Structural Health Monitoring; an Enabler for Responsive Satellites

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The Air Force Research Laboratory/Space Vehicles Directorate (AFRL/RV) is developing Structural Health Monitoring (SHM) technologies in support of the Department of Defense's Operationally Responsive Space (ORS) initiative. Such technologies will significantly reduce the amount of time and effort required to assess a satellite's structural integrity. Although SHM development efforts abound, ORS drives unique requirements on the development of these SHM systems. This paper describes several technology development efforts, aimed at solving those technical issues unique to an ORS-focused SHM system. Additionally, this paper will describe how SHM can be implemented, within a holistic satellite surety process, to dramatically truncate the time necessary to test and validate the performance of a potential Responsive satellite.

AFRL/RV = Air Force Research Laboratory Space Vehicles Directorate
CLA = Coupled Loads Analysis
MUF = Model Uncertainty Factor
ORS = Operationally Responsive Space
SHM = Structural Health Monitoring

I. Introduction

The Department of Defense is developing an Operationally Responsive Space (ORS) capability, and recently stood up the ORS Joint Program Office, at Kirtland AFB, NM, in support of that goal. As stated in Reference 1 ("Plan for ORS") "ORS is focused on the timely satisfaction of the urgent needs of the JFC (Joint Force Commander) and other users." The "Plan for ORS" also describes a three-tiered approach to delivering these capabilities to our combatant commanders:

Tier 1: Utilizes existing, or on-orbit capabilities to provide the required space-based capability within days from establishing the need.

Tier 2: Utilizes field-ready, or nearly field-ready capabilities to satisfy warfighter needs within days-to-weeks of establishing the need.

Tier 3: Development of an entirely new, or unforeseen capability, within a year.

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In order to meet the unique demands of ORS, the DOD research community has invested heavily in technologies that allow satellites to be designed and assembled via more modular approaches. Today's satellites tend to be highly optimized point designs and the traditional methods used to develop these systems are inadequate for meeting the aforementioned Tier 3 objectives. Additionally, current practices are cost prohibitive (and result in obsolescence) when used to meet Tier 2 timelines for the wide range of mission that fall under the purview of ORS. Developing an ORS capability requires a framework and the necessary infrastructure that allows the accomplishment of a wide range of missions, in a very short amount of time, while keeping inventory to a reasonably low level. Although these requirements lack a great deal of specificity, they have spurned efforts to develop standards and technologies that enable satellites to reap the benefits of more modular approaches.

At the Air Force Research Laboratory/Space Vehicles Directorate (AFRL/RV), there are many technology development efforts aimed at enabling modular satellite architectures. These efforts include: Space Plug-and-play Avionics[2], reconfigurable thermal management systems[3], autonomous satellite operations[4], satellite design and analysis tools[5], modular flight software, and configuration-flexible structural architectures[6]

However, all of these efforts are for naught if we are forced to follow the current arduous surety processes. This paper discusses AFRL/VS's efforts to develop alternative test and analysis procedures that conform to the timelines of ORS. Additionally, this paper focuses on the pivotal role that Structural Health Monitoring (SHM) technologies will play in these alternative methods, as well as the unique requirements that ORS drives on the development of an appropriate SHM system.

II. Current Structural Surety Process

Traditionally, a satellite's structural performance is validated through three phases: static loads, environmental or dynamic loads, and coupled loads analysis (although some of these phases may be avoided at the discretion of the satellite manufacturer, launch vehicle, and launch service provider team).

1. Static loads verify the satellite structure is able to handle the highest anticipated loading scenario during the launch sequence. Typically used to validate the finite element model, so that the margin of safety/safety factor can be assessed. For ORS-class satellites (<1000kg), this test is often validated through analysis, or from the results of dynamic tests.
2. The environmental and dynamic tests assess the satellite's ability to survive the launch segment, as well as characterize the dynamic behavior of the satellite. Two series of tests are usually performed: shock and random vibration. Shock tests impart the maximum expected impulsive load into the satellite. Random vibration tests measure modal characteristics of the satellite, accomplish a workmanship baseline for the satellite, and subject the satellite to flight level random vibration spectrums customized for the launch vehicle being used for the mission. To our knowledge, no satellite has flown without undergoing dynamic testing.
3. The Coupled Loads Analysis (CLA) takes the flight-representative satellite structural model (including its test-verified dynamic behavior) of the satellite and couples it to a high fidelity model of the LV (including the expected loads producing forcing functions for each flight event). The CLA looks for interactions that could damage the satellite or cause problems with the launch vehicle control software. The value of a CLA is that it explores the impact of random vibration on all the components of the satellite (it typically outputs expected accelerations and loads at each node of interest), returning critical data required to assess the readiness of the satellite structure to survive the launch. To our knowledge, the only satellites that have not required a CLA are extremely small picosatellites.

Unfortunately, these tests and analyses procedures that have been developed for conventional satellites take much too long to conform to the timelines of ORS. For some satellites, the iterative process of testing and analysis can take over three years[7].

It is the authors' contention that Structural Health Monitoring may prove critical for determining a responsive satellite's ability to survive the launch sequence and operate in space. It can be used to determine the health of structural components, and assess mechanical connections. It can be run in parallel with other ground-based satellite check-out procedures and is amenable to ORS timelines. Additionally, unlike traditional testing processes, SHM can pinpoint the location, type, and severity of damage, enabling rapid component swap-out, maintenance action, and go/no-go decisions.

III. Proposed Implementation of SHM

The DOD, as well as a number of other entities, have investigated methods for determining the modal characteristics of a satellite, and other complex structures, through purely model-based means[8,9,10,11]. Many of these efforts have made substantial progress in developing highly accurate dynamic models. However, these efforts have also shown that uncertainty in the dynamics of the constituent parts, electrical harnessing, and mechanical interfaces play a considerable role in expanding the divergence in the dynamic solution for the system, as a whole.

