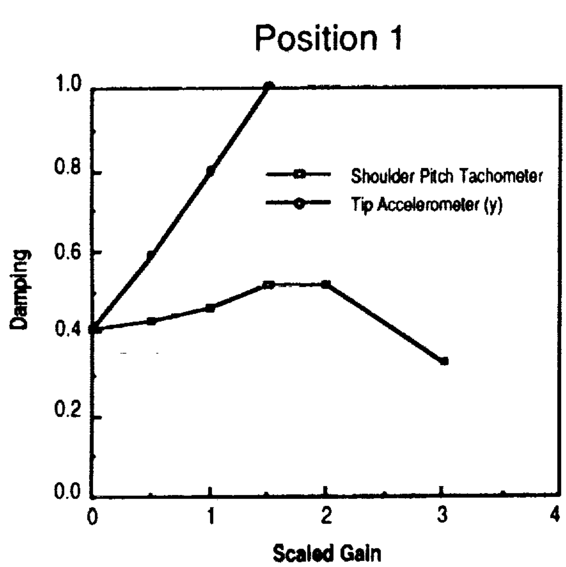


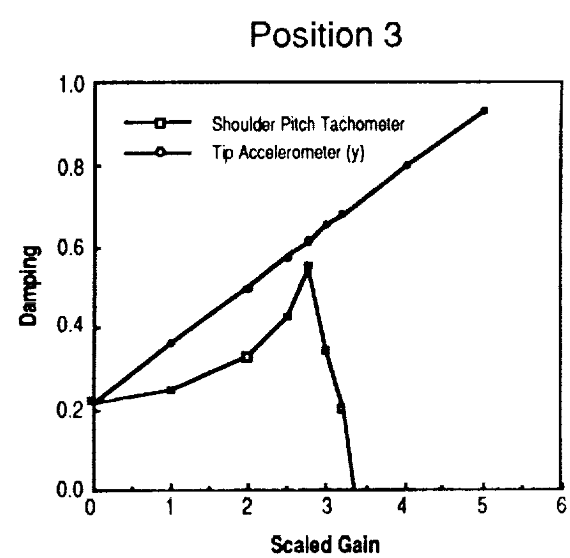
SISO ACTIVE DAMPING AUGMENTATION RESULTS

Results similar to the previous page further illustrate the configurational dependence of RMS dynamics. The result on the left, which is the same as previously shown for shoulder pitch in CSI Position 1, is now compared the shoulder pitch result in CSI Position 3. Note the differences in open loop damping and the effect of tachometer feedback for the two configurations. Feedback of tip acceleration is less affected by the configuration change, and appears to be more desirable than tachometer feedback for active damping augmentation.

SISO ACTIVE DAMPING AUGMENTATION RESULTS

Shoulder Pitch Joint

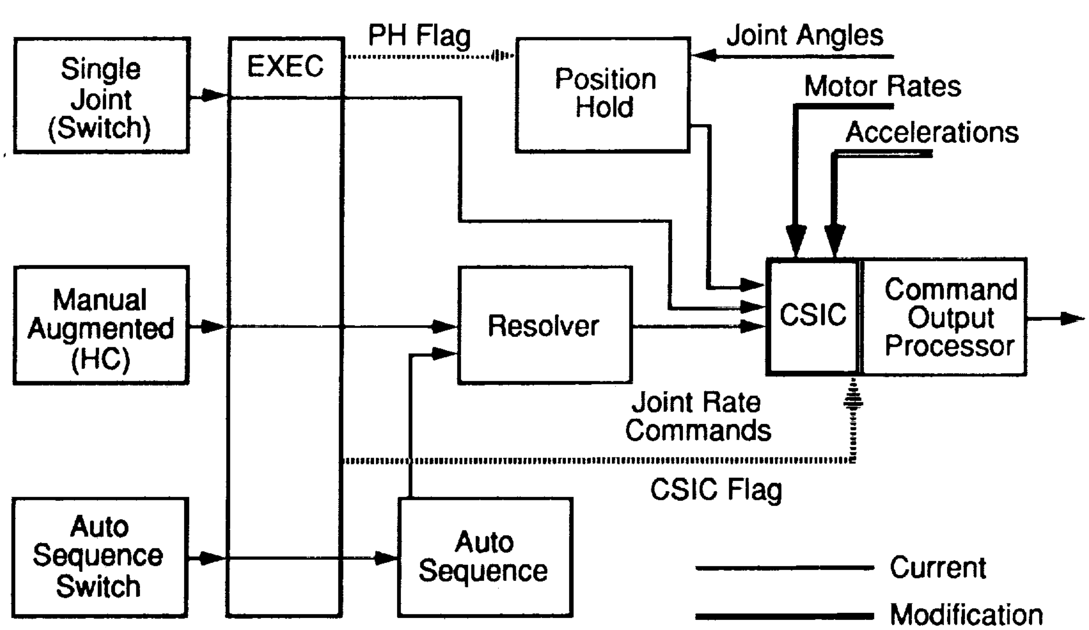




CSI CONTROLLER IMPLEMENTATION IN GPC SOFTWARE

Based on the recommendations of CSDL, a potential means of implementing an active damping augmentation controller in Shuttle GPC software has been identified. This implementation would allow the use of all existing RMS health and safety monitoring functions, greatly simplifying flight experiment requirements. The Control-Structure Interaction Controller (CSIC), as it is called, would be a software module which acts as a preprocessor to the existing Command Output Processor (COP). It would be controlled by the executive function of the existing software by a flag which would activate the CSIC when joint movement commands are zeroed. Using motor rate and acceleration feedback signals, the CSIC would damp the free response of the arm to some level, at which time the normal position-hold function of the arm would be activated. With this implementation, the damping function of the CSIC could be expanded to damp RMS motions following Shuttle thruster firings as well, since the GPC software knows when thruster firings have occured.

