

# **Responsive Satellites and the Need for Structural Health Monitoring**

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## **ABSTRACT**

The United States is developing an Operationally Responsive Space (ORS) capability. The goal is to deliver tailored spacecraft capabilities to the warfighter as needs arise. This places a premium on the timespan between generating that requirement and having a functioning satellite performing its mission on orbit. In order to meet this timeline, the satellite flight qualification and launch vehicle integration process needs to be dramatically truncated. This paper describes the Air Force Research Laboratory's attempts to validate the use of Structural Health Monitoring (SHM), in lieu of traditional structural flight qualification testing schemes (static and shock loads, random vibration, coupled loads analysis), for potential Responsive Space (RS) satellites.

## **INTRODUCTION**

### **Attributes of Operationally Responsive Space**

The Department of Defense is actively pursuing an Operational Responsive Space (ORS) capability. The attributes of a robust ORS capability are [1]:

1. Provide data products to the warfighter in 6 days. This timeline includes tailoring the satellite for the specified mission, testing, integrating onto the Launch Vehicle (LV), launch operations, and on-orbit satellite check-out.
2. Low total mass and low mission costs. Mass and cost must remain low to allow these satellites to take advantage of existing LV designs, achieve a truncated call-up process, and remain cost effective for theater commanders.

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3. Satellites must be capable of tasking and data dissemination utilizing existing infrastructure; ORS is no longer cost effective if an entirely new infrastructure is required to operate the satellites.
4. Satellites are taskable by theater commanders/forces; likely the greatest paradigm shift related to ORS. The satellite is now the asset of the theater commander, and not under the control of operators in the Continental US.
5. Missions are tailored for the specific theater of operations. The satellite's data product (i.e., imaging, communications, blue-force tracking, etc.), orbit, concept of operations, etc., are all tailored to suit the needs of the warfighter.

ORS will allow our warfighters to directly utilize the space environment and provide an unprecedented level of capability and battlefield situational awareness. ORS is surgical in nature, providing additional capabilities precisely where they are needed. It ensures the troops in the field can take full use of the unique capabilities of space assets. ORS also provides us a capability to perform rapid replenishment of space assets, should they suddenly be taken off-line.

### **AFRL/VS Technology Approach**

There are many potential methods for implementing an ORS capability. The simplest is to use stockpiles of completely built satellites to provide this capability. Unfortunately, this is the most costly solution, induces risks associated with obsolescence, and limits the variety of missions that can be performed. On the other end of the spectrum are modular satellites that are largely designed and assembled after getting the "call" from a theater commander. This approach implies a requirement for robust satellite design tools, capable of reducing a tremendously complex problem into a matter of hours, an infrastructure that allows a satellite to "come together" in a very short amount of time, and a very abbreviated (and often incomplete) testing process.

The Air Force Research Laboratory/Space Vehicles Directorate is developing technologies that allow a more modular approach to Responsive Space satellites. Although this path is more technically difficult, it provides greater capability and flexibility for our national defense. Current research efforts include the development of satellite design tools, Plug-and-Play Avionics[2], autonomous satellite control methodologies, thermal management schemes[3], rapidly configurable structures, standard interfaces, and "Responsive" components and payloads. The goal of these efforts is to develop a technology infrastructure that allows a satellite to be rapidly designed, assembled, tested, integrated, and checked-out on orbit. These technologies are focused on allowing flexibility in mission-type, duty cycle, orbit, and configuration, as well as using open standards so that new technologies can be incorporated as they come on-line.

### **Structural Surety Process**

A satellite that is built upon request (or even one that is stored for significant periods of time) will present many opportunities for non-optimal structural performance. Storage, shipping, and handling all carry potential damage liabilities, but the most concerning is the satellite Assembly, Integration and Test (AI&T)

process. In order to meet the timelines of ORS, these satellites must be assembled rapidly. This fast-pace implies that much of the care and Quality Assurance (QA) currently taken in assembling satellites will simply not be feasible due to time constraints. Additionally, the satellite will likely have to be “opened” repeatedly to accommodate component swap-outs due to upgrades, “hiccups” (highly likely due to extended storage periods and lesser care due to rapid assembly activities), or last-minute changes in mission requirements (probable due to the fluidity of battlefield data requirements). This will only exacerbate the likelihood of structural damage or out-of-spec connections.

Typically, the suitability of 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-size satellites, this test is often “validated” through analysis, or results from dynamic tests.
2. The environmental, or dynamic, tests assess the satellite’s ability to survive the launch segment. 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. The entire testing and analysis “process typically takes three or more years[4].”

The current structural approaches for making a satellite acceptable for launch can largely be binned into three basic design philosophies; make a “rock,” “test, test, test,” and a middle position that takes some elements from both approaches.