In the predominant vision of ORS, a minimal set of satellite components is stored in something akin to today's aircraft depot. And much like at an operational depot, each component is rigorously tested, validated, and characterized before it arrives. Additionally, as the components sit in storage, they are periodically tested to ensure they still function properly, so that when a requirement to build a satellite arises, there is a high level of confidence that each piece of the satellite will work. Another inherent advantage is that the vast majority of components can be utilized for multiple mission scenarios (rather than using custom parts for each mission-type); ORS can therefore reap the benefits of repeatability that come along with larger production runs. From a structural standpoint, this process of prior testing and characterization works to dramatically decrease the Model Uncertainty Factor (MUF) for each component.

Another factor in our favor is that the preponderance of the electrical harnessing is likely to be contained within the structure of an ORS satellite[6]. Figure 1 shows a picture of PnPSat (Plug-and-Play Satellite, a technology demonstrator for ORS), with structurally embedded wiring and avionics boards. The structural integration of the electrical infrastructure truncates the build-up process and increases the footprint available to components. Through this architecture, electrically integrating a component is theoretically as easy as plugging a USB, of FireWire device into your computer. However, this approach also conveys significant benefits to the dynamic modeling task. Because the preponderance of the electrical harnessing is already recessed within the structure, the layout of the wiring can be pre-designed and manufactured in bulk (leading to less variability), and more exhaustive efforts can be undertaken to properly attach the harnesses to the structure. Additionally, the influence of this wiring can be characterized during component-level testing. The uncertainty that remains will reside with the much shorter electrical leads that integrate the component directly into the panel. Figure 2 shows 3 of the satellite's 6 panels, with components integrated for a test of the Guidance, Navigation, and Control system. Additionally, the use of a standard electrical interface requires that each of these harnesses be of the same type; again reducing the variability of the wiring harnesses.

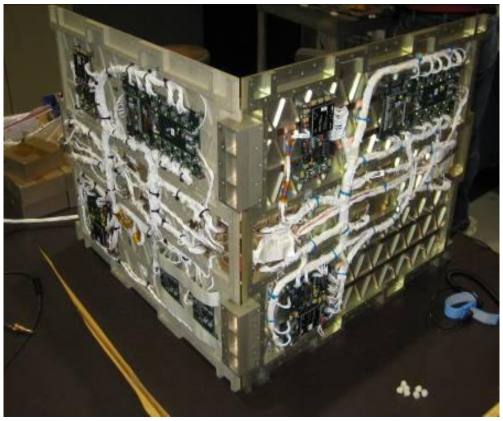

Figure 1. Electronics embedded within structure. *Outer surface is removed*

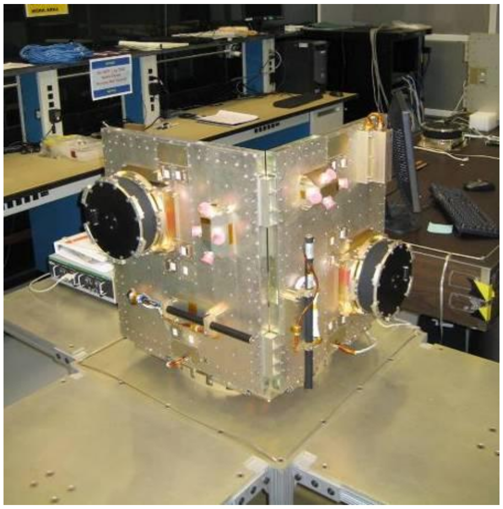

Figure 2. Components integrated for sub-system testing

At that point, it is the interfaces between satellite components that pose our greatest source of variability. This is precisely why AFRL is interested in SHM technologies for ORS satellite applications. As stated before, an ORS satellite that is assembled in a rapid fashion cannot afford to go through the time-consumptive and onerous Quality and Assurance (Q&A) process typical of traditional satellite programs. Expedited methods must be developed to ensure the technician fastened a bolt to the specified torque, or that a bond-line is acceptable. Having the ability to accurately assess the integrity of the connections between satellite components and subsystems will dramatically reduce the variability in the model used to assess the satellite's modal properties. Additionally, the capabilities of the SHM system can be fed directly into that model, in order to bound the uncertainty at the interfaces.

The following is one vision of how a satellite's structural surety could proceed:

1. Perform a "variational CLA" (vCLA) on each pertinent launch vehicle, a priori[7]. This analysis can be used to establish envelopes detailing satellite mass, center of mass location, and fundamental frequency combinations for each launch vehicle. These envelopes greatly ease the surety process, because satellites that conform to these envelopes will not require a dedicated CLA. It is our desire that these envelopes be used as design inputs for ORS satellites.
2. The SHM system is used to periodically assess the condition of satellite structural members. These checks will search for the presence of damage, providing valuable feedback regarding storage conditions (i.e. is the humidity too high for the composite parts, has somebody dropped a panel, etc.?).
3. When the requirement for a satellite comes in, an automated software tool is used to quickly generate the design for the satellite[5]. In parallel, the Finite Element Models of all the required components and their connections is assembled in order to assess the satellite's modal properties. Key modal properties include the satellite's fundamental frequency (to assess compatibility with the launch vehicle) as well as anti-resonances (which are critical for Guidance, Navigation, and Control purposes). As stated before, the capability of the SHM system can be used to bound the variability on the interfaces between structural members, satellite components, payloads, etc. A preliminary modal assessment can be fed back into the Satellite Design Tool as input to determine the suitability of the satellite design.
4. If the satellite does not conform to the envelope of the vCLA, a traditional CLA will need to be pursued. However, this testing can be performed in a much shorter timeline, because a high fidelity model of the satellite has already been developed, and the model possesses significantly reduced variability (when compared to current satellites of comparable mass and volume).
5. The SHM system is used to assess the integrity of the satellite's structure and connections. A lack of faults provides a degree of confidence that the satellite will successfully survive the launch sequence and that it exhibits modal behavior matching that of the model. The detection of faults is followed by rapid corrective maintenance actions, followed by another SHM-based assessment, until no further faults are detected.

It is anticipated that these SHM-based tests will take a matter of hours, and can be conducted while other satellite systems are being checked. This is critical, because the truncated timelines of ORS dictate that numerous satellite checks be run in parallel; traditional satellite dynamic testing does not accommodate this requirement.