CSI CONTROLLER IMPLEMENTATION IN GPC SOFTWARE



CSDL currently modifying DRS for evaluation of CSIC concepts

CONCLUSIONS AND FUTURE PLANS

This paper has summarized an ongoing analytical study to determine the feasibility of actively augmenting the damping of the Shuttle RMS as a proposed CSI flight demonstration. Based on initial results, such an experiment appears feasible using the existing joint hardware and Shuttle computers and software. However some additional feedback sensors in the form of accelerometers located at the tip of the arm will be required. Because of the high dependence of the arm dynamics on configuration, the actual flight demonstration would likely be restricted to a few known configurations. The current feasibility study is continuing, with the assessment of controller performance using a modified version of the DRS, which includes the CSIC controller implementation, to begin shortly. The multi-input, multi-output system identification efforts and linear flexible model development efforts will continue, as will studies to define the minimum set of new feedback sensors.

CONCLUSIONS AND FUTURE PLANS

Active damping demonstration using RMS appears feasible

- GPC software implementation using existing joint motors
- Linear single-input, single-output studies indicate acceleration feedback necessary
- Flight tests would be limited to known configurations
- Technology could be applied for general RMS use

Feasibility study is continuing

- Plan to evaluate gain closures using DRS
- Define minimal additional sensors (accelerations)
- System ID and control designs for manual mode operations
- Linear flexible models for control concept evaluation

REFERENCES

[1] Demeo, M. E.: Remote Manipulator System (RMS) - Based Controls - Structures Interaction (CSI) Flight Experiment Feasibility Study. NASA CR 181952, January 1990.

[2] Demeo, M. E.; Fontana, A.; and Bains, E. M.: Shuttle Remote Manipulator System (RMS) - Based Controls - Structures Interaction Flight Experiment. Fourth NASA / DOD Conference on Controls - Structures Interaction Technology, Orlando, Florida, November 5-7, 1990.

[3] Lamb, B. A.; and Nowlan, D. R.: Benefits of Control Structure Interaction (CSI) Technology to Space Station Assembly by Flexible Rebotic Systems (RS). CRAD NAS1-18763, November 1989.

[4] Gray, C.; et. al.: Validation of the Draper RMS Simulation (DRS) Against Flight Data. CSDL-R-1755, Volumes 1-2, April 1985.

[5] NSTS 07700, Volume XIV, Appendix 8, System Description and Design Data - Payload Deployment and Retrieval System, Revision J, May 1988.

[6] Abelow, A. V.: Comparisons of Remote Manipulator System Finite Element Models. Charles Stark Draper Laboratory Report R-1210, November 1978.

[7] Juang, J.-N.; and Pappa, R. S.: An Eigensystem Realization Algorithm for Modal Parameter Identification and Model Reduction. Journal of Guidance, Control, and Dynamics, Vol. 8, No. 5, September-October 1985, pg. 620-627.

Report Documentation Page

National Aeronautics and Space Administration

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-102763		

4. Title and Subtitle	5. Report Date
Active Damping Application To The Shuttle RMS	January 1991
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Michael G. Gilbert, Michael A. Scott, and Sean P. Kenny	
	10. Work Unit No.
	590-14-61-01
9. Performing Organization Name and Address	11. Contract or Grant No.
NASA Langley Research Center Hampton, VA 23665-5225	
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address	Technical Memorandum
National Aeronautics and Space Admininstration Washington, DC 20546-0001	14. Sponsoring Agency Code

15. Supplementary Notes

Presented at the Fourth NASA/DOD CSI Conference
Orlando, FL
November 5-7, 1990

16. Abstract Control-Structure (CSI) is a relatively new technology developed over the last 10 to 15 years for application to large flexible space vehicles. The central issue is recognition that high performance control systems necessary for good spacecraft performance may adversely interact with the dynamics of the spacecraft structures, a problem increasingly aggravated by the large size and reduced stiffness of modern spacecraft structural designs. CSI analysis and design methods have been developed to avoid interactions while maintaining spacecraft performance without exceeding structural capabilities, but they remain largely unvalidated by hardware experiments or demonstrations, particularly in-space flight demonstrations. One recent proposal for a low cost flight validation of CSI technology is to demonstrate active damping augmentation of the Space Shuttle Remote Manipulator System (RMS). This paper describes an analtical effort to define the potential for such an active damping augmentation demonstration to improve the structural dynamic response of the RMS following payload maneuvers. It is hoped that his study will lead to an actual inflight CSI test with the RMS using existing shuttle hardware to the maximum extent possible. By using the existing hardware, the flight demonstration results may eventually be of direct benefit to actual Space Shuttle RMS operations, especially during the construction of Space Station Freedom.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Active Damping Remote Manipulator System Control-Structure Interaction	Unclassified-Unlimited Subject Category 39

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price
Unclassified	Unclassified	18	A03

NASA FORM 1626 OCT 86