1. “Rock:”  
Implies making a satellite so stiff and strong that it can be modeled as a lumped mass in the coupled loads analysis. This approach is typically only feasible for very small satellites (< 100 kg), and tends to be mass prohibitive for larger ones. Do to the wide range of potential missions, payloads, and configurations within the confines of Responsive Space, this is likely not feasible.
2. “Test, Test, Test:”  
Typical of large satellites, where structural margins tend to be small. Errors in the models are such that mission planners and launch service providers require all of the above testing in order to ensure successful launch and on-orbit operations. Many large satellites have even had to incur retrofits due to faults discovered during the conduct of these tests and analyses. Timelines make it infeasible for Responsive Space.
3. Middle Ground:  
Many microsats (100-1000 kg class) are designed to have extra margin for certain loading scenarios. This extra margin allows many of these satellites to avoid static loads testing. Additionally, increasing the fundamental frequency of the satellite greatly simplifies CLA and provides maximum flexibility for potential launch opportunities (which are often hard to come by for these smaller satellites). A modification of this approach will likely be pursued for Responsive Space.

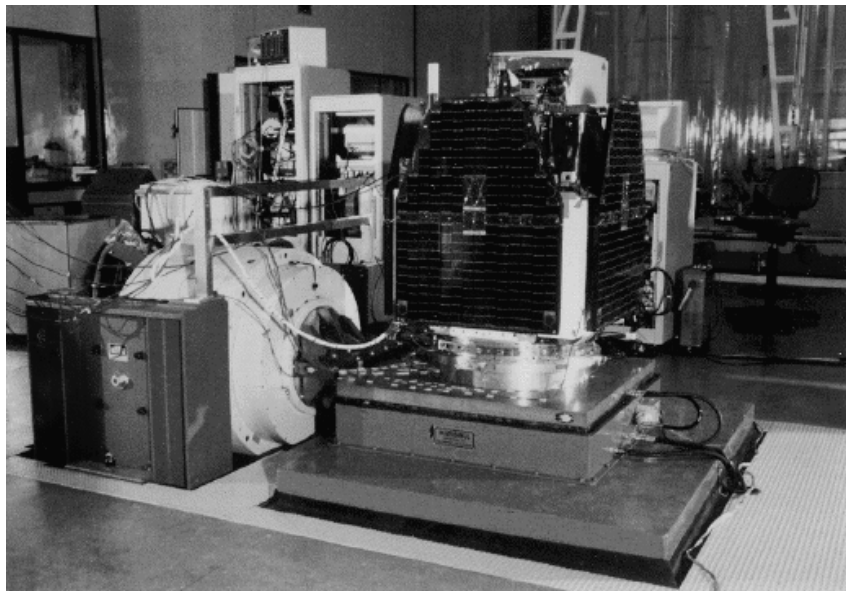


Figure 1. SAC-B satellite on horizontal shake table

It is the authors' contention that structural health monitoring will prove critical for determining a responsive satellite's ability to survive the launch sequence. 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 the "6-Day Satellite" concept. Additionally, unlike

traditional loads testing, SHM can pinpoint the location, type, and severity of damage, enabling rapid component swap-out, and “go/no-go” decisions.

## **PROPOSED IMPLEMENTATION OF SHM**

SHM is by no means a panacea. It will not allow designers to avoid all tests and analyses entirely; rather the authors are attempting to use SHM to minimize the time associated with these tasks. Additionally, such a methodology will imply that a healthy safety margin is designed into the satellites to ease the validation process.

A proposed implementation would require a “variational CLA” (vCLA) be performed for each potential launch vehicle [4]. Each vCLA would vary satellite mass, center of mass location, and fundamental frequency to determine an envelope, within which a satellite can be expected to not couple deleteriously with the launch vehicle. These envelopes would then set the bounds to which a responsive satellite design must conform.

However, if traditional validation methods are pursued, structural testing must still be performed to validate the satellite’s fundamental frequency, strength, and integrity of components [4]. It is our position that “responsive” components should be designed and tested to the highest anticipated load levels, with appropriate margin, to obviate the requirement for mission specific testing. Additionally, this class of satellites is stiffness, and not strength-driven (especially in light of the previously defined vCLA envelopes, and their high fundamental frequency requirement), so strength verification will likely be considered superfluous. However, the structure’s fundamental frequency will still need to be verified. Fortunately, with proper utilization of “design of experiments,” it is possible to verify a broad range of potential satellite configurations, by “pre-testing” a few of the most stressing configurations.

Additionally, some SHM systems may prove capable of assessing the satellite’s modal properties; i.e. the fundamental frequency. If this is proven out, it may help obviate the need for any and all structural testing for responsive satellites.