SHM also provides a capability that is not available through other means; if there is a fault, the SHM system will pinpoint the location, type, and severity of the fault. This is helpful in that repair action can be immediate (which may be as simple as tightening a bolt) and focused. Traditional dynamic testing only points to the presence of a fault. Locating the fault often comes down to educated guesses on the part of test engineers who possess significant expertise and experience in the area.

IV. Complexities of the Problem

The development of a suitable Structural Health Monitoring system is no trivial task. Creating a robust capability that allows us to realize the vision of ORS will require that the SHM system be able to accomplish the following.

1. **Interface with the Satellite Design Tool**

   When the requirement for a space asset comes from the Joint Force Commander, the Satellite Design Tool will be tasked with developing the assembly instructions for that satellite. The SHM system will have to take information about the satellite's configuration, characteristics and placement of components, attachment schemes, etc., from the Satellite Design Tool, in order to assess damage with minimal false positives.
2. **Flexible to accommodate numerous configurations**

   This flexibility is not limited to just different structural configurations, but must also encompass near innumerable iterations regarding component, payload placement, and fastener locations, as well differing types of all three. Again, it must be able to take information from the Design Tool and utilize it in order to perform its health assessment tasks. A critical component of this requirement is the ability to differentiate damage from configuration change. If a component is moved, or the technician has to drill a hole to accommodate a specific component, will the SHM system now be bogged down with false positives? Any SHM system that seeks traceability to ORS must be able to differentiate between the two.

3. **Detect damage in complex, multi-functional structures**

   It is the opinion of this team that the satellite structures must be multi-functional to enable Responsive Space[6]. Many parallel efforts are underway to integrate electrical and thermal functions within a structural framework, allowing rapid satellite assembly and disassembly. The goal of these efforts is to allow simultaneous mechanical, electrical, and thermal connection between structural members and components. Additionally, the spacecraft structures under consideration utilize a honeycomb sandwich lay-up or isogrid architecture. The complexities of these architectures, as well as the presence of embedded circuit boards, electrical harnessing, heat pipes, fluid loops, etc., will only make the process of structural health monitoring all the more difficult.

   However, as previously discussed, the embedding of electrical harnessing and thermal management components will significantly reduce the amount of model uncertainty. Although this complicates the SHM task, it eases the dynamic modeling effort.

4. **Detect if mechanical and electrical interfaces are properly connected**

   Satellites typically feature numerous bolted interfaces. It is imperative, in lieu of traditional dynamic tests, that designers are able to ensure these mechanical fasteners are connected properly, e.g. are all the bolts in place and are they torqued properly? There is also sincere interest in using a greater number of bonded joints in satellite assembly, and these too, will need to be adequately assessed. Additionally, other satellite check-out procedures will need to be similarly truncated and SHM systems may prove beneficial for these other check-outs. As an example, the SHM system can ensure electrical connections are properly seated as a part of their continuity check.

Requirements 3 and 4 will likely leverage heavily from ongoing SHM research[12]. SHM systems are continuously able to interrogate more complex structures, and recent advances have shown an ability to detect very minute changes in bolt torques[13-18]. However, 1, and 2 may prove to be unique problems for Responsive Space, due to the inherent flexibility that this paradigm demands.

The current approach of AFRL/VS is focus on the unique aspects of ORS, thus maximizing the results from our investment in SHM technologies. For this reason, initial emphasis has been placed on developing systems and methodologies with the necessary flexibility to accommodate the ORS paradigm. Development of that configuration flexible system has fallen into two distinct thrusts: developing a flexible SHM system architecture and developing flexible detection methodologies that do not require baselines captured on “pristine,” geometrically identical samples. A robust SHM capability for ORS will require a system that is able to detect damage and out-of-spec conditions on satellites with a near limitless variety of configurations. The envisioned system will frequently be asked to detect flaws and damage on configurations it has never been taught.

The initial efforts described below, have focused on detecting structural flaws and the condition of bolted and bonded joints in aluminum isogrid and aluminum honeycomb panels, which are the leading near-term structural approaches. Additionally, anecdotal evidence suggests that the schedule of the ORS assembly process implies that out-of-spec bolted connections are likely the greatest source of risk for structural non-compliance.

Although this paper outlines a very difficult problem, it is important to note a couple considerations that must be taken into account to show that the problem may not be intractable.

1. The SHM system will only need to determine the region of damage, and not the specific location (i.e. specify the area of an out-of-spec mechanical connection, and not the particular bolt). Current satellite testing methods do not lend themselves to locating the source of the problem, so any directing on the part of the SHM system is of great benefit.
2. Specifically for mechanical connections, bolts will likely either be fully torqued or not torqued at all. ORS is likely to drive standard interfaces, with standard bolt torques, in order to ease the assembly process (i.e. all #10 bolts are torqued to one specified value, all #8 bolts are torqued to a different value). If that is the case, the SHM system will have to assess a binary situation (torqued versus not-torqued), instead of a problem with multiple intermediary solutions (Is the bolt torqued to the specified value?).

V. Current Technology Development Efforts

A. Configuration Independent Architecture

Acellent Technologies, of Sunnyvale, CA has been tasked with developing a SHM architecture that will work independent of the satellite's configuration. As mentioned before, a responsive satellite may take a near infinite variety of configurations, based on warfighter needs, technology readiness levels, satellite orbit, and a wide range of other associated factors.

