ABSTRACT. The model verification of large flexible spacecraft is a new field of experimentation that expands the envelope of instrumentation systems with heretofore unseen performance and environmental demands. This paper will describe the hardware and software implementation of an on-orbit instrumentation system to be flown on the International Space Station (ISS) for the purpose of gathering structural response data on-orbit for use in model verification of the fully integrated space station structure. The Structural Dynamic Measurement System (SDMS) is comprised of 33 accelerometers, 38 strain gage bridges, and two signal conditioning units externally mounted and distributed along the main truss of the ISS. The output from the sensors is processed through the ISS Command and Data Handling (C&DH) system and telemetered to the ground for data reduction using the Eigensystem Realization Algorithm (ERA). The implementation of SDMS on the ISS has required new sensor construction and installation techniques never before used in order to provide an instrumentation system that will survive the hostile environment of space for a prolonged period of time. Many discussions have been provided on the analytical reduction of data for model verification of the ISS, but little work has been published addressing the physical implementation of such an instrumentation system. Therefore, the model verification of the integrated structure will be completed on-orbit during and after assembly.

The section of the ISS manufactured by Product Group 1 (PG-1) includes the main truss between the Solar Alpha Rotary Joints (SARJs) and sections of the pressurized module pattern (See Figure 1). PG-1 is responsible for instrumenting the five segments of the main truss between the SARJs so that structural response data can be gathered for model verification of the on-orbit configurations. The PG-1 data acquisition system is called the Structural Dynamic Measurement System (SDMS) and is comprised of 33 accelerometers, 38 strain gage bridges, two signal conditioning units, and controlling software. The SDMS hardware is externally mounted and distributed along the PG-1 main truss. Other sensors may be mounted to sections of the ISS manufactured by other product groups and the international partners, but this paper will discuss the hardware and software design processes and issues associated exclusively with SDMS on PG-1 hardware.

The main points of discussion include: sensor locations and distribution, exciting the ISS structure, data acquisition architecture, software requirements, on-orbit assembly stages to be verified, accelerometer performance specifics, methodology for installing accelerometers, installation process for strain gages, and failure detection.
Space Station Freedom and the ISS

The hardware to be used for SDMS on the ISS was originally designed for the Space Station Freedom (SSF). When SSF was transitioned into ISS, the design environment changed, but the performance requirements for SDMS remained the same. Most significantly, the thermal environment became considerably colder due to a change in orbital inclination, so that most of the SDMS hardware that was designed for SSF no longer worked on the ISS. The budget and schedule demands added to the design problem such that it was necessary to implement the SSF hardware in the ISS environment without degraded performance while minimizing cost and schedule impacts. The economic and political concerns became necessary design constraints for SDMS, so that the best design from a technical point of view often had to be weighed against what was cost and schedule effective.

Sensor Locations and Distribution

Accelerometers are mounted to the PG-1 truss in groups of one, two, or three at the designated bulkhead/longeron joints shown in Figure 2.

- X, Y, Z direction
- X, Z direction
- X direction

Starboard SARJ

S3 S1 S0

Zenith Trunnion Longeron

Figure 2. Accelerometer Locations for PG-1 SDMS

The coordinate system used for defining accelerometer line of action (i.e., the direction in which an accelerometer will measure an acceleration) is centered at the geometric center of truss Segment SO and is fixed to the unperturbed structure, with the positive x axis pointing out the center of face 1 of Segment SO (toward the US LAB module) and the positive y axis pointing along the starboard truss. The line of action of an accelerometer must be parallel to the designated axis in the body frame.

The strain gages are mounted on four PG-1 hardware systems. Figure 3 shows the six locations on the Module to Truss Structure (MTS) that connects the truss to the pressurized modules. Figure 4 shows the four locations on the cradle that supports the starboard Thermal Radiator Rotary Joint (TRRJ). There are fourteen locations on each of the two SARJs. All strain gage locations use a four-active-arm bridge circuit. The strain levels anticipated at the strain gage locations range from 200 micro strain (p) to 1500 με.

Exciting the ISS Structure

The ISS structure will be excited by normal on-orbit transient loading events, such as orbiter docking, reboost, and Extra Vehicular Activity (EVA). No plan currently exists to perturb the ISS structure to excite selected target modes. Data will be collected during the resulting free response of the structure and then reduced to determine as much modal information about the structure as possible. Modes of interest range from the lowest natural frequency, on the order of 0.01 Hz, up to 5.0 Hz.

Signal Conditioning

Each Signal Conditioning Unit (SCU) has 43 channels (21 accelerometer and 22 strain gage). However, only 36 channels are used from SCU-1 and 35 channels are used from SCU-2. Each channel is filtered through a 5 pole Bessel filter with a cut off frequency of 7.5 Hz and can be individually amplified to any one of four different gain settings. The accelerometer gain settings are 1, 3, 6, or 24, and the strain gage gain settings are 65, 255, 660, or 2040. The desired gain settings can be loaded from the ground for each channel before a test begins, and the SCU returns a confirmation that gain settings were received.

