CSI Flight Computer System and Experimental Test Results

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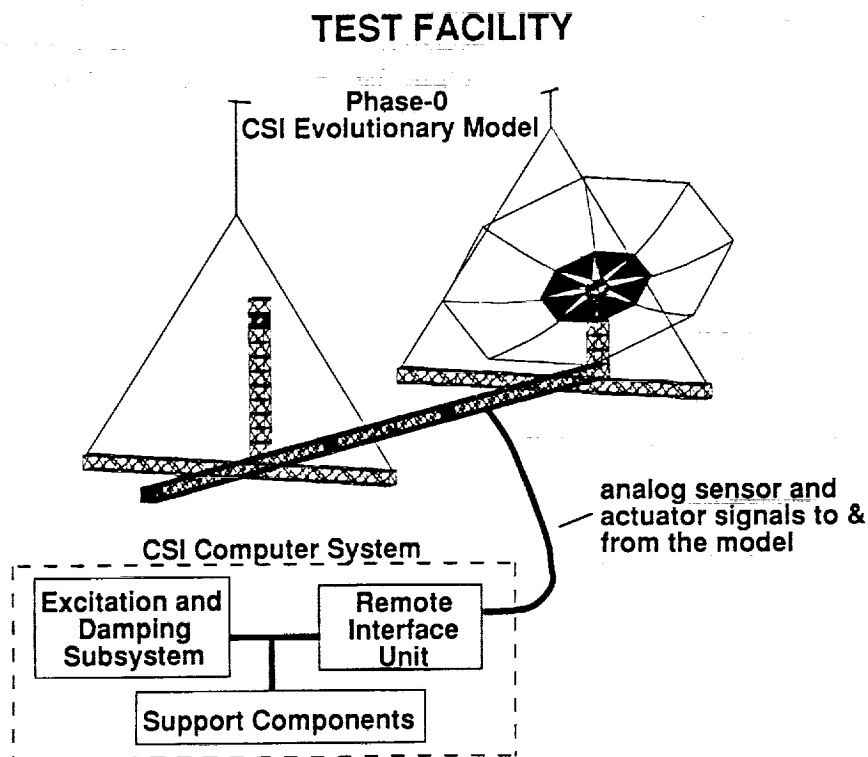NASA Langley Research Center
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INTRODUCTION

This paper describes the CSI Computer System (CCS) and the experimental tests performed to validate its functionality. This system is comprised of two major components: the space flight qualified Excitation and Damping Subsystem (EDS) which performs controls calculations; and the Remote Interface Unit (RIU) which is used for data acquisition, transmission, and filtering. The flight-like RIU is the interface between the EDS and the sensors and actuators positioned on the particular structure under control. The EDS and RIU communicate over the MIL-STD-1553B, a space flight qualified bus. To test the CCS under realistic conditions, it was connected to the Phase-0 CSI Evolutionary Model (CEM) (Ref. 1) at NASA Langley Research Center. The following schematic shows how the CCS is connected to the CEM. Various tests were performed which validated the ability of the system to perform control/structures experiments.

The EDS is capable of acquiring, from the RIU, up to 16 digital sensor values and calculating up to 8 actuator outputs for the RIU. The EDS software resides on a space flight qualified computer which was designed to be configurable to various applications requirements. The current card complement for this specific application consists of: a MIL-STD-1750A computer, serving as the master processor; a MIL-STD-1553B card, used to communicate with the RIU; and a high-speed array processor, used to perform matrix multiplications for control law computations. The software for the MIL-STD-1750A was written in the Ada programming language and the array processor was programmed in microcode. The EDS can be configured to: perform output and state feedback controls calculations; calculate excitation commands; and perform sensor safety limit checks. In addition, the rate at which sensor data is acquired from the RIU is user configurable. The CSI Computer System has three support components. The Console Debugger/ PROM Programmer (CDPP) is used to download code to, or burn PROM's for, the EDS. The Ground Support Equipment (GSE) is used to supply power to the EDS. The last component, the Ground Support Equipment Terminal (GSET), is the user's interface to the system. It communicates with the EDS and the RIU via the MIL-STD-1553B. The functions of the GSET include: configuring the RIU and EDS for a particular experiment; recording in real-time the sensor and actuator data transmissions between the RIU and EDS; and reporting any errors encountered during experiment executions.

The RIU is the interface between the structure under control and the EDS. It is capable of acquiring up to 16 analog sensor signals and providing up to eight analog actuator outputs. It transmits sensor data from the structure to the EDS, and then receives actuator data from the EDS and sends it to the structure. The RIU is a modular instrument comprised of several flight-like components. It was designed so that minimal repackaging would be necessary to harden the RIU for space flight. The instrument is comprised of the following: a MIL-STD-1750A computer; a Digital Signal Processor (DSP); a MIL-STD-1553B card; and various in-house designed and fabricated boards to handle data processing. The software for the MIL-STD-1750A computer was written in Ada and programmed to initialize upon power-up. The DSP is used to filter the sensor signals. The RIU can be configured to filter multiple channels simultaneously with a variety of predefined and user defined digital filters implemented in the DSP. Sensor inputs are arranged in groups of eight and each group has a configurable sampling rate of either 60, 600, or 6000 Hz. In addition, the RIU has the capability of performing control law computations without the EDS. In this standalone mode, the RIU is connected to the sensors and actuators of the structure but not to the EDS or support components. The sensor data is sent to the DSP, where it is processed in the programmed control law to compute the required actuator commands. Any remote computer can download the control law to the RIU via a standard RS-232 serial port. By operating the RIU autonomously, higher system sampling rates can be achieved.

The CSI Computer System (CCS) tests, conducted on the CSI Evolutionary Model (CEM), included the following: open-loop excitation, safing, closed-loop control, and RIU digital filtering. The intent of these tests was to thoroughly check the functionality of the CCS under actual laboratory operations. For example, typical excitation inputs were used to excite the CEM in the open-loop tests. In addition, existing control laws, previously verified on other real-time computer systems (i.e., a CYBER 175 and a VAX workstation 3200), were executed on the CCS to verify closed-loop control. By using existing open and closed-loop test parameters, the results obtained from the CCS could be verified with previously known results. As a further form of validation, computer simulations of these tests were developed and executed off-line. In all cases, the results obtained from the CCS agreed with those from other CEM real-time computer systems and from the simulations.

TEST FACILITY

Phase-0 CSI Evolutionary Model

CSI Computer System

| Excitation and Damping Subsystem | Remote Interface Unit |

Support Components

analog sensor and actuator signals to & from the model

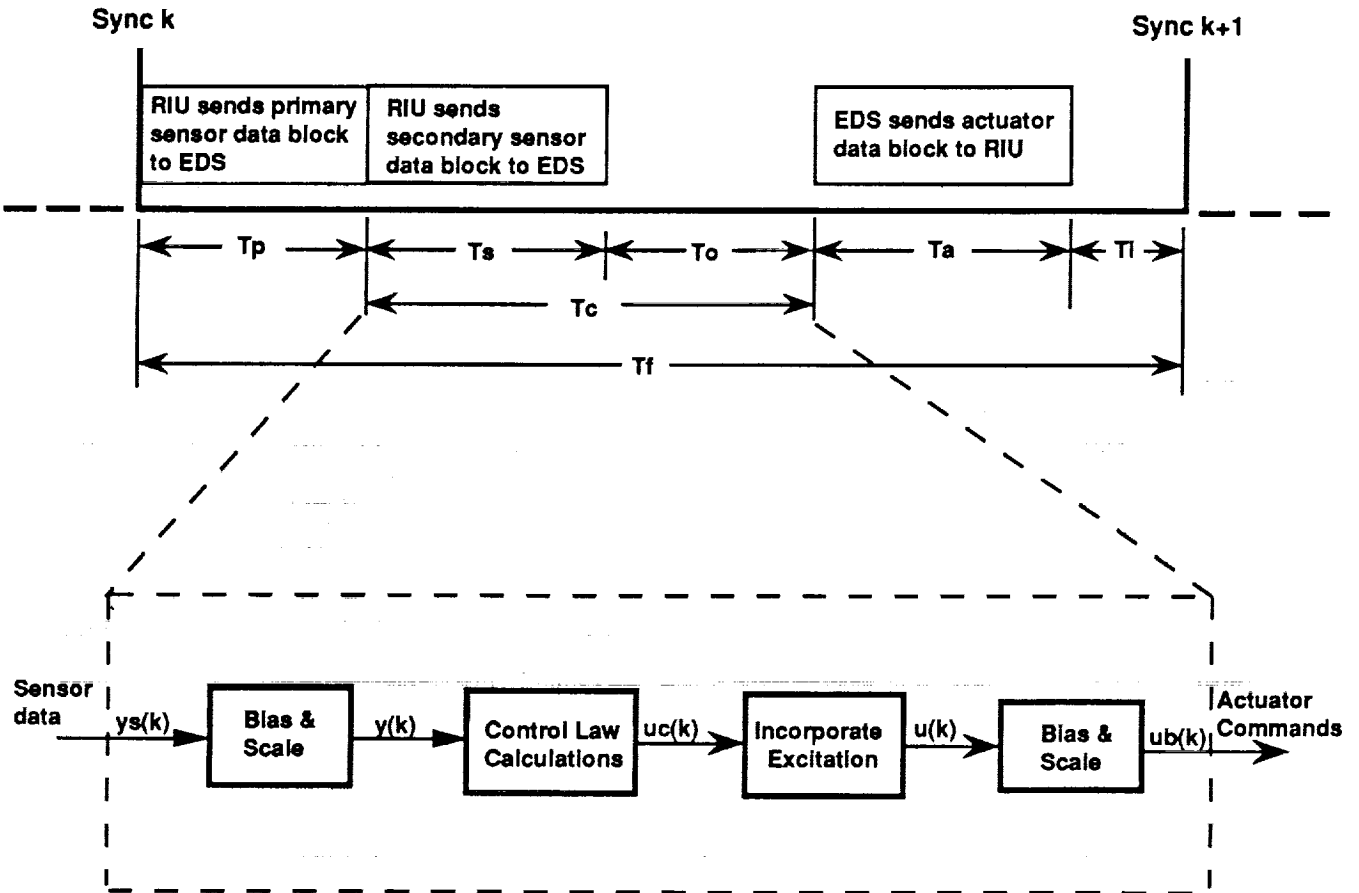## CSI COMPUTER SYSTEM (CCS)
TIMING AND CONTROL FLOW DIAGRAM

The following diagram shows the data transfers across the MIL-STD-1553B bus during a typical timeframe k. It also shows a subset of the calculations performed on that data by the Excitation and Damping Subsystem (EDS). The length of a timeframe is defined by the user specified sampling rate. A timeframe starts when the EDS sends a MIL-STD-1553B sync command to the Remote Interface Unit (RIU) and the RIU responds by recording the current values of the sensor data. A timeframe ends when, according to the user specified sampling rate, it is time to record sensor data again. However, during the entire timeframe the RIU continues to sample the sensor signals. It is only when the RIU receives the MIL-STD-1553B sync command that the sensor values are recorded on the local memory of the RIU for subsequent transmission to the EDS.