The SHM technology developed by Acellent was used to develop a system that can be innovatively used to:

1. detect whether the panels are configured correctly
2. assess the structural integrity of the panels in real-time
3. rapidly assess structural integrity of satellite panels and components prior to launch

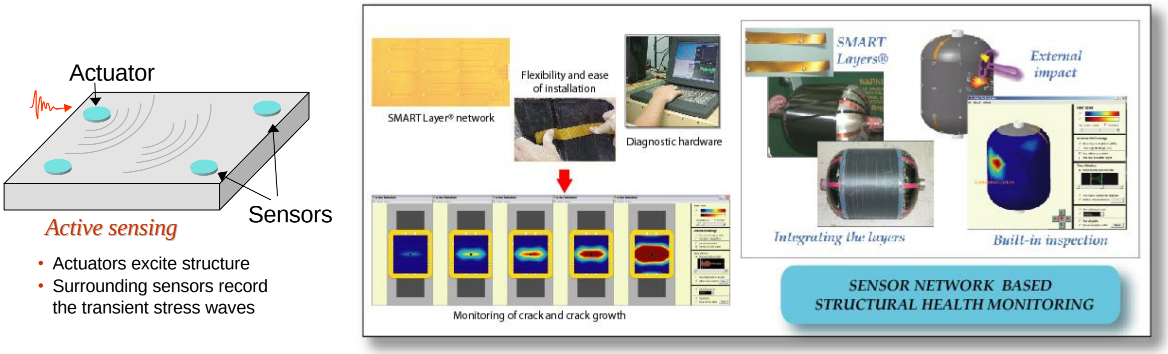

Figure 3. Functioning and example of usage of a Sensor network based SHM system

Acellent's system utilizes a network of distributed piezoelectric sensors/actuators embedded on a thin dielectric carrier film called the SMART Layer® to monitor and evaluate the integrity of a structure. A portable diagnostic unit is used to collect and process diagnostic signals obtained from the sensors/actuators during the monitoring process. The signals obtained can then be analyzed to determine the integrity of the structure. The functioning of the active sensing system is analogous to that of a built-in acousto-ultrasonic NDE with a network of miniaturized piezoelectric sensors. External factors causing changes in mechanical and/or thermal properties of a structure induce the piezoelectric actuators to emit diagnostic signals to neighboring piezoelectric sensors. These signals are subsequently transmitted to the diagnostic hardware for comparison with previously recorded baseline test signals obtained from the structure prior to its application. The diagnostic software uses the difference in these signals to identify the location and extent of damage or other structural anomalies. By using different signal processing techniques to process the diagnostic signals, information concerning the structure can be obtained. Figure 3 shows the functioning and usage of the piezoelectric network based SHM system.

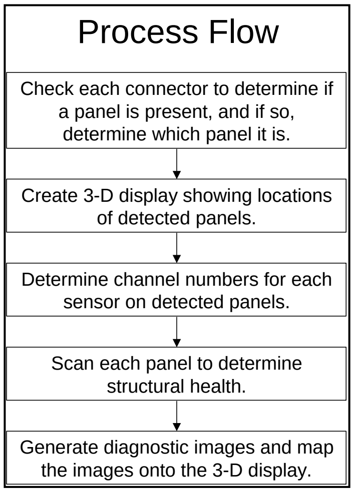

Figure 4: Acellent Process flow

Using the process flow depicted in figure 4, Acellent's system was able to discriminate multiple, simultaneous damage types (panel removal, relocation, or simulated damage) in near real time. Figure 5 shows the test hardware in its test configuration. The panels on the structure were color coded in white, blue, red, and grey for ease of identification.

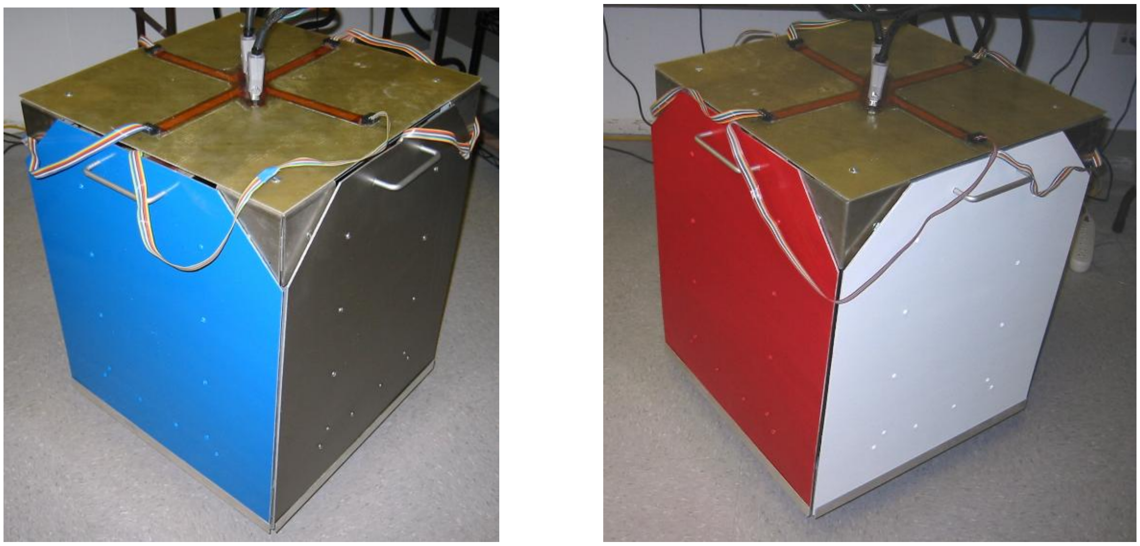

Figure 5. Test hardware for configuration independent SHM system

To test the system, a number of independent and simultaneous damage "events" were conducted. To illustrate, Figure 6 shows a test where the red panel was removed and simulated damage was placed on the blue panel. The system easily detected both problems for simple and focused corrective action.

Figure 6. Blue panel shown with simulated damage after Red panel is removed. *System is easily able to discern multiple simultaneous damage types*

The hardware demonstration shows Acellent's SHM system could be adapted to a reconfigurable structural concept to locate and assess damage, determine if the satellite is in the correct configuration, and direct potential maintenance action. This is extremely advantageous, given the configuration variability inherent to responsive space. Another advantage is that Acellent's approach enables real-time assessments of the structure, during storage. As stated before, this capability enables depot-like operations for ORS, and helps ensure the validity of the satellite dynamic model.

B. Configuration Independent Detection Methodology

Quartus Engineering Incorporated (QEI), in collaboration with the University of California-San Diego (UCSD), is presently developing a SHM capability designed to mitigate the lengthy Q/A certification and testing processes by assessing the integrity of adhesively bonded and bolted joint assemblies. Figure 7 illustrates the concept, where potential ORS satellite structures are pre-configured with sensor/actuators tied into a data acquisition system to continuously monitor, extract, and statistically quantify relevant data during satellite assembly.