Each of the 43 channels of the SCU acts independently and has a separate Bessel filter circuit. The type of electrical component used for the Bessel filter will fail if struck by a particle of ionizing radiation while powered on. The original design specifications for the SCU to be used on Space Station Freedom required that the unit have a design lifetime of five years and be functional fifteen minutes per day, which corresponds to a yearly duty cycle of 1.0%. The component parts for the SCU were selected based on this duty cycle. The longer the SCU is powered on, the greater the probability that a particle of ionizing radiation will come into contact with one of the 43 Bessel filter circuits in the SCU when current is passing through the circuit, which will cause a single event latch up of the filter circuit and the corresponding channel in the SCU will no longer function. The probability of a channel failing from ionizing radiation when the SCU operates only 15 minutes per day is sufficiently low that the SCU has an adequate probability of meeting the five year design lifetime in the SSF environment. In order to solve the thermal problems for SDMS in the ISS environment, an initial solution was to leave the SCU turned on all the time to help keep the unit warm. Unfortunately, this solution increased the duty cycle and correspondingly the failure rate of the SCU so that every channel in the unit would fail in less than one year due to ionizing radiation. Redesigning the SCU to replace the Bessel filter circuit was not an option due to cost and schedule concerns. As a result, the 1.0% duty was maintained and heaters and temperature sensors were placed in the SCUs to keep the units warm when functioning and when turned off.

The original design specifications for the SCU to be used on SSF also required that the unit meet extremely tight weight constraints. The entire unit was required to weigh less than nine pounds. As a result, the SCUs provide only the very basics in signal conditioning. Different gain settings may be selected for each channel and the analog signal is filtered as noted previously.
Data Acquisition Architecture

The controlling software for all ISS functions resides in the Multiplexer/Demultiplexer (MDM) units mounted along the truss and inside the pressurized modules. Figure 5 shows the SDMS integrated architecture. The two SCUs are both located on Segment SO in the center of the PG-1 truss.

The SO-1 and SO-2 MDMs control all software functions on segment SO. SCU-1 is connected to MDM SO-1, and SCU-2 is connected to MDM SO-2 via an RS-485 bus. SCU-1 controls all sensors on the starboard side of the ISS truss, and SCU-2 controls all sensors on the port side of the ISS truss, with the exception of the MTS, which has port and starboard side sensors but is controlled completely by SCU-2. The A/D conversion of sampled data takes place in the SO MDMs.

The external (EXT) MDMs control all PG-1 truss segment MDMs, and the Command and Control (C&C) MDMs control all functions on ISS. Communication between MDMs is done via a MIL-STD-1553 serial data bus.

Software Requirements

The Command and Data Handling (C&DH) design for ISS was never intended to be used for data acquisition for modal analysis. The primary function for C&DH on ISS is process control of the ISS subsystems (e.g., open and close valves, latches, etc.), and the sampling rate and volume of data needed for modal analysis of ISS exceeded the capability of the C&DH system. Moreover, the total budget for SDMS is far less than one-tenth of one percent of the total budget for all of ISS, which dictated that SDMS would not be permitted to drive the C&DH requirements for ISS. Instead, SDMS was forced to work within the confines of the existing data acquisition capability.

Modes will be identified up to a natural frequency of 5.0 Hz. A 7.5 Hz roll-off frequency for the 5 pole Bessel filter and a 40 Hz sampling rate provide adequate signal strength at 5.0 Hz and sufficient attenuation of the sensor signal at the Nyquist frequency of 20 Hz. With a sampling rate of 40 Hz, all 71 sensors need to be sampled once every 25 ms. The C&DH system is capable of sampling at 40 Hz, but a significant problem to overcome was the necessity of sampling all 71 sensors at the same instant. The time history data measured by the sensors will be reduced using ERA to generate natural frequencies, mode shapes, and damping information about the ISS structure. When ERA is used with multiple sensor inputs, the algorithm assumes that all sensors are sampled simultaneously. Realistically, every sensor would be sampled over a very small window, where the elapsed time between the first sensor and the last sensor sampled is so small relative to the sampling rate and the natural period of the modes to be measured that the sensors are effectively sampled simultaneously. At the time the software requirements were written, the best prediction for what the C&DH system could manage was to sample all sensors controlled by a given SCU over a span of 3 ms, which was considered to be too large of a window relative...
to the 25 ms sampling period. The 3 ms window is defined as one strobe, such that each strobe of the sensors will collect one sample from every sensor connected to one SCU.