Once the MIL-STD-1553B sync command is transmitted, the EDS checks to determine if the experiment time has expired or if the user has issued the stop-test command. If neither of these have occurred, the EDS requests from the RIU a primary sensor data block. The primary data block contains the vector ys(k). The vector ys(k) is biased and scaled to make the sensor units compatible with those of the control law. The resulting vector y(k) is then used in the control law calculations. Depending on the option chosen by the user, prior to system configuration, either output feedback or state feedback control will be used to calculate the appropriate actuator commands, uc(k). User specified excitation values are then incorporated into the vector uc(k) to produce the vector u(k). The elements of u(k) are then biased and scaled, to make the units compatible with those of the actuators, and transmitted via the actuator data block to the RIU.

The RIU transmits to the EDS one primary sensor data block each timeframe. The EDS starts performing calculations on the primary block of data as soon as it arrives. The EDS may request the optional secondary sensor data block from the RIU immediately after the primary block has been received. Each sensor value from the primary and secondary data block is checked to determine if it is within the prescribed safety limits. These checks are performed by the MIL-STD-1750A computer while the array processor is performing the control law computations. If any of the sensors have exceeded their safety limits, the elements of the vector u(k) are set to zero. The vector is then biased and scaled to create ub(k), which is transmitted to the RIU via the actuator data block, and the test is terminated. The sensor data from the primary data block is used in the control law computations and the safety checks. The data from the secondary data block is only used for additional safety checks. The EDS safety and control law computations must be completed and the actuator data block transmitted to the RIU before sync (k+1).

Test configurations that specify large primary data blocks and actuator data blocks will cause a degradation in system throughput. Therefore, a compromise must be made between the amount of data that is to be transmitted over the MIL-STD-1553B bus and the desired sampling rate. By limiting the amount of bus traffic, times Tp and Ta can be decreased, thereby increasing the computation interval, Tc, for a given timeframe, Tf.

CCS TIMING AND CONTROL FLOW DIAGRAM

Sync k   **Sync k+1**

| RIU sends primary sensor data block to EDS | RIU sends secondary sensor data block to EDS | | EDS sends actuator data block to RIU | | |

$$\leftarrow Tp \rightarrow \quad \leftarrow Ts \rightarrow \quad \leftarrow To \rightarrow \quad \leftarrow Ta \rightarrow \quad \leftarrow Tl \rightarrow$$

$$\leftarrow \qquad Tc \qquad \rightarrow$$

$$\leftarrow \qquad\qquad\qquad Tf \qquad\qquad\qquad \rightarrow$$

Sensor data $\xrightarrow{ys(k)}$ **Bias & Scale** $\xrightarrow{y(k)}$ **Control Law Calculations** $\xrightarrow{uc(k)}$ **Incorporate Excitation** $\xrightarrow{u(k)}$ **Bias & Scale** $\xrightarrow{ub(k)}$ Actuator Commands

Where: Tp = Primary RIU to EDS sensor data transfer time
       Ts = Secondary RIU to EDS sensor data transfer time
       Tc = EDS safety and control law computations
       To = Unused bus time during EDS computations (Tc - Ts > 0)
       Ta = EDS to RIU actuator data transfer time
       Tl = Idle time prior to start of next timeframe (Tl = 0 when the
            CCS is running at full capacity)
       Tf = Timeframe

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EXCITATION AND DAMPING SUBSYSTEM (EDS)
REQUIREMENTS

Each sample period, the EDS is required to obtain a primary data block containing up to 16 sensor values from the Remote Interface Unit (RIU). The values must be biased and scaled to make the units compatible with those of the control law. The EDS is also required to perform user defined state and output feedback control law calculations to compute up to eight actuator commands. Sine wave, uniform random, and single pulse excitations are then incorporated into the actuator commands specified by the user. The actuator commands are then biased and scaled and transmitted to the RIU before the end of the sample period. All data transmissions between the EDS and the RIU are performed via the MIL-STD-1553B bus.

The EDS is responsible for controlling the length of the experiment and the sampling rate. The EDS is also responsible for verifying that the sensor data has not exceeded the prescribed safety limits. If this occurs, or if an emergency arises and the user issues the stop-test command, the EDS is required to transmit a zero command to the RIU for each of the actuators. Finally, the EDS is required to obtain a secondary data block containing up to 16 additional sensor values from the RIU. These values are not used in the control law calculations but are checked against the prescribed safety limits as an additional safety precaution.

The EDS software is designed to obtain and transmit data to more than one RIU, although this capability was never verified under actual lab operations. In addition, by increasing the value of the constants specified in the software, the EDS can operate with primary, secondary, and actuator data blocks of up to 32 words each. All data blocks are limited to 32 words since the message size for a MIL-STD-1553B bus transmission is limited to a maximum of 32 words.
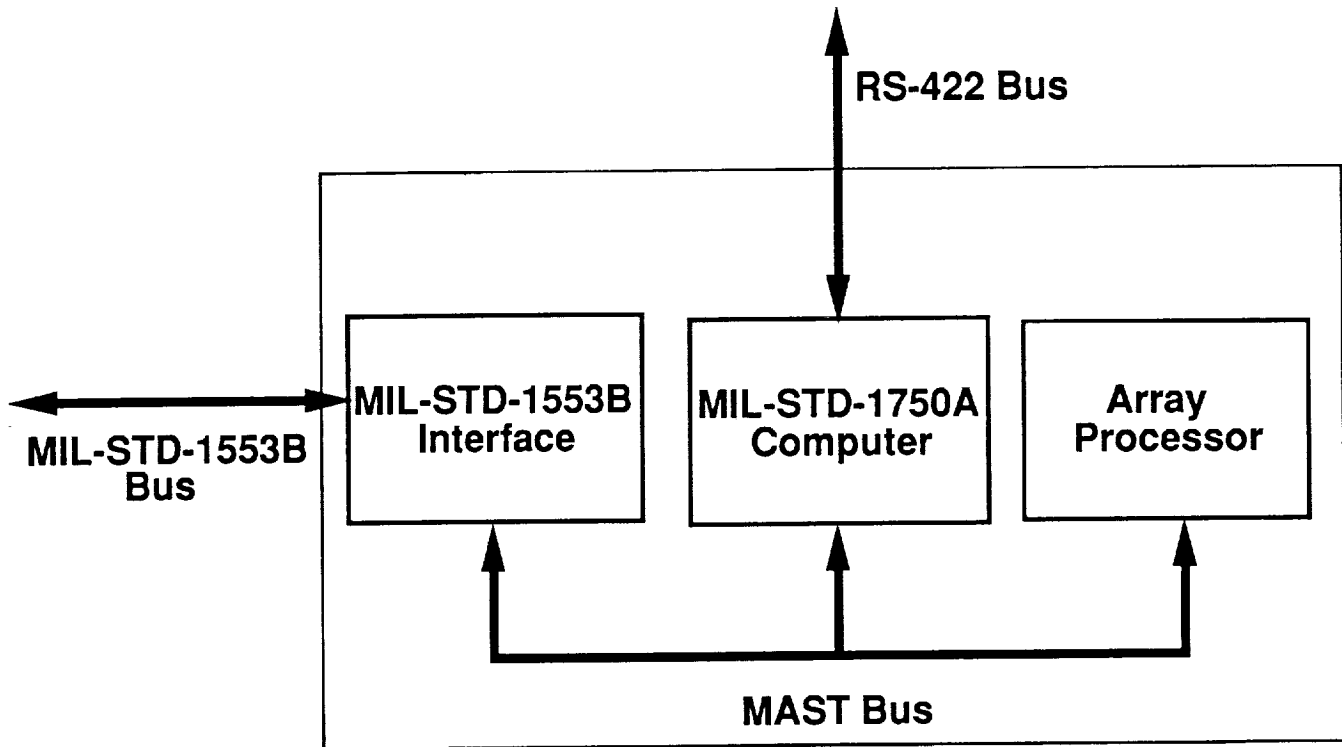
- ### Perform user defined state and output feedback control calculations

- ### Scale and bias sensor and actuator data

- ### Provide sine wave, uniform random, and single pulse excitation

- ### Control experiment timing according to user specified parameters

- ### Perform experiment safety and emergency shutdown procedures

EXCITATION AND DAMPING SUBSYSTEM (EDS)
BLOCK DIAGRAM

The EDS software was developed in-house, and resides on the commercially available, space flight qualified, Multi-processor Architecture Space Technology (MAST) computer, manufactured by SCI Systems, Inc. (Ref. 2). The MAST Computer was designed to be modular so that it could be configured with different combinations of processor, memory and I/O interface boards to support various applications requirements. The block diagram shows the configuration used with the CSI Computer System (CCS). The MIL-STD-1750A computer controls the EDS and was programmed primarily in the Ada language. However, assembly language was used for the math library, interrupt routines and utilities to perform activities such as block memory moves. The entire Ada program fit in the 64k RAM provided by the MIL-STD-1750A board. Memory words use 16 bit resolution with an additional 6 bit code for Error Detection and Correction (EDAC). The MIL-STD-1750A uses a floating point representation composed of two 16 bit words. The board also provides an RS-422 serial port which was used by the CCS system operator to issue a stop-test command directly to the MIL-STD-1750A if an emergency arose during test execution. A single array processor, programmed in microcode, was used to perform all control law matrix multiplications. Under the current configuration, the maximum size matrix that the single array processor can hold is 128x128 and the cumulative sum of the number of elements contained within the actuator, sensor and state vectors must not exceed 128. Lab experiments have been performed to demonstrate that the addition of a second array processor could be used for matrices larger than 128x128, but this substantially reduced throughput due to the increased overhead of moving large data blocks in and out of the array processor memory. The array processor was designed specifically to efficiently process large matrices such as those used in structural dynamics applications. The processor is built around the Analog Devices 3200 series chip set which adheres to the IEEE standard 754 for floating point arithmetic. The clock speed is 6.7 MHz, and the maximum theoretical throughput is 13.4 MFLOPS. The MIL-STD-1553B card handles all the communications with the Remote Interface Unit and the Ground Support Equipment Terminal. The card provides the three standard operational modes of Bus Controller, Remote Terminal, and Bus Analyzer. For this CSI application, code was written for both Bus Controller and Remote Terminal modes. The three boards described are mounted in three of the 16 slots provided by the motherboard and communicate through the MAST Bus located on the motherboard.