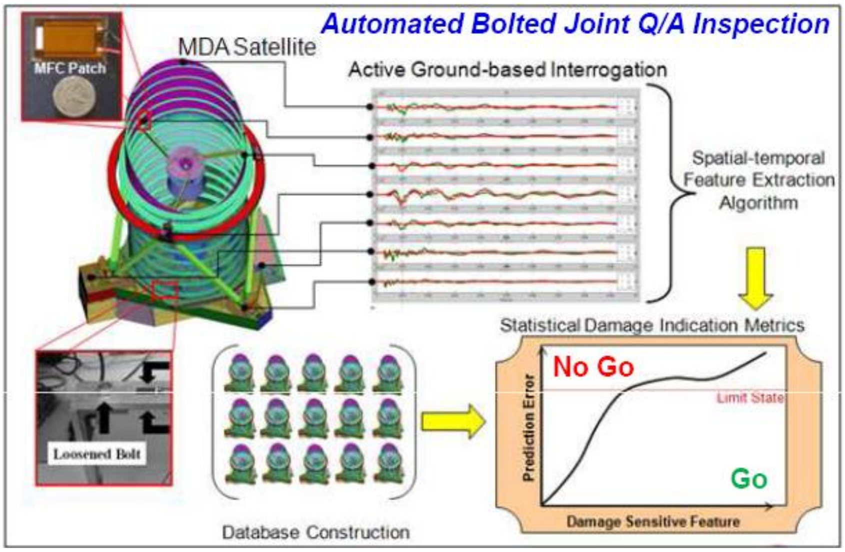

Figure 7: Conceptual SHM System Overview

The QEI/UCSD technology takes an online, data-driven approach to system verification/monitoring of bolted joints, namely, joint connectivity and bolt preload through the use of macro-fiber composite patches (MFC) and novel data processing[20]. MFCs were utilized for their wide bandwidth, ability to provide directional actuation/sensing, and flexibility (which allows conformal application to curved surfaces, as well as provides a high level of damage tolerance).

Using supervised learning on bolted assemblies, QEI/UCSD have developed trained computational algorithms that autonomously extract generalized correlation error features that directly couple to joint physics (preload or bond condition) and which compute statistical condition indication metrics (SCIMs), providing the user a quantifiable level of condition awareness. This is especially important given the highly variable operational and/or environmental fluctuation under which qualification could be executed. For similar structures, such as the envisioned modular satellite concept, caches of extracted features could be stored in database repositories to further enhance the sensitivity and overall performance of SCIMs for SHM in a continual on-line learning mode.

During the first phase of their effort, QEI/UCSD has successfully demonstrated the detection of bolt torques on a variety of structural configurations. Utilizing chaotic guided ultrasonic waves, in the 80 kHz range, the team used the mechanical interface as a filter. The resulting “filtered” signal was rich in features that showed extreme sensitivity to damage. The team investigated joints with multiple bolts and was able to correctly determine the torque status (loose, finger tight, or fully torqued to the specified value) for each bolt, on over 85% of the test cases run. If the problem statement was eased to the binary statement of “fully-torqued or not,” the system demonstrated an accuracy of 100%. This is a critical point, because as stated previously, ORS satellites will likely enable the use of the binary problem statement.

A particularly noteworthy item is that for this effort, the detection test cases were run on situations that had not been previously learned. This ability to correctly identify status, on conditions outside the learning set, shows extreme promise for implementation on potential ORS systems. Figure 8 shows the test set-up for the experiments investigating multiple bolted connections.

Results from this effort also suggest that non-linear techniques appear capable of reliably distinguishing damage from configuration changes. When using these techniques, damage events create specific non-linear features that are not readily created through more linear “engineering changes.” Additionally, these non-linear features may significantly improve the resolution of the interrogation scheme, due to their sensitivity and specificity. As stated before, it is critical that any SHM system with traceability to ORS be able to differentiate between flaw and potential changes in configuration.

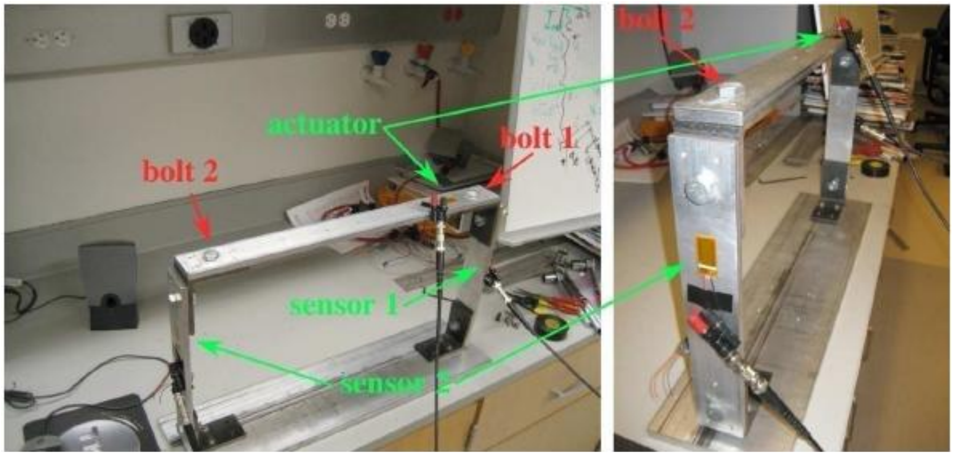

Figure 8. Multiple Joint Experimental Configuration

C. Basis Research on Acoustic Wave Physics through Bonded and Bolted Joints

A research team at the New Mexico Institute of Mining and Technology (NMT) is investigating physical properties of structural assemblies that would impact the assessment of a joint's integrity, enabling prediction of structural performance and assisting in determining qualification margins for structural envelopes. The proposed approach is illustrated in Figure 9, where physical properties measured with a SHM system would contribute into updating and validating the satellite structural model. The updated model, which carries information acquired from individual structural components, is utilized in modal analyses for particular satellite configurations. The ability of the SHM system to determine actual physical properties (e.g. material parameters) is important because of a direct connection to physics-driven theoretical descriptions that form a basis of large-scale analytical and numerical models used in satellite qualification. Availability of such properties could potentially enable an estimate of satellite structural dynamics from the data furnished by the SHM system.