A baseline requirement for SDMS is to be able to collect at least ten minutes of structural response data at one time or over several consecutive tests, and to store this data on-orbit until it can be telemetered to the ground. Ten minutes worth of data for 71 sensors at 40 Hz consumes almost all available RAM memory of the SO and EXT MDMs. The C&C MDMs have long term storage capability, but the SDMS data must pass through the SO and EXT MDMs to get to the C&C MDM, which means the volume of data that can be collected at one time is limited by the temporary memory storage capability of the SO and EXT MDMs. One possible solution to the 3 ms strobe problem was to apply a time stamp to every measured value, which would double the volume of data. Unfortunately, this would only allow approximately five minutes of data to be recorded at one time. In order to meet the ten minute requirement, it was necessary to permit only one time stamp to be applied to each strobe.

The best solution found for this problem was to assume that the sensors are sampled at regular time intervals during the strobe and that sensors are always sampled in the same order during one strobe. The A/D conversion of one sampled value requires 36 microseconds, along with an overhead of 144 microseconds to set up and to complete one strobe. When the software requirements were written, a possibility existed for other software applications residing in the SO MDMs to demand service from the MDM during an SDMS strobe, which could have added up to 1.0 ms to the total strobe duration. Doing the math for SCU-1, 36 channels at 36 microseconds each, plus 144 microseconds overhead, plus 1.0 ms of delay time adds up to 2.44 ms. The C&DH designers rounded the 2.44 ms number up to 3.0 ms to be conservative. If the assumption is initially made that there will be no interruptions during one strobe, then by knowing the time when the strobe begins, the overhead needed to set up one strobe, the order in which sensors are sampled, and the duration between the sampling of each sensor in one strobe, which is 36 microseconds, it is possible to accurately predict when the A/D conversion of a sensor value actually takes place within the strobe. Since the possibility exists for up to 1.0 ms of delay within the strobe, then the time of the ND conversion of a sensor value can be approximated to be within 1.0 ms of when the A/D conversion of the sensor value actually takes place. Using linear interpolation, the sampled value from a sensor can be 'backed up' to the time stamp of the strobe, so that the effective strobe length is 1.0 ms instead of 3.0 ms, where the 1.0 ms effective strobe duration results from the anticipated 1.0 ms delay during the strobe. The 1.0 ms strobe duration is a small enough window to provide reasonable accuracy with ERA

Assembly Stages

Segment SO is the first PG-1 truss segment to be launched and carries both SCUs and the SO and EXT MDMs. SDMS is designed so that it may be operational after Segment SO is deployed before the other four PG-1 truss segments are launched. Therefore, structural response data will be gathered for all assembly stages after Segment SO is launched, and the volume of data will increase as more PG-1 truss segments with more sensors are added to the ISS configuration.

Accelerometer Performance Specifics

A summary of the accelerometer performance specifications is presented in Table 1.

<table>
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<th>Table 1. Accelerometer Specifications Summary</th>
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<tr>
<td><strong>Weight</strong></td>
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<tr>
<td><strong>Linear range</strong></td>
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<tr>
<td><strong>RSS overall error</strong></td>
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<tr>
<td><strong>Zero bias</strong></td>
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<tr>
<td><strong>Minimum detectable change</strong></td>
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<tr>
<td><strong>Operational design lifetime</strong></td>
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<tr>
<td><strong>Excitation voltage</strong></td>
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<td><strong>Maximum operating current</strong></td>
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For the installation of the strain gages, special precautions must be taken to ensure that the strain gages can survive in the environment of space. The most significant environmental threat to the strain gages is atomic oxygen, which will act against the backing material of the strain gages and the adhesives that affix the strain gages to the structure. The atomic oxygen can pummel the strain gages, having an effect similar to sandblasting, and the atomic oxygen can also react chemically with the backing material or the adhesive compound. For this reason, the installation process of the strain gages also requires the strain gages and terminal strips to be covered for protection from atomic oxygen. The covering process is summarized in Figure 7. The strain gages and terminal strips are covered with a layer of fiberglass cloth impregnated with epoxy resin. An additional coating of metal-filled epoxy resin is placed under the glass cloth to provide a smooth surface to which the glass cloth can better conform. The layer of metal-filled epoxy between the strain gages and the glass cloth will become extremely rigid and could rigidize the strain gage.
lead wires if allowed to come into direct contact with the strain gages, in which case the epoxy could cause the strain gage lead wires to be disconnected when the structure is strained. For this reason, an additional layer of Teflon tape is placed between the metal filled epoxy resin and the strain gages, to provide a smooth surface under which the strain gages may slide. The Teflon tape needs to adhere to the substrate as the epoxy layer is applied and while the epoxy is cured. Unfortunately, the thermal environment of the strain gages is cold enough that the adhesive on the Teflon tape will rigidize on-orbit, creating the same problem as the epoxy resin. Therefore, two layers of Teflon are used, with one cut slightly larger than the other, and the adhesive surfaces pressed together. This method provides a band of adhesive around the perimeter of the strain gages allowing the two layers of Teflon tape to adhere to the substrate during installation without allowing any adhesive to come into direct contact with the strain gages. After the epoxy resins are cured, the Teflon will be held in place by the epoxy in the event that the on-orbit thermal environment causes the adhesive on the Teflon to fail.