Tests that were run at Marshall Space Flight Center qualified the design of the MAST computer, with its full card complement, for levels called out for Shuttle and Titan IV general computer use. The MAST computer was designed to provide: data collection and storage; high-speed data processing; output control and communication with other computers of its own type, and with standard space shuttle and experiment interfaces. Although they were not used for this CSI application, the MAST computer is capable of supporting several other different types of cards: a Serial Input-Output board; a Buffered Input-Output board for discrete inputs and outputs; a High Rate Multiplexer board; an analog multiplexer/analog-to-digital converter board; and a Mass Memory board configured to provide 256k words of additional memory.

EXCITATION AND DAMPING SUBSYSTEM BLOCK DIAGRAM

RS-422 Bus

MIL-STD-1553B Bus

MIL-STD-1553B Interface

MIL-STD-1750A Computer

Array Processor

MAST Bus

REMOTE INTERFACE UNIT (RIU)
REQUIREMENTS

The primary requirement of the RIU is to support data acquisition and filtering for flexible combinations of sensors and actuators. To speed the control law computations in the Excitation and Damping Subsystem (EDS), the sensor data is ordered in the RIU to create the proper sensor vector required by the control law. The sensors and actuators are hardwired to the RIU channels but a flexible test configuration is maintained since the sensor signals can be ordered within the RIU.

To accommodate various types of sensors, the RIU provides the capability to process input data with different analog and digital filters. Digital filters provide enhanced filtering capabilities compared to analog filters. However, the analog filters are necessary to avoid aliasing when using digital filters. The RIU uses variable gain amplifiers for each sensor channel to support different sensor gains.

Another requirement of the RIU is to perform control law computations without the EDS. In this standalone interface configuration the sensor data is fed through local RIU filters implementing the control law and sent to the actuator channels. The limiting factor for the system sampling rate is the speed at which data can be transferred to the MIL-STD-1553B interface. By eliminating the use of this interface, higher system sampling rates can be achieved. However, the control laws must be limited to those that can be implemented with the RIU digital filters.

- **Order sensor data to conform to control law state variables**

- **Provide variable gain amplifiers, and variable bandwidth analog filters to support a variety of sensors**

- **Provide digital filters for greater filtering flexibility**

- **Support multiple interfaces for different host configurations**

REMOTE INTERFACE UNIT (RIU)
BLOCK DIAGRAM

The RIU is comprised of several components interfaced via two buses, a VME bus, and a custom designed Interface and Control Bus. Each of the components is a circuit board that is contained within a card cage. A MIL-STD-1553B bus is used to provide communications between the RIU, the Excitation and Damping Subsystem, and the Ground Support Equipment Terminal. A MIL-STD-1750A computer controls the operation of the RIU, maintains a dual ported RAM for local storage, and also has an RS-232 port for the RIU to use as the standalone interface. A Digital Signal Processor (DSP) provides digital filters for the RIU. Sensor signals can be filtered using Finite Impulse Response, or Infinite Impulse Response digital filters. The Analog Interface Board responds to commands from the DSP to record a data sample. This board is also responsible for providing the analog actuator outputs for the RIU. The components in the RIU exchange data via the VME and Interface and Control buses. The final component of the RIU is the Analog Processing Board. This board contains the analog to digital converter, multiplexer, analog amplifiers, and analog anti-aliasing filters. Two of these boards are used within the RIU and each of these boards supports eight sensor inputs. These boards are interfaced to the remaining components of the RIU via the Interface and Control Bus.
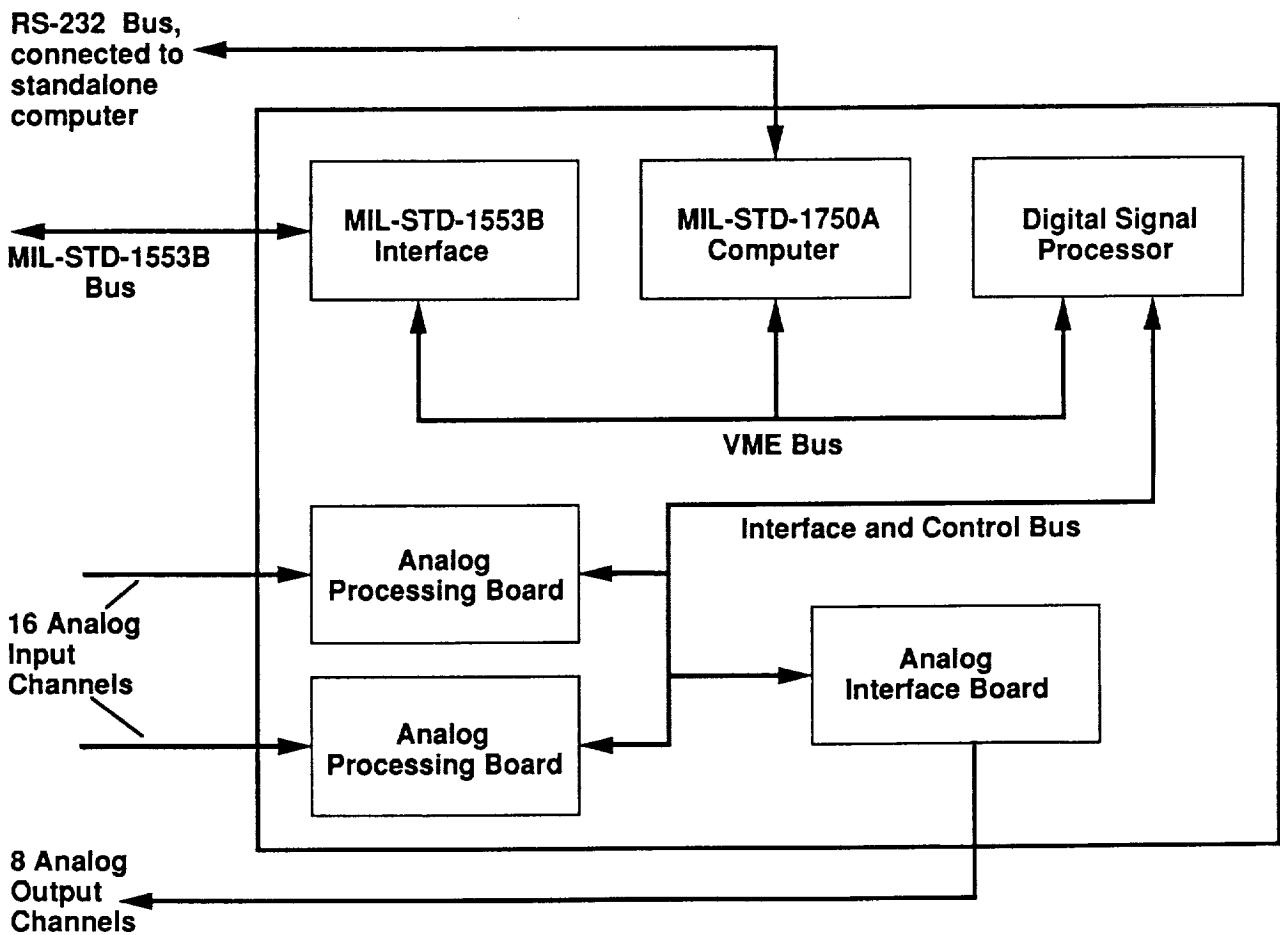
REMOTE INTERFACE UNIT (RIU)
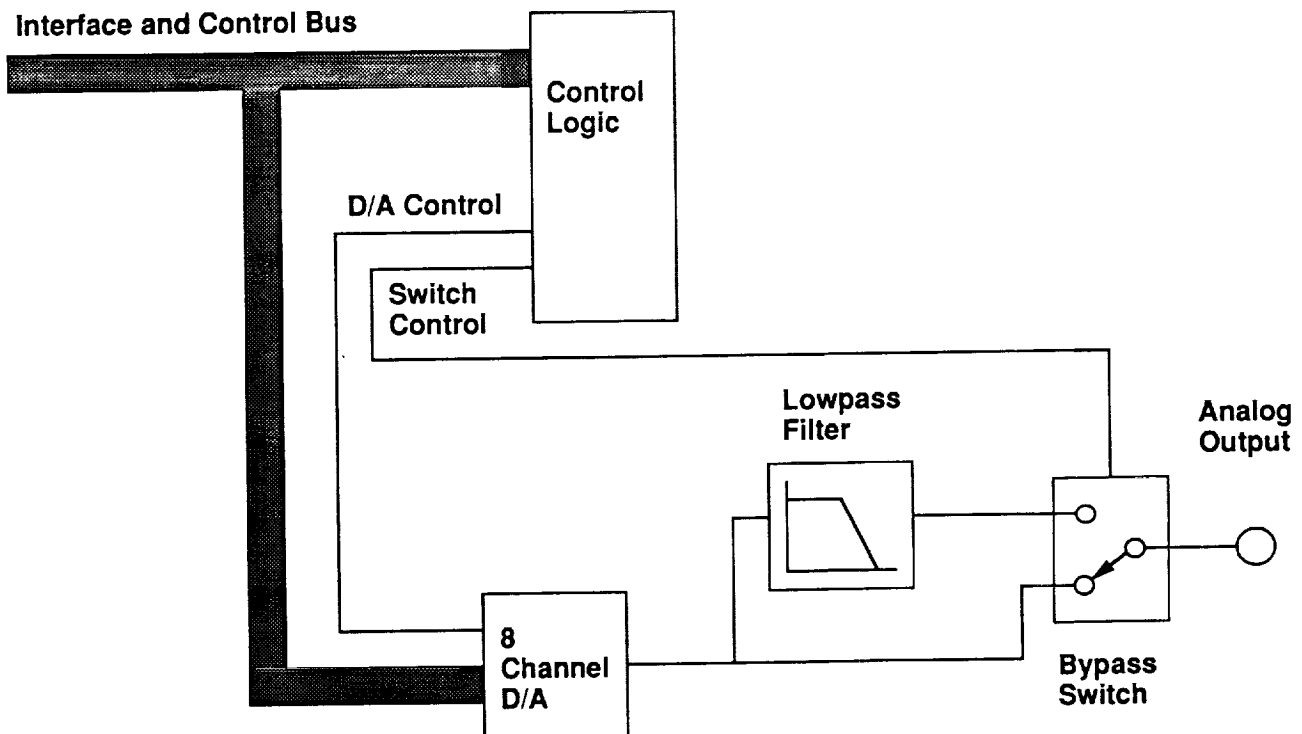# ANALOG PROCESSING BOARD