When the call comes to rapidly assemble a satellite, the SHM system will be called upon to verify that the assumptions and conditions of the “pre-test” are valid for the satellite preparing for launch. Namely, are the structural members undamaged, are mechanical and/or electrical connections in accordance with the specifications, and are components placed such that they conform to the mass model of the satellite (to confirm the location of the center of mass). In essence, SHM will be utilized to assess the workmanship baseline of the satellite.

It is anticipated that these SHM tests will take a matter of hours, and can be conducted while other satellite systems are being checked. Additionally, SHM provides a capability that is not available through other means; if there is a fault, the SHM system will pin-point the location, type, and severity of the fault. This is helpful in that repair action can be immediate (it may be as simple as tightening a bolt), without a requirement to first locate the fault. A dynamic test, on the other hand, 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.

Additional benefits can be reaped from integrating a Structural Health Monitoring system. An SHM system can assess shipping and storage conditions, providing continuous feedback for potential corrective action. If a structural component is swapped out of a satellite, the SHM system can determine if the assembly/disassembly sequence resulted in any damage to that component. All of the above tasks can be accomplished by developing a SHM system that operates by connecting the satellite structure to ground support equipment. However, additional benefits can be accrued by making the SHM system a stand-alone component within the satellite. As alluded to earlier, these satellites will likely have excess margin in order to ease the testing 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 validate the models and further reduce the test (or “pre-test”) burden on future satellite iterations. Additionally, a SHM system may provide valuable status and environmental information when used on-orbit, providing our satellites unprecedented situational awareness.

## **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 the “6-Day Satellite” will require that the SHM system be able to accomplish the following:

1. Interface with the Satellite Design Tool:  
The Satellite Design Tool will be tasked with developing the assembly instructions for the satellite. The SHM system will have to take information about the satellite’s configuration, characteristics and placement of components, attachment schemes, etc., 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 and payload placements and fastener locations. It must be able to take information from the design tool and utilize it in order to perform its health assessment tasks. This will place a premium on the SHM system’s learning process. The learning set will never be able to cover all potential configurations, so care must be taken to make the “lessons” as extensible as possible.
3. Detect damage in complex, multi-functional structures  
It is the opinion of this team, that the satellite structure must be multi-functional, in order to enable Responsive Space. 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, many spacecraft structures utilize a honeycomb sandwich lay-up, or isogrid architectures. 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.

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? Additionally, as stated before, other satellite check-out procedures will need to be similarly truncated. SHM systems may prove beneficial for these other check-outs; e.g. the SHM system can ensure electrical connections are properly seated as a part of their continuity check.
5. Assess system-level modal properties  
One of the key outputs of the dynamic tests are the modal properties of the satellite (primarily the fundamental frequency). To circumvent the requirement for any dynamic testing, the SHM system must provide independent verification of a satellite's fundamental frequency.

Requirements 3, 4, and 5 will likely leverage heavily from ongoing SHM research [5-15]. 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 and assess the modal properties of simple systems at higher frequency regimes. However, 1 and 2 may prove to be unique problems for Responsive Space, due to the inherent flexibility that this paradigm demands.

## CURRENT TECHNOLOGY DEVELOPMENT EFFORT

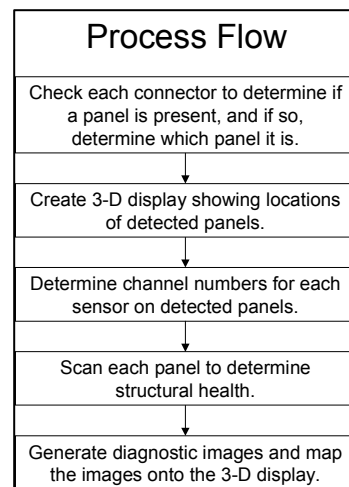
### Configuration Independent Architecture

Acellent Technologies, of Sunnyvale, CA is 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, etc.

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 2 shows the configuration of the structure used to demonstrate the capabilities of the developed system. The panels on the structure were color coded in white, blue, red, and grey for ease of identification. Using the process flow depicted on the right, the



system functionality for panel and damage detection can be seen for any combination of panel removal, relocation, or damage level. To illustrate this, the red panel was removed and simulated damage was placed on the blue panel. The system easily detected both “problems” for easy corrective action.

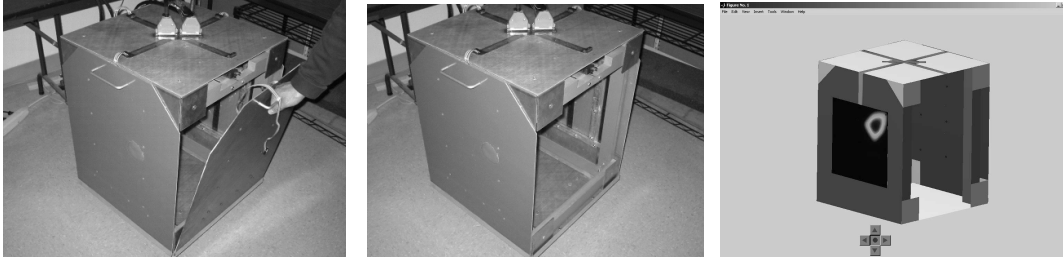


Figure 2. Blue panel shown with simulated damage after Red panel is removed.