The desired strain values to be measured for the MTS are the axial loads in the selected struts (Figure 3). It is not feasible to snake connecting wires along the length of the truss struts because the struts are telescoping and can also be removed and replaced if necessary. This means any wires attached to the truss struts would need EVA accessible connectors installed, which would appreciably complicate the design and increase the total cost of SDMS. As a result, the fittings for the truss struts are instrumented instead. The truss strut terminates with a clevis that fits over the rotating clevis fitting shown in Figure 8. By measuring the bending loads in the rotating clevis fitting, the axial loads in the truss struts can be calculated directly. The bending bridge circuit for the rotating clevis fitting is shown in Figure 9.

The bridge circuits for the TRRJ cradle are axial bridges and are therefore mounted at right angles instead of parallel as seen with the MTS strain gages. The four locations will provide a measure of the loads acting on the rotary joint supported by the cradle so that effective bending moments and torque on the rotary joint can be determined.

The strain gage bridge at location 2 on the cradle X-brace (Figure 4) presented a challenging problem. The design of the cradle originally used a Z-brace with only one support between the upper and lower cradles instead of the X-brace with two supports. The location 2 bridge was to be installed on the single support and would provide a measure of the load acting in the axial direction of the rotary joint supported by the cradle. When the design was modified from the Z-brace to the X-brace, the number of sensor channels permitted for the TRRJ cradle was already well established and could not be changed. In order to provide a means of measuring the load on the cradle acting in the axial direction of the rotary joint, two individual bridges were installed on the X-brace in the locations shown in Figure 4, and then connected in parallel to provide a measure of the net load acting in the axial direction of the rotary joint. The problem was further complicated by the necessity of maintaining a net resistance across the bridge of 1000 ohms, because the SCU was designed to support only a 1000 ohm strain gage bridge. When the two bridges at location 2 are connected in parallel, the net resistance becomes one-half of the resistance of the two bridges. This means that the two individual bridges need to have a net resistance of 2000 ohms, and 2000 ohm strain gages were not available from the vendor selected to provide the strain gages without a significant increase in cost. Therefore, each strain gage of one bridge is actually two 1000 ohm strain gages wired together in series. This requires 8 strain gages to be used for one bridge and a total of 16 strain gages to be used for the circuit. The resulting bridge circuit is extremely complicated and is presented in Figure 10.
The strain gages on the Solar Alpha Rotary Joints (SARJs) will measure the effective bending and torsional loads as well as axial and shear loads. The general locations for the strain gages on the SARJs have been determined, but the precise locations and the circuit wiring has not yet been chosen. The results of static load tests performed on the SARJ static test article will be used to help determine the best locations and orientation of the SARJ strain gages.

Failure Detection

The SCUs are Orbital Replacement Units (ORUs), which means that if a SCU fails on-orbit, or if several channels of a SCU cease functioning, the SCU may be replaced by an EVA astronaut. However, there is no means to test the SCU on-orbit to confirm operational integrity. The only way to determine when an entire SCU or an individual channel has failed is to examine the data on the ground. The problem of identifying a SCU failure is further complicated by the potential for accelerometers to stop working at cold temperatures. The temperature distribution across the PG.1 truss is not constant, which means that one or more accelerometers may be outside of the thermal operational regime while all other accelerometers are fully functional, and it is not possible to determine the temperature of an accelerometer from the ground. Further, an accelerometer outside of the thermal operational regime may continue to generate output, but the output may be erroneous. It then becomes the responsibility of the ground operators who will process the SDMS data to determine by observation if accelerometer data is useable and if erroneous accelerometer data is caused by the accelerometer or by the SCU.

There is no means of replacing the accelerometers or strain gages on-orbit, and attrition of the sensors is expected during the lifetime of the ISS. However, the anticipated lifetime of the SDMS sensors will provide for a viable means of collecting sufficient structural response data from the PG-1 truss segments on-orbit through assembly complete.

Conclusion

The development of SDMS as a component of an on-orbit instrumentation system for model verification of ISS has proven to be a challenging effort that has balanced demanding technical needs with difficult environmental demands and practical cost and schedule limitations. Despite these challenging design issues, SDMS, in conjunction with instrumentation systems on hardware produced by the other PGs and the international partners, will provide a sufficient means of verifying the mathematical models of the integrated, on-orbit configurations of ISS during the assembly cycle and at assembly complete.