The Analog Processing Board was designed in-house to provide the RIU with an interface to the sensors on the structure. This board supports eight analog inputs, however, for simplicity the diagram only shows one analog signal path. The signal path consists of a prefiltering amplifier, an anti-aliasing analog lowpass filter, a postfiltering amplifier, and a 12 bit, eight channel analog to digital converter (A/D). The board is designed so that most of the functions can be either adjusted or bypassed. The amplifiers have programmable gains of 1, 10, 100, or 1000. This allows a variety of sensors to be connected to the RIU. The lowpass anti-aliasing filter has a variable bandwidth of 1666 Hz, 166 Hz, or 16 Hz. This filter can be bypassed if there is no concern for aliasing. A first-in-first-out (FIFO) buffer is used to store each of the eight samples from the A/D during an acquisition cycle to maintain phase coherency between channels. This board receives control signals from the Analog Interface Board and transmits data to the Digital Signal Processor via the Interface and Control Bus.
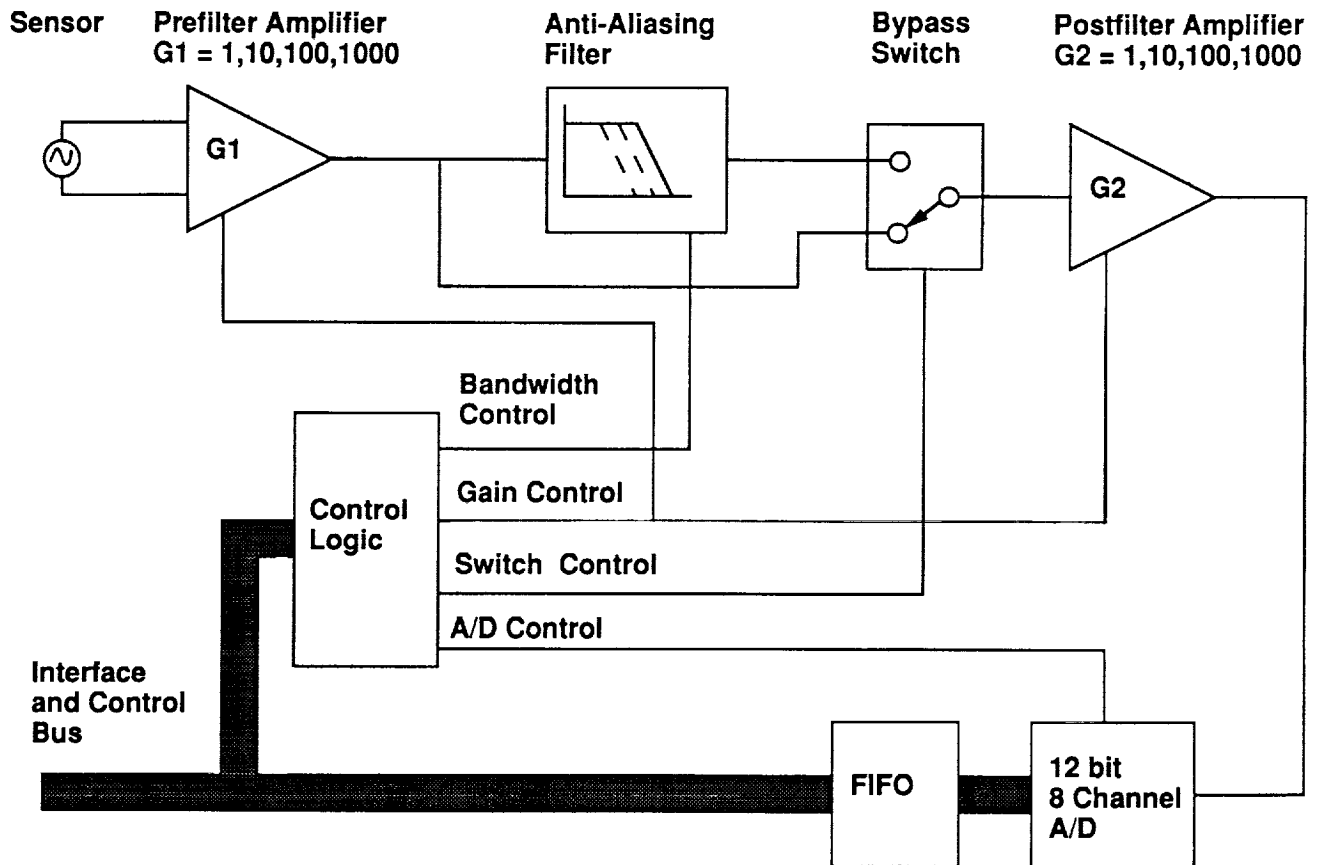
REMOTE INTERFACE UNIT (RIU)
ANALOG INTERFACE BOARD

The RIU Analog Interface Board was designed in-house to provide the analog outputs that control the actuators on the structure. This board supports eight analog outputs, however, for simplicity the diagram only shows one analog signal path. This board converts the digital data received from the Excitation and Damping Subsystem over the MIL-STD-1553B bus into analog signals that can be applied to the actuators. A digital to analog converter (D/A) with an eight channel multiplexer is used to construct the analog signals. After the data is converted, the signals can be smoothed with an analog lowpass reconstruction filter. There is one analog filter for each actuator output. These filters can be bypassed if the signals do not contain frequency components above the sampling rate of the RIU.

This board also controls the operations of up to four Analog Processing Boards by providing the control signals to select the various gains and filter bandwidths.
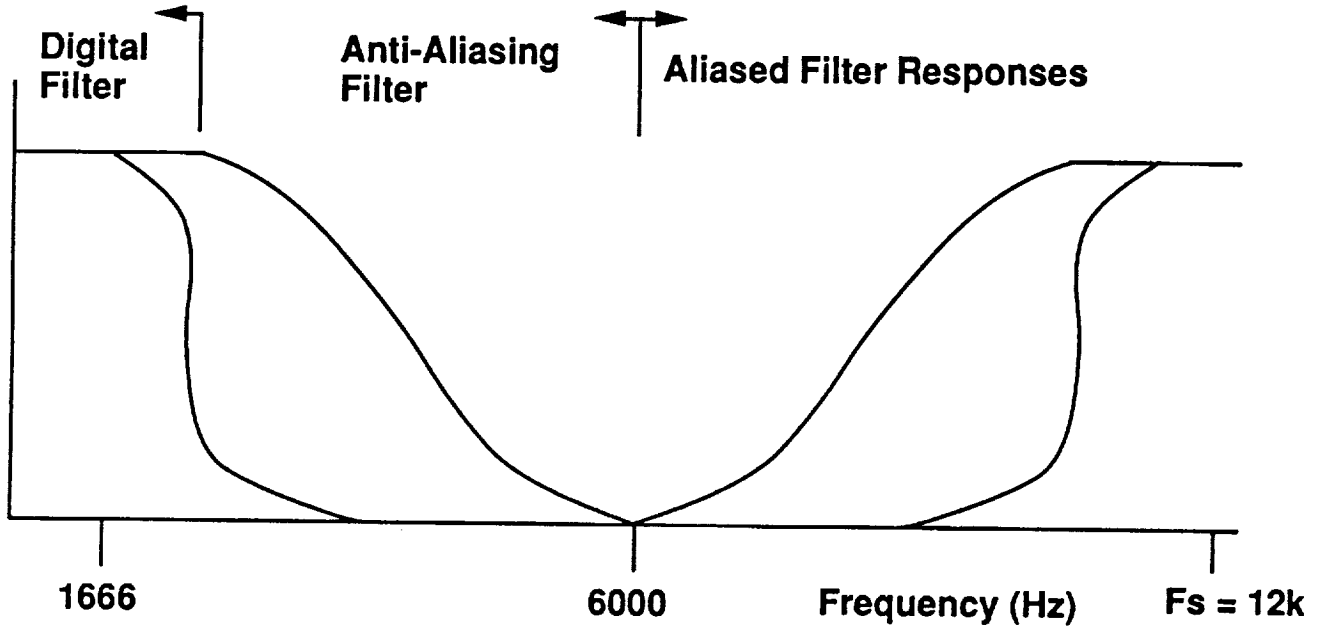
Interface and Control Bus