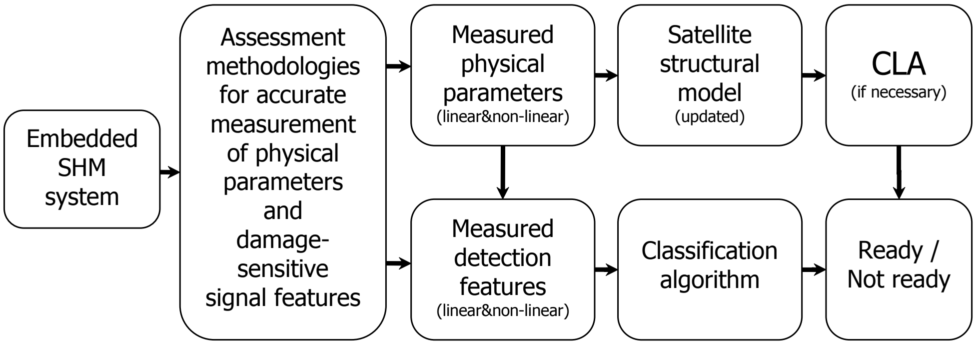

Figure 9: Proposed integration of SHM data into satellite structural model and condition assessment algorithm

Current research activities at New Mexico Tech are focused on the fundamental aspects of joints behavior and utilizing relevant physical parameters for structural integrity assessment. In the bolted joint experiment depicted in Figure 10, a pair of piezoelectric active sensors was utilized to study elastic wave propagation through the joint. The elastic wave data was acquired at various levels of torque applied to the joint. Results of the test, as presented in Figure 10, show a dependence of the damage detection feature versus the applied torque. Red dots in the figure represent measurement points calculated as average values of 8 tests. Experimental investigation revealed a distinct dependence of the elastic wave data on the torque in the joint and indicated opportunities in quantifying the load. Further studies are directed towards understanding behavior of the bolted joints in complex structures.

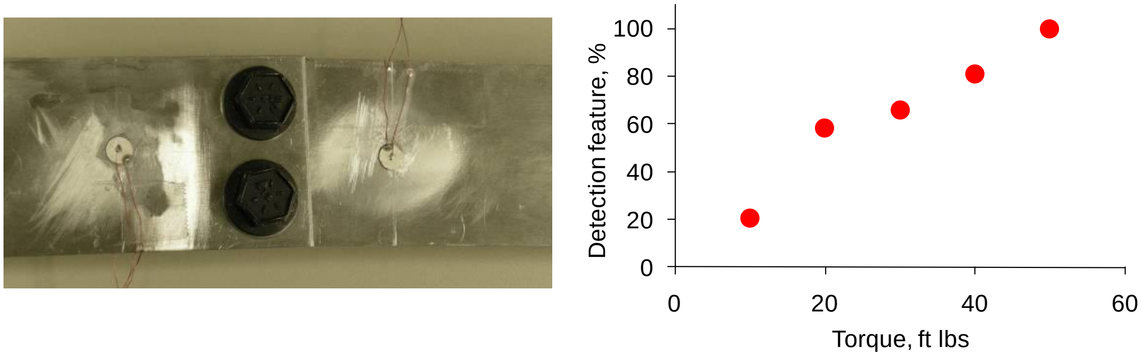

Figure 10: Tests on simple bolted joints. *On the left, a bolted joint with piezoelectric active sensors bonded to the surface. On the right, results of the joint integrity test showing dependence of detection feature on applied torque*

Epoxy joints were simulated using Hysol® EA 9309NA epoxy and aluminum panels similar to those presented in Figure 10. Two specimens were considered: a specimen with the intact bond and a specimen with de-bonded area of approximately 1 square inch. Piezoelectric active sensors were installed 1 inch away from the edge of the lap joint. An additional receiving sensor was placed at the distance of 7 inches or 1 inch from the end of the plate. Figure 11 provides comparison of the spectral data obtained from the good bond (GE3), the bad bond with a sensor located near the joint (BE3) and the bad bond with a sensor located far away from the joint (BE4). The figure indicates a substantial level of higher harmonics typically associated with the nonlinear behavior. It is possible that spectral features reflecting the system's nonlinearity may be used to discriminate good and bad bonds.

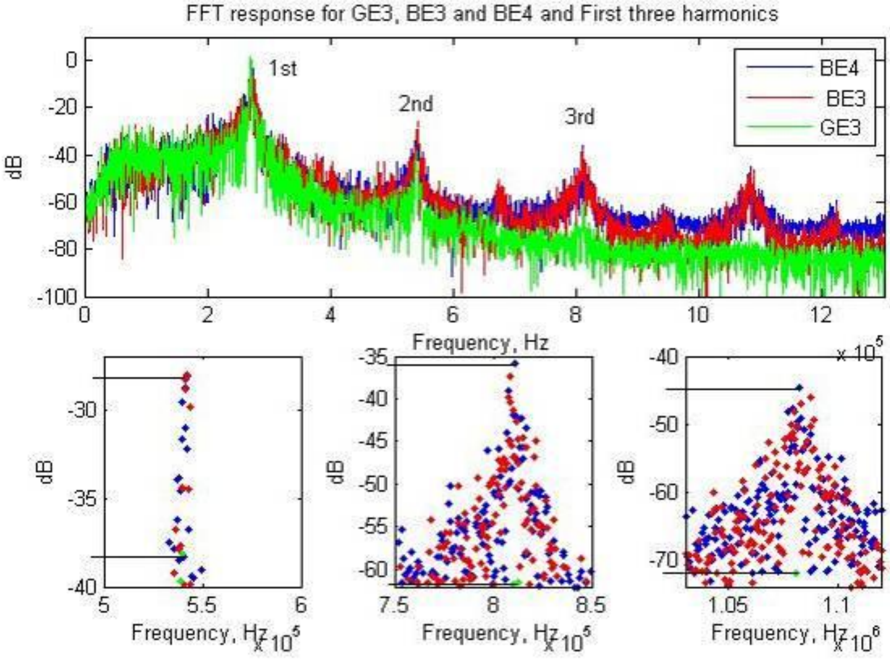

Figure 11. Spectral characteristics of good (GE3) and bad (BE3 and BE4) bonds.