The hardware demonstration shows Acellent’s SHM system could be adapted to an inter-changeable structure to locate position, type, and damage in satellite panels. This is extremely advantageous, given the configuration variability inherent to responsive space.

### **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 for adhesively bonded and bolted joint assemblies. Figure 3 illustrates the concept, where a potential “6 – day satellite” is pre-configured with sensor/actuators tied into a data acquisition system to continuously monitor, extract, and statistically quantify relevant data during satellite assembly [6-9].

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. Using supervised learning on bolted assemblies, QEI/UCSD are developing 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.

Algorithm performance and validation is presently under investigation through both explicit 3D numerical simulations and experimental ‘through-the-joint’ test configurations designed to assess the ability to simultaneously monitoring multiple joint interfaces. The underlying goal of this approach is to detect, locate, and assess

defects in bolted and adhesively bonded joint assemblies, with quantified uncertainty, within an architecture that can be implemented in-situ.

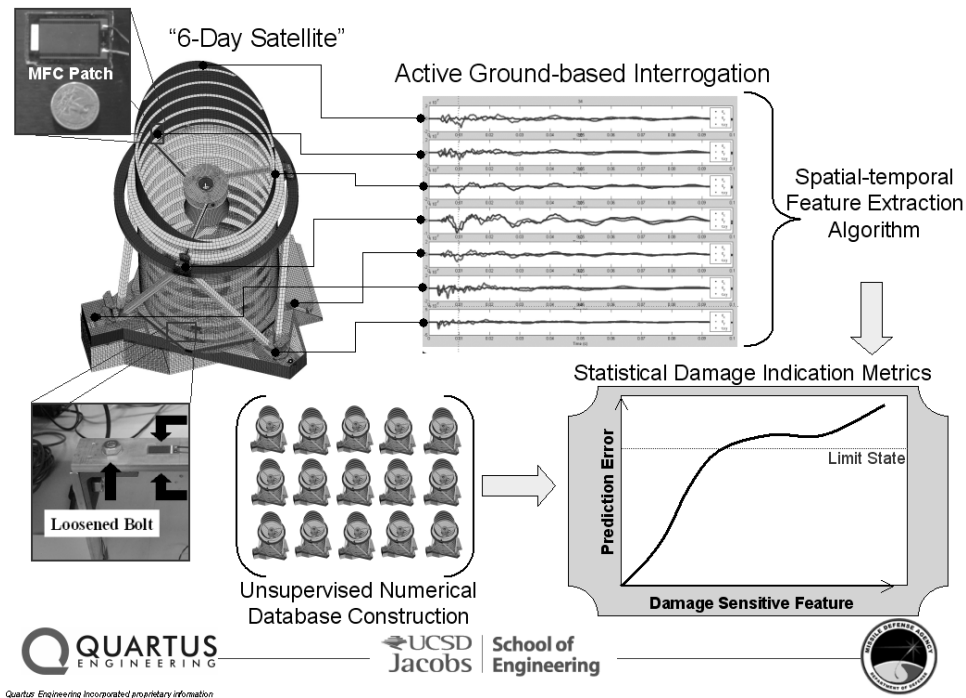


Figure 3: Conceptual SHM System Overview

## CONCLUSION

Structural Health Monitoring may be 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. SHM may allow us to perform prior testing and analysis to develop envelopes of acceptable satellite structural behavior (fundamental frequency, mass, center of mass location, etc). When a mission is requested, the SHM system can perform an immediate assessment of the satellite’s structure to ensure it conforms to a pre-established envelope. SHM can not only 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, be able to interrogate mechanical connections, and assess system level modal properties. Improving the resolution of the SHM system reduces the amount of structural margin that must be built into the structure (translating into reduced mass and cost), reduces the amount of “pre-testing” that must be performed, and increases the configuration flexibility of potential responsive satellites.

Responsive Space may drive unique requirements on its SHM system. Applicability to Operationally Responsive Space implies that 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.

SHM may also be able to provide other benefits to the satellites. Data from the SHM system may lead to structural revisions that reduce excess mass and provide our assets an unprecedented level of on-orbit situational awareness. SHM can provide our satellites with game-changing capabilities; we are just now starting to see these benefits. It will be exciting to see what additional benefits can be construed once we scratch below the surface.

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