Control Logic

D/A Control

Switch Control

Lowpass Filter

Analog Output

8 Channel D/A

Bypass Switch

REMOTE INTERFACE UNIT (RIU)
FILTER DESCRIPTION

The RIU contains both analog and digital filters. The analog filter is an eighth order lowpass Butterworth design. Three cutoff frequencies are available: 1666 Hz, 166 Hz, and 16 Hz. The corresponding RIU sampling rates for these three cases are: 6000 Hz, 600 Hz, 60 Hz. To avoid compromising the phase response of the digital filter by using sharp roll-off analog anti-aliasing filters, the transition region of the analog filter is extended. At the largest cutoff choice of 1666 Hz, the transition region of the analog filter starts at 1666 Hz and continues to approximately 6000 Hz. As shown in the first figure, the bandwidth of the digital filter is contained entirely within the passband region of the analog filter. In this region the phase shift from the analog filter is near zero. With the transition region of the analog filter extended beyond the digital filter cutoff frequency, the required sampling rate to eliminate all aliased components of the analog filter would be approximately 12 kHz. This sampling rate places a strenuous load on the data processing requirements for the MIL-STD-1750A computer; therefore, it is necessary to reduce the rate as much as possible. The sampling rate can be decreased at the risk of allowing some of the aliased components of the analog filter to enter the transition region of the digital filter. Since the resolution of the analog to digital converter (A/D) in the RIU is 1 bit in 12, which is a relative magnitude of -72 dB, the sampling rate can be lowered until the aliased portion of the analog filter response just reaches -72 dB. This will not allow any of the aliased frequency components to interfere with the signal of interest since the magnitude will be below the range of the A/D. The resulting sampling frequency is 6000 Hz. The second figure shows the resulting frequency responses of the digital and analog filters. Similar results apply to the analog bandwidths of 166 Hz and 16 Hz.
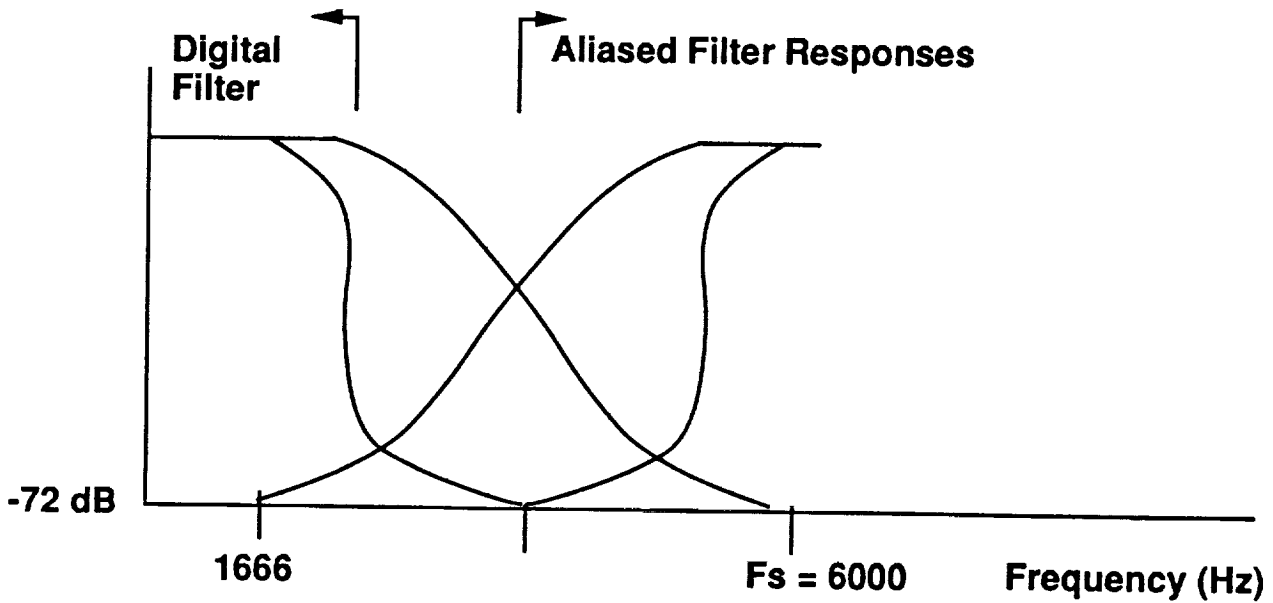
The RIU implements both Finite Impulse Response (FIR) and Infinite Impulse Response (IIR) digital filters in the Digital Signal Processor (DSP). The RIU has two predefined lowpass FIR filters and can support additional user defined filters. The first predefined filter has a length of 110 and was designed to have a sharp roll-off with little consideration given to phase shift. The second predefined filter has a length of 54 and was designed to have less roll-off and to introduce smaller phase shift. FIR filtering is accomplished by performing convolutions with the digital filter coefficients and blocks of sampled data (Ref. 3). The RIU can support two user defined IIR filters. The DSP processes sensor data with this filter by rearranging the IIR coefficients into a difference equation and computing the output from delayed values of the input and output data (Ref. 3).

REMOTE INTERFACE UNIT
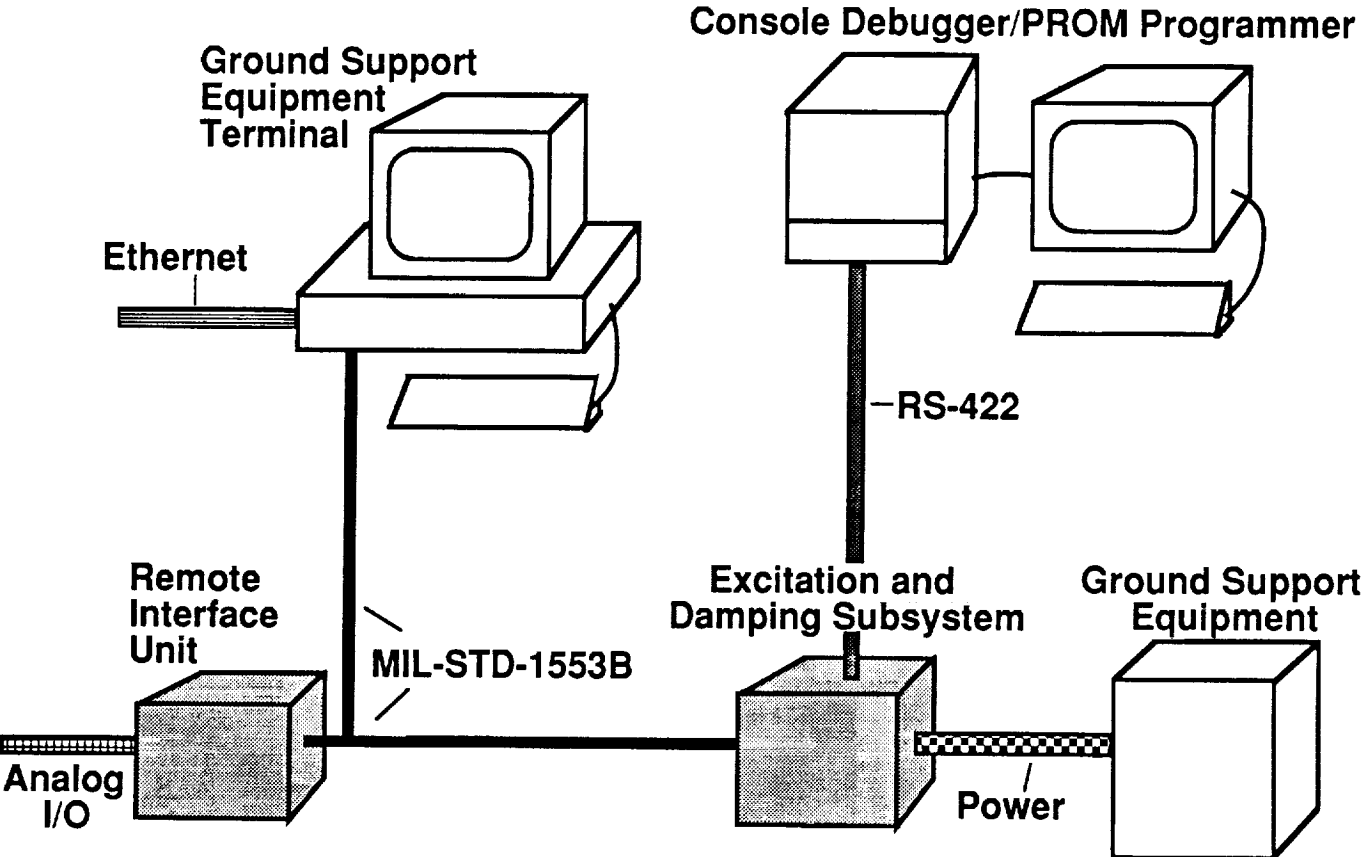# FILTER RESPONSES

Full sampling rate

Digital
Filter

Anti-Aliasing
Filter

Aliased Filter Responses

1666   6000   Frequency (Hz)   Fs = 12k

Undersampling

Digital
Filter

Aliased Filter Responses

-72 dB

1666   Fs = 6000   Frequency (Hz)

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CSI COMPUTER SYSTEM (CCS)
SUPPORT COMPONENTS

The CCS contains three support components. A diagram showing the components and their connections to the Excitation and Damping Subsystem (EDS) and the Remote Interface Unit (RIU) can be seen in the figure. The Console Debugger/PROM Programmer (CDPP) is a PC XT with an attached PROM burning expansion chassis. The CDPP has the capability to: download code, via a standard RS-422 interface, to the EDS; burn PROM's on boards designed for the MAST computer; and provide the user with a direct interface to the EDS, via the RS-422, in order to manually halt test execution in case of an emergency. In addition, the CDPP has debugging capabilities which were used extensively during development of the software for the EDS. The Ground Support Equipment (GSE) has only one function in the CSI Computer System and that is to supply power to the EDS. However, the GSE has data recording and numerous I/O capabilities to support communications with various MAST I/O boards which were not used by this CSI application. The third component, the Ground Support Equipment Terminal (GSET), is a PC AT which provides the user interface to the CSI Computer System. It is connected to the EDS and RIU via the MIL-STD-1553B bus. The GSET is responsible for configuring the RIU and EDS prior to test execution with parameters obtained from user provided files, a system file, and pretest calculations. Information such as RIU sensor channel gains and filter cutoff frequencies and EDS sensor critical limits and control matrix coefficients are contained within the parameters. It is those specified values that will define how a particular experiment will be executed. The GSET is also responsible for: recording, in real-time, the sensor and actuator data transmissions between the RIU and the EDS during the execution of an experiment; reporting any errors encountered during test executions; and post processing the experimental data once a test run is complete. After post processing is complete, the experimental data can be transferred to other systems, via Ethernet, where the actual test results can be compared with simulation results such as those obtained from PRO-MATLAB.