This effort has also initiated research activities using a representative structural panel. The clam-shell orthogrid panel, pictured in Figure 12, adds a great deal of complexity to the task of modeling and analyzing the propagation of acoustic waves. However, this test article will help demonstrate how a significant non-linear damage feature can be culled from an overwhelming amount of data. Each rib and hole in the panel, as well as the interface between the clam-shell halves of the panel, will produce reflections. A successful method must be able to pull the true marker of damage from a virtual torrent of propagating acoustic waves.

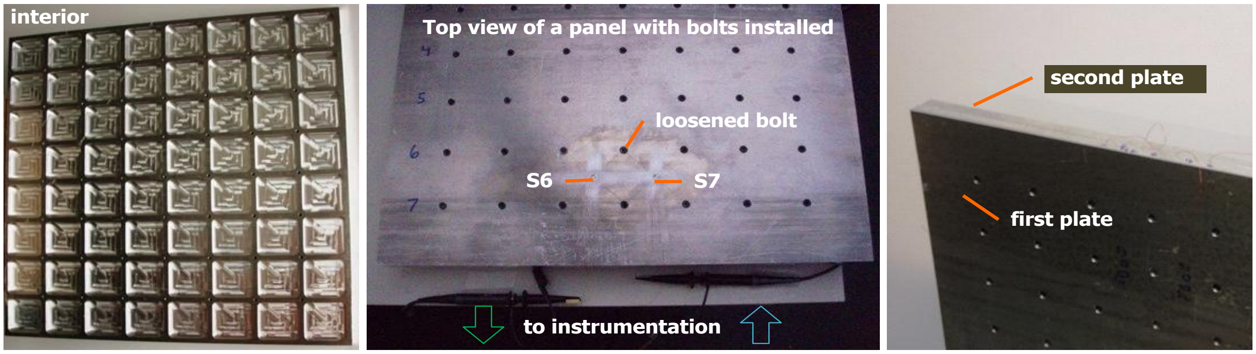

Figure 12. Orthogrid satellite panel comprised of two aluminum clam-shelled halves

VI. Potential to Interrogate Thermal Interfaces

During the development of this paper, a novel idea occurred to the members of this team; could the same type of process also be used to obviate the requirement for a dedicated Thermal-Vacuum (thermal-vac) test? Thermal-vac testing is employed to ensure the thermal management system is able to operate and control component temperatures sufficiently, throughout the extremes of the anticipated thermal environment. Additionally, certain tests and specific steps are conducted during a thermal-vac, because they are impossible to perform without pulling a vacuum; e.g. determining if entrapped air will cause a component to fail or allowing parts to outgas/bake-out (e.g. removing moisture content for a composite part). However, this testing is time-intensive, requires significant test capabilities, and does not conform to the timelines of ORS (specifically the Tier 2 time objectives); for test chambers sized for ORS-class satellites, the mere act of pumping down to vacuum typically takes at least 3 days.

As a first step, a sensible approach to ORS might dictate that components either not require pre-flight time in a vacuum, or be previously validated in a vacuum environment. This might help to alleviate the other requirements for performing a dedicated thermal-vac test for every satellite. However, removing the purely thermal requirement for a Thermal-Vac test is still a daunting task. As a first-order approximation, radiation is a function of Temperature to the Fourth power, as opposed to dynamics, which are a function of the Mass squared. This could imply that acceptable margins of error are significantly lower than they are in the case of a dynamic model.

Initial investigations are underway to determine if a process, similar to the one laid out in Section III, could help alleviate the requirement for Thermal-Vac testing. Much like the dynamic case, a satellite thermal model would benefit greatly from component level characterization testing. And again, the primary source of uncertainty would reside at the interfaces. For the vast majority of components, the primary mechanism for heat transfer from a component to the underlying structure is conduction. Additionally, a number of thermal management schemes for ORS rely purely on conductive heat transfer between structural members. Because of this, the current train of thought is that methods for interrogating interfaces may help to significantly reduce that uncertainty. For thermal management systems that require fluid transfer across structural members, a simple leak test, with a small molecule (Helium is often used because of its inert nature and small atomic size) can be performed.

As for developing a method to interrogate thermal interfaces, it may require a level of complexity beyond that of the mechanical interfaces. In terms of heat transfer, conduction over an interface is largely a function of contact area and pressure. If the thermal model is to be verified, without a dedicated Thermal-Vac test, a detailed pressure map will need to be produced for every critical thermal connection. It is important to note that these pressure maps may need to cover a relatively large contact surface. Additionally, the means for producing that pressure map must be unobtrusive, flexible to accommodate the nearly limitless potential configurations of ORS, suitable for spaceflight, and not significantly degrade the thermal conductivity of the interface itself.

Being able to circumvent both dynamic and thermal-vac testing would convey significant advantages to ORS. Each of the tests can typically take at least a week to conduct; therefore neither conforms to the objective timelines of ORS. As stated before, assessing thermal interfaces is an entirely new direction for our research. However, the outlook appears promising given the synergy with existing dynamics efforts, and the fact that initial queries suggest the possibility of technical solutions. Further studies are required to fully understand the technical and process impediments that must be overcome in order to mitigate the requirement for a thermal-vac test on ORS satellites.

VII. Conclusions

Structural Health Monitoring is a critical technology for enabling Responsive Space. Current methods to assess the satellite's structural surety are not amenable to the short timelines of Responsive Space. When a mission is requested, the SHM system provides input, bounding the uncertainty of the interfaces in the satellite dynamic model. Additionally, the SHM system will be required to validate the assumptions within the model; primarily that the structure is not damaged, and assembled according to specifications. SHM systems can also be used to perform periodic checks on the structural components, providing feedback on storage condition and component health. SHM may not only help to truncate test requirements, it can also direct rapid repair actions, and allows other check-out procedures to be run in parallel.