CSI COMPUTER SYSTEM SUPPORT COMPONENTS

Console Debugger/PROM Programmer

Ground Support Equipment Terminal

Ethernet

—RS-422

Remote Interface Unit

MIL-STD-1553B

Excitation and Damping Subsystem

Ground Support Equipment

Analog I/O

Power

CSI COMPUTER SYSTEM (CCS) VERIFICATION TESTS

After delivery and installation in the Space Structures Research Laboratory (SSRL), the following series of tests were conducted on the CCS to verify the functionality of the system in real laboratory operations. The first set of tests followed the SCI System Inc., procedures for verifying that the Excitation and Damping Subsystem (EDS) hardware and ground support components were functioning. These tests included checking the EDS power supply, the EDS memory and the capability of the EDS to properly communicate over the MIL-STD-1553B bus. After completing these tests, a series of additional tests were performed to verify that the CCS software requirements were met. These tests verified that the CCS could be configured for an experiment, compute the user defined excitations, perform the control law calculations and record test data.

After completing the hardware and software requirements tests, the following operational tests were performed: Remote Interface Unit digital filtering tests; open-loop excitation tests; closed-loop control tests; software safety tests; and computational speed tests.

- **Excitation and Damping Subsystem hardware and ground support components**

- **Software computational requirements**

- **Remote Interface Unit digital filtering**

- **Open-loop excitation**

- **Closed-loop control**

- **Software safety requirements**

- **Computational speed**

REMOTE INTERFACE UNIT (RIU) DIGITAL FILTERING TESTS

To test the RIU predefined digital filters, the RIU input channels were connected to a signal generator. Fixed-frequency sine waves were then sent to the RIU to simulate the sensor signals. The same sine wave was sent to eight RIU sensor channels. However, different RIU digital filters were selected for various channels. All the sensor data was recorded on the Ground Support Equipment Terminal for later analysis. Post test analysis involved the comparison of the RIU digital filter outputs with PRO-MATLAB simulated filter outputs for the same sine wave input. Several tests were made, involving different frequency sine wave inputs; the results of one test are presented here. For these tests, the RIU sampling rate was 600 Hz.

The top figure shows a time history plot of the raw 1.0 Hz test sine wave produced by a signal generator superimposed over the plot of test output from the RIU filter with the sharp roll-off. The group delay effects of the initialization of the digital filter were not recorded because the RIU begins to process the sensor signals in the Digital Signal Processor as soon as the RIU is fully configured, not when the data recording begins (time = 0 on the plot). The bottom figure shows a comparison between the time history plots of the sharp roll-off filter output and a PRO-MATLAB simulation output of the same filter for the 1.0 Hz test sine wave input. The 1.0 Hz tests show excellent agreement between the test and simulation. Similar results were obtained in the filtering tests with lower and higher frequency sine waves. In addition, similar tests were successfully conducted with the second predefined filter.
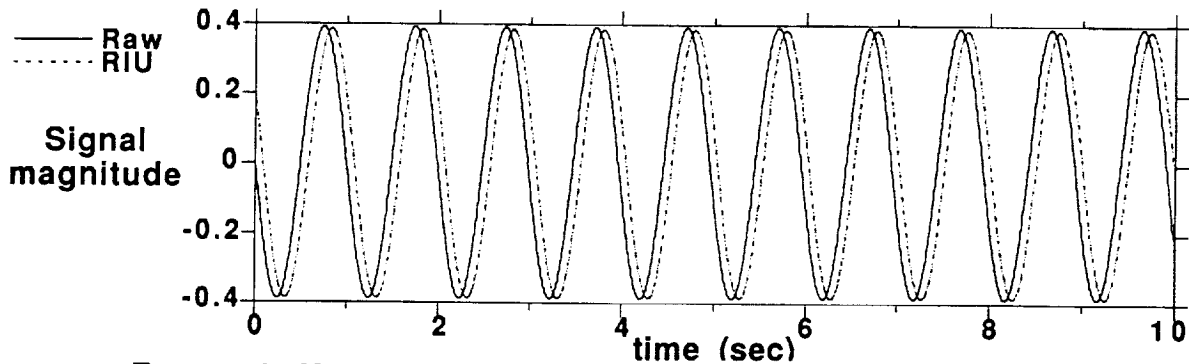
Raw 1.0 Hz sine wave Input and filter output overlay plot
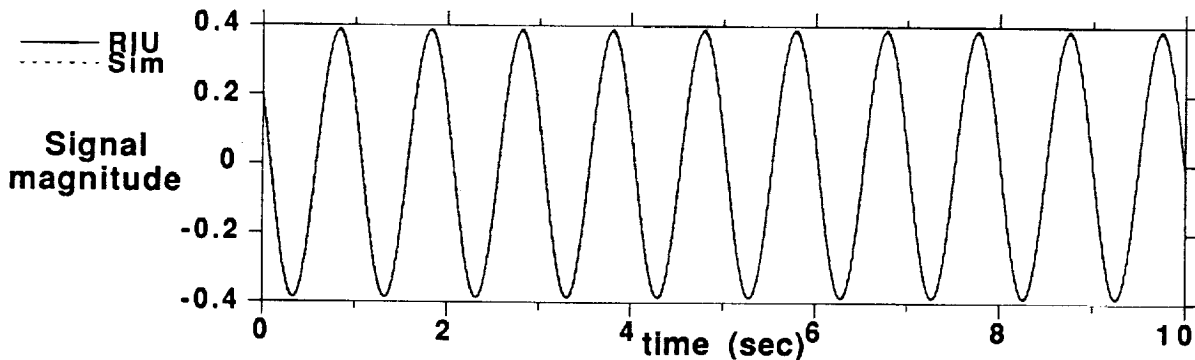
Filter output and simulated filter output overlay plot

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OPEN-LOOP TEST RESULTS WITH THE CSI EVOLUTIONARY MODEL (CEM)

For these tests, open-loop commands were sent from the CSI Computer System (CCS) to the thrusters on the CEM test article, and the responses of eight servo accelerometers were recorded. There were 16 separate thruster units on the CEM, commanded in pairs (Ref. 1). A single computer command signal sent to a thruster pair was split into two, one for each thruster making up the pair. The current CCS software is capable of commanding three different types of excitation for use as disturbances: sine waves, single pulses (of one sample period duration), and uniform random excitation. In the software, any thruster pair can be commanded to output any of the above three excitations during a test, although each thruster pair can only be commanded to perform one type of excitation per test.

All three types of excitation were tested on the CEM. Results from a sine wave excitation test are presented. This test was 30 seconds long and involved exciting the CEM with four thruster pairs for 7 seconds, then turning off the excitations and allowing the motions to freely decay for the remaining 23 seconds of the test. The top figure shows a recorded sample accelerometer response. The bottom figure shows sample thruster commands. The sample thruster pair was commanded with a 1.9 Hz frequency, 2 lb amplitude sine wave. Note the open-loop response growing from 0 to 7 seconds, and the free decay response after the thrusters were turned off. For this sine wave test, all eight accelerometer responses matched those obtained on the existing VAX workstation 3200 real-time computer using the same open-loop excitation.

Similar to the sine wave excitation tests, the CCS also successfully passed the pulse and uniform random open-loop excitation tests.

OPEN-LOOP EXCITATION TESTS
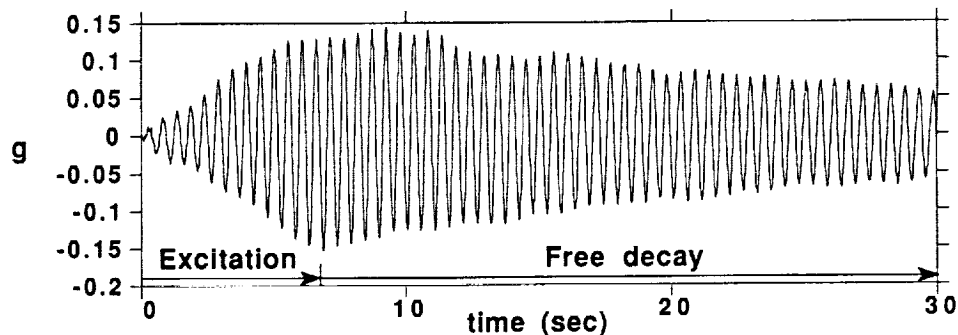
Sample accelerometer response to an open-loop sine wave excitation
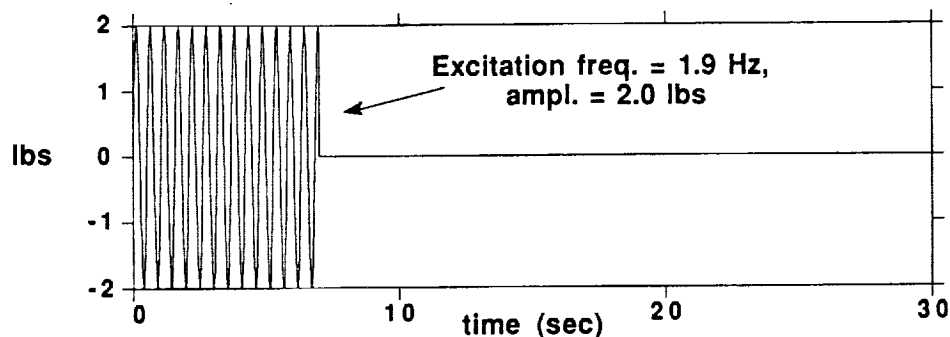
Sample thruster commands for open-loop sine wave excitation

CLOSED-LOOP CONTROL TESTS WITH THE CSI EVOLUTIONARY MODEL (CEM)

Three different closed-loop state feedback control laws were executed on the CSI Computer System (CCS). The number of states were 16, 42 and 60, respectively. Each used 8 servo accelerometers and all 8 thruster pairs. The performance goal of damping the vibrational motions of the CEM was the same for all three control laws. Each control law test was 30 seconds long, and the same sine wave excitations which were described in the open-loop testing section were used to excite the CEM for the first 7 seconds of each test run. After a period of 3 seconds of free decay, the control law was then turned on for the remainder of each test run.

The first closed-loop control law tested was a 16 state control law (Ref. 4), digitally simulating second-order mass-spring-damper systems at accelerometer/thruster pair locations which actively absorb vibrational energy from the CEM. This control law was executed at 150 Hz and at 200 Hz; the results of the latter test are presented here. For verification purposes, the same control law was executed on the existing VAX workstation 3200 at 200 Hz. This VAX is used as the primary real-time control computer in the Space Structures Research Laboratory, and is tied into a Computer Automated Measurement and Control (CAMAC) rack which performs the data acquisition and conversion duties. The first two figures show a sample accelerometer response from the control law tests conducted on the VAX and CCS, respectively. The responses matched, although the accelerometer data from the CCS was noticeably noisier. This was attributed to the fact that the CAMAC A/D converters had 16 bit resolution, as opposed to only 12 bit resolution for the A/D converter in the RIU. This in turn led to the slight differences in thruster commands issued from the two computers. This can be seen in the last two figures, which show commands from the two respective computers for the same thruster. Another factor to be considered, when comparing the CCS to the VAX, is computational precision. The control law on the VAX was executed in double precision (i.e., 64 bits), while the CCS was limited to 32 bit precision in its computations on the array processor. As a final check, the accelerometer responses, from both computers, were fed into a PRO-MATLAB simulation of the 16 state control law. The resulting simulated thruster command time histories matched their respective CCS and VAX computed thruster commands.

The two other closed-loop control laws, H–infinity based designs of 42 and 60 states, respectively, were successfully executed on the CCS in real-time at 200 Hz.
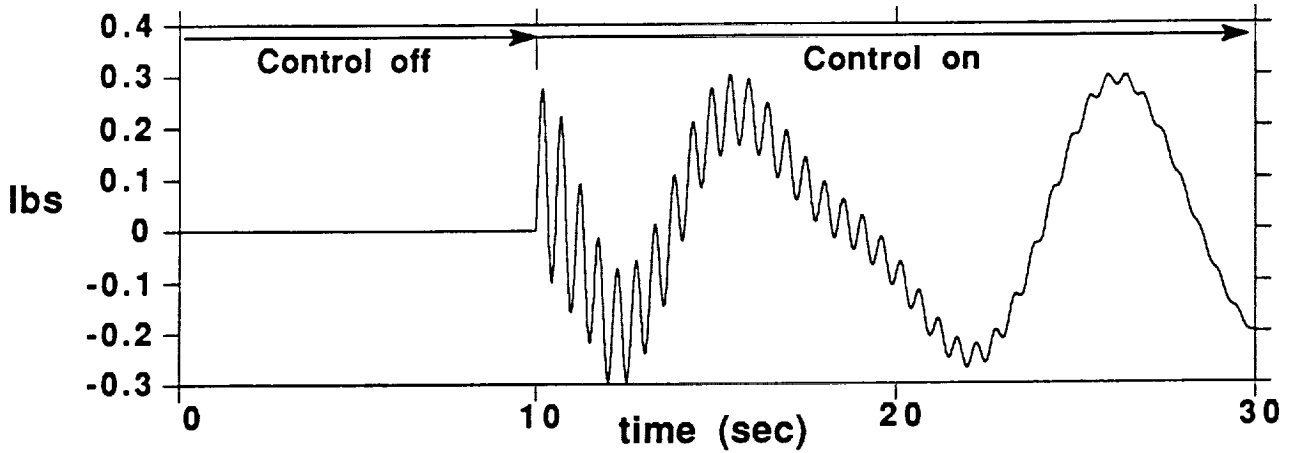
CLOSED-LOOP CONTROL TESTS
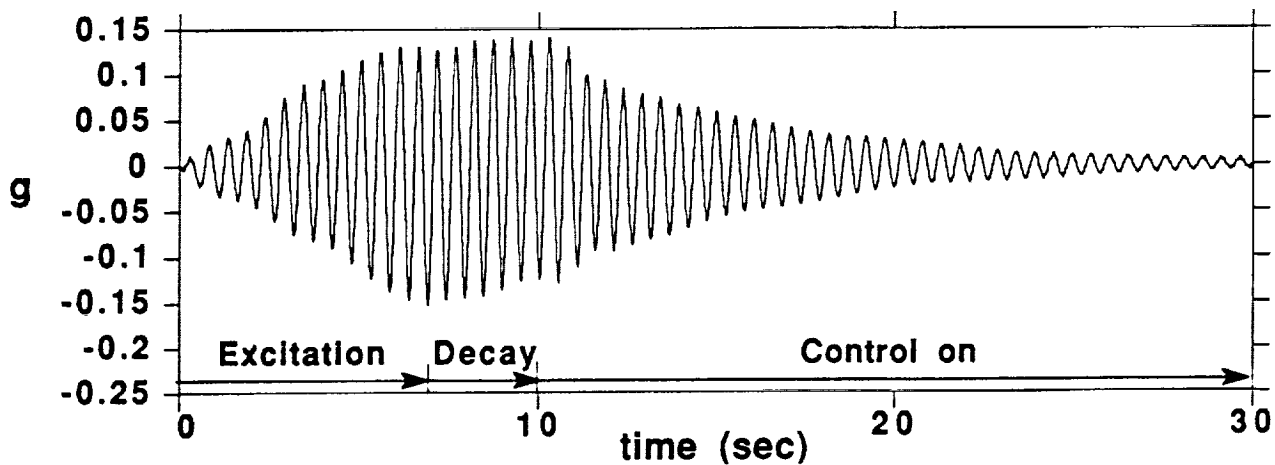
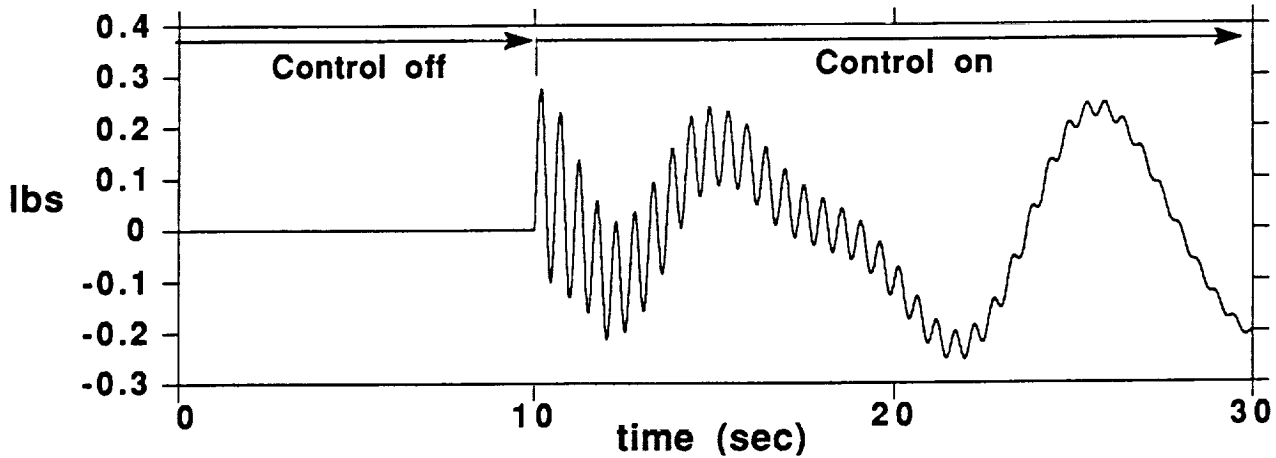Sample accelerometer response from control test executed on VAX 3200
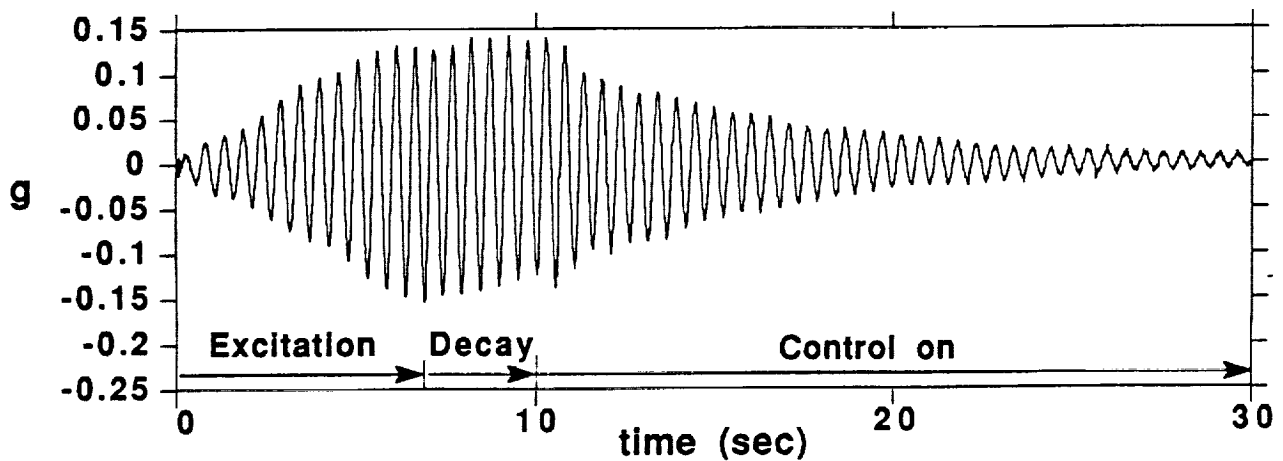
Accelerometer response from control test executed on CSI Computer System

CLOSED-LOOP CONTROL TESTS (CON'T)

Sample thruster commands from control test executed on VAX 3200

Commands to thruster from control test executed on CSI Computer System

SAFING TESTS WITH THE CSI EVOLUTIONARY MODEL (CEM)

One necessary feature of any computer system which is used to conduct dynamic experiments with large test articles, such as the CEM, is safing. During the open-loop command testing phase, both the manual shutdown command and the automatic safety shutdown features of the CSI Computer System (CCS) software were tested. Manual shutdown commands, issued by typing in "halt" on the Console Debugger/ PROM Programmer (CDPP), were successful in zeroing all the thruster commands and stopping the experiment in all instances. During the closed-loop tests with the 16 state control law, the manual shutdown command from the CDPP was tested again, to ensure that it can function during an actual closed-loop control experiment. The manual shutdown command was tried on several closed-loop tests, always being issued after the control law was turned on. In each case, the halt command successfully zeroed out all of the thruster commands and terminated the control execution.