In order to reach its full potential, the SHM system must be able to detect and assess flaws in complex, multifunctional structures, as well as interrogate numerous mechanical connections. Improving the resolution and reliability of SHM systems may reduce the amount of structural margin that must be built into the structure (translating into reduced mass and cost), because it translates into decreased uncertainty in the dynamic model of the satellite.

Operationally Responsive Space drives unique requirements on its SHM system. Applicability to ORS implies the SHM system must be amenable to a wide range of satellite configurations, missions, and architectures. The ultimate SHM system will be designed to work on a structure for which it has no, or very minimal, a priori knowledge. The system will essentially "go in blind," get pertinent information regarding the configuration of the satellite through interaction with the Satellite Design Tool, and be expected to perform its job of detecting, locating, and analyzing damage. This team cannot think of another application where the SHM system is expected to perform such a complex mission with so little upfront information.

A final point to mention is that all of the above tasks can be accomplished by developing a SHM system that operates only during pre-flight operations. These systems can be designed to operate with dedicated ground support equipment that could plug into the satellite, much like present day car diagnostics. However, significant additional benefits can be garnered by making the SHM system a stand-alone component within the satellite. Initially, it is recommended that these satellites carry excess structural margin in order to help ease the testing and validation requirements. Monitoring of the structure, during the launch sequence, may indicate where some of that margin may be reduced in order to provide a more mass-efficient structure. This data may also be used to further validate the models and reduce model uncertainty. Additionally, a SHM system may provide valuable status and environmental information when used on-orbit; providing our satellites unprecedented situational awareness.

VIII. References

[1] "Plan for Operationally Responsive Space; A Report to Congressional Defense Committees," *National Security Space Office*, 17 April 2007.

[2] Lyke, J. et al, "Space Plug and Play Avionics," Paper RS3-2005-5001, *Proceedings of the 4th Responsive Space Conference*, April 2006

[3] Williams, A., and S. Palo, "Issues and Implications of the Thermal Control System on the 'Six Day Spacecraft,'" *Proceedings of the 4th Responsive Space Conference*, April 2006

[4] Reilly, J., and Y. Terrance, "Autonomous Operations for Responsive Spacecraft," *Proceedings of the 4th Responsive Space Conference*, April 2006

[5] Strunce, R., et al, "Responsive Space's Spacecraft Design Tool (SDT)," *Proceedings of the 4th Responsive Space Conference*, April 2006

[6] Arritt, B., et al., "Development of a Satellite Structural Architecture for Operationally Responsive Space," *SPIE Smart Structures and Materials and Nondestructive Evaluation and Health Monitoring,* March 2008

[7] Sarafin, T.P., P.G. Doukas, "Simplifying the Structural Verification Process to Accommodate Responsive Launch," *Proceedings of the 5th Responsive Space Conference,* AIAA-RS5 2007-5003, April 2007.

[8] Hasselman, T.K., R.N. Coppolino, and D.C. Zimmerman. "Criteria for Modeling Accuracy: A State-of-the-Practice Survey", *18th International Modal Analysis Conference*. 2000. San Antonio, TX.

[9] Bergman, E. J., M. S. Allen, D. C. Kammer & R. L. Mayes, "Probabilistic Investigation of Sensitivities of Advanced Test-Analysis Model Correlation Methods," *26th International Modal Analysis Conference* (IMAC XXVI), Orlando, Florida, Feb. 2008

[10] Robertson, et al, "Cable Effects on the Dynamics of Large Precision Structures", *48th AIAA/ASME/ASCE/AHS Structures, Structural Dynamics and Materials Conference*, Honolulu, HI, April 23-26 2007, AIAA Paper 2007-2389

[11] Chebli, H. and C. Soize, "Experimental Validation of a Nonparametric Probabilistic Model of Non-Homogeneous Uncertainties for Dynamical Systems", *Journal of the Acoustic Society of America*., **115**(2) 697-705 (2004)

[12] Derriso, M., S. Olsen, “The Future Role of Structural Health Monitoring for Air Vehicle Applications,” *Structural Health Monitoring 2005, Advancements and Challenges for Implementation.* Proceedings of the 5th International Workshop on Structural Health Monitoring, September 2005

[13] Todd, M. D., et al., “Vibration-based Damage Assessment Utilizing State Space Geometry Changes: Local Attractor Variance Ratio,” *Journal of Smart Materials and Structures,* October 2001

[14] Fasel, T. R., et al.,“Piezoelectric Active Sensing using Chaotic Excitations and State Space Reconstruction,” *Proceedings of the SPIE,* 2005

[15] Clayton, E. H., et al., “Active Joint Integrity Adjudication for Real-Time Structural Health Monitoring,” *SPIE Smart Structures and Materials and Non-Destructive Evaluation and Health Monitoring,* Mar 2008

[16] Giurgiutiu, V. “Embedded NDE with piezoelectric wafer active sensors in aerospace applications*,” Journal of Materials*, on-line publ. JOM0301, 2003

[17] Guyott, C.C.H., et al., “The non-destructive testing of adhesively bonded structures: a review,” *Journal of Adhesion* **20**, 129-159, 1986

[18] Matt, H., et al., “Ultrasonic guided wave monitoring of composite wing skin-to-spar bonded joints in aerospace structures,” *Journal of the Acoustic Society of America*., 118, 2240-2252, 2005

[19] Overbey, L. A. and M. D. Todd, “Analysis of Local State Space Models for Feature Extraction in Structural Health Monitoring,” *Journal of Structural Health Monitoring, In Press,* 2006

[20] Clayton, E. H., et al, “Off-the-shelf modal analysis: Structural health monitoring with motes,” *Proceedings of the 24th International Modal Analysis Conference,* 2006

[21] Clayton, E. H., et al “Frequency correlation-based structural health monitoring with smart wireless sensors,” *M.S. Thesis, Washington University in St. Louis,* May 2006

[22] Clayton, E. H. et al., “Damage detection and correlation-based localization using wireless sensor mote sensors,” *Proceedings of the 13th Mediterranean Conference on Control and Automation*, 2005

[23] Qian, Y. et al., “Experimental study on localization and quantification of structural damage using Zigbee motes,” *Third European Workshop on Structural Health Monitoring*, July 2006.