The automatic safety shutdown software keyed on the magnitude levels of the accelerometer signals. Each accelerometer was assigned a maximum allowable signal level, called the critical value. If any accelerometer signal magnitude exceeded its critical value during the test, all the thruster commands were automatically set to zero and the experiment was terminated. In order to test this automatic shutdown feature without exciting the CEM to a high (and potentially damaging) degree, artificially small critical values were assigned to the accelerometers. The sine wave excitation commands, described in the open-loop testing section, were used to disturb the CEM. The figure shows the response of an accelerometer which was assigned a critical value of 0.1g. In addition, the figure shows that the 0.1g level was exceeded at 4.5 seconds, at which time the experiment automatically stopped and the thrusters were issued a zero command. The messages indicating that a "sensor limit was exceeded" and the "experiment terminated" were correctly displayed on the Ground Support Equipment Terminal.

# SOFTWARE SAFETY REQUIREMENTS TESTS
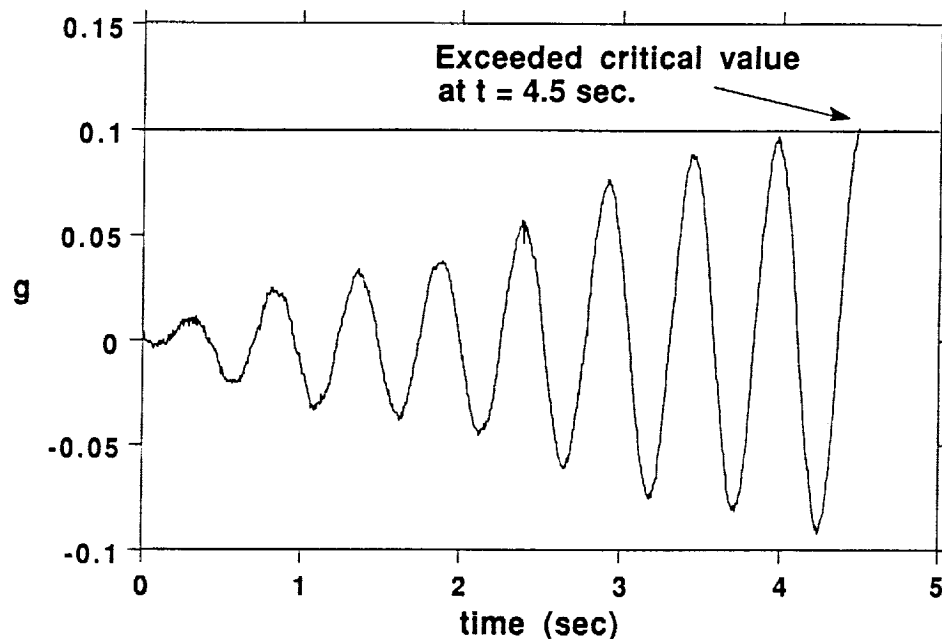
Sample accelerometer response from an automatic software shutdown test - critical value = 0.1g

CSI COMPUTER SYSTEM (CCS) COMPUTATIONAL SPEED TESTS

A set of five "dummy" control experiments were executed on the CCS to determine the achievable sampling rates for state feedback control laws of varying sizes. For these tests, the CCS was connected to the CSI Evolutionary Model (CEM), however, the computed thruster commands were not transmitted to the test article since the "dummy" control law matrices were not taken from real control laws, but were arbitrarily defined. Each one of these test runs was the same, with the exceptions being the control law size and the sampling rate. Each of the control laws used 8 servo accelerometer signals to compute commands for all 8 thruster pairs.

The figure shows a comparison of computational speeds, as a function of control law size, between the Excitation and Damping Subsystem (EDS) and the VAX workstation 3200. The "Basic VAX" plot represents the initial performance of the VAX workstation 3200 as delivered from the vendor. The "Enhanced VAX" plot represents the current performance after in-house optimization was completed on the workstation real-time software. The "EDS" plot represents the fastest speed that the EDS can process and compute a control law of a given size. These sampling rates are the rates at which the EDS requests data updates from the RIU; the current RIU, however, can only transmit updated sensor data to the EDS at a rate of 200 Hz. Thus, the control laws which were executed above 200 Hz were not using refreshed sensor data in every EDS sample period. For this reason, the maximum practical CCS sampling rate, for control laws with 80 states or less, is 200 Hz with the present system.
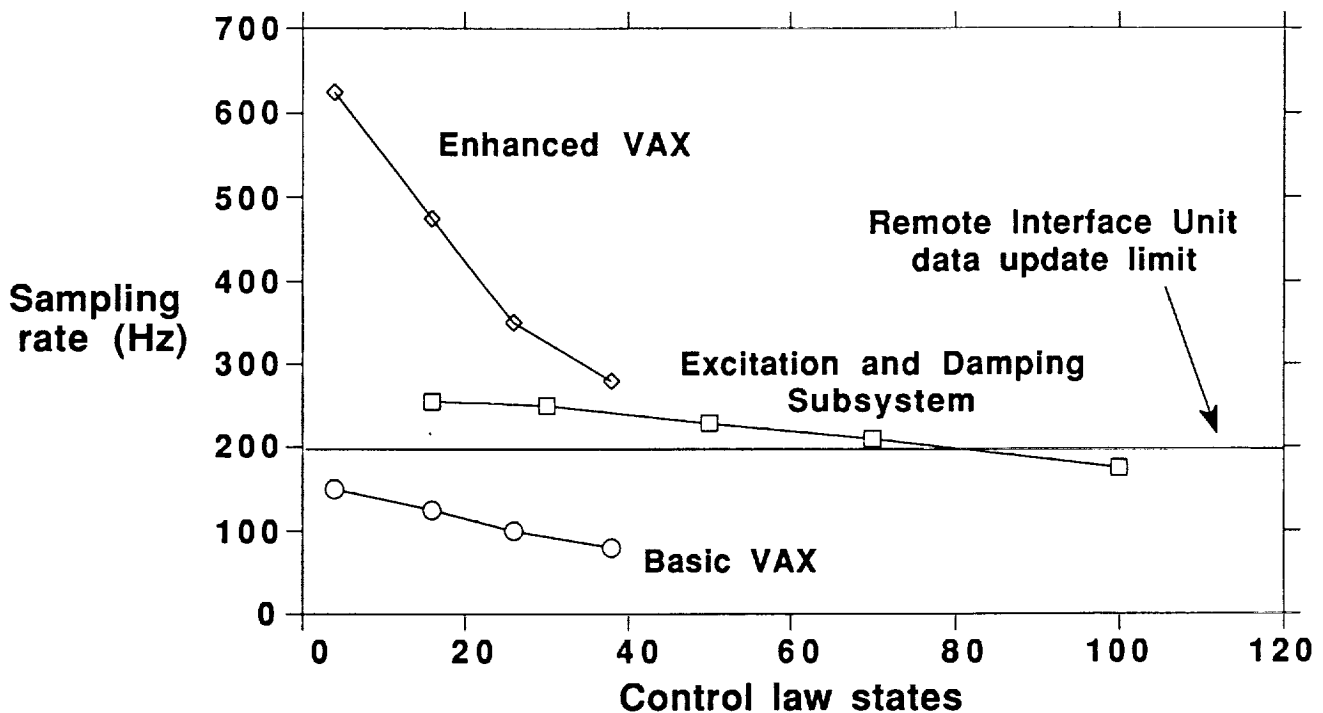
VAX workstation 3200 and Excitation and Damping Subsystem
achievable sampling rates versus control law size

SUMMARY

The CSI Computer System (CCS) is composed of the Excitation and Damping Subsystem (EDS) software, resident on the space flight qualified Multi-processor Architecture Space Technology (MAST) computer, and the Remote Interface Unit (RIU), an in-house built, flight-like data acquisition/filtering system. Both the EDS and the RIU use MIL-STD-1750A computers which were successfully programmed in Ada . The CCS has been installed in the Space Structures Research Laboratory (SSRL) for testing. Both open and closed-loop tests have been successfully conducted with the CSI Evolutionary Model (CEM), and have demonstrated that the CCS system is capable of performing meaningful real-time control experiments on actual laboratory test articles. Also, these initial tests results have indicated that the CCS shows promise as a viable space flight computer, and further study in this direction is warranted.

- **The CSI Computer System is comprised of a flight qualified computer and a flight-like data acquisition and filtering subsystem**

- **The capability of the system to conduct control/structures experiments has been successfully verified on the CSI Evolutionary Model**

- **The system shows promise as a viable space flight computer and further study in this direction is warranted**

- **Demonstrated Ada programming expertise on a real-time embedded system**

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