

Structural Health Monitoring Systems for Inflatable Softgoods Space Structures

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ABSTRACT

Habitats are an essential component of any human spaceflight mission, called upon to provide the maximum amount of livable volume with the minimum amount of mass. Inflatable, deployable structures in particular have been investigated by NASA since the early 1950s and used in a number of spaceflight applications. Inflatable habitats, airlocks, and space stations can be used for in-space living quarters and surface-exploration missions. Inflatable structures are being pursued as candidates for long-term habitats in space and on the surfaces of the Moon and Mars. Many concepts by NASA and industry utilize high-strength, low-weight softgoods materials, such as Vectran, as the primary load-bearing structure in inflatable habitats. The ability to monitor and assess the structural health and integrity of an inflatable module is an important factor in determining the feasibility of using these technologies for space habitats, especially in the presence of micrometeoroid and orbital debris (MMOD) threats. There is therefore a critical need for Structural Health Monitoring (SHM) methods to perform detection, localization, and quantification of damage to structural layers throughout the mission. This capability must be accomplished within real constraints for sensor volume, mass, and crew resources, including being able to perform effective damage monitoring of the inflatable habitat layers from the interior during a mission, either on a routine or quick-response basis.

This paper discusses the design of new SHM sensor modules (consisting of co-located piezoelectric transducers and strain-gauge sensors) for inflatable softgoods and integration of a complete SHM system into inflatable habitat test articles for laboratory proof-of-concept testing. An experimental test setup for performing the initial feasibility demonstration of impact detection using the SHM sensor modules is discussed. Testing for high strain and impact detection was also conducted. The project demonstrates the feasibility of the newly-developed SHM sensor modules to provide impact detection and strain/load monitoring on inflatable softgoods for next-generation space habitation structures.

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INTRODUCTION

Inflatable structures are being pursued as candidates for long-term habitats in space (Figure 1). The ability to monitor and assess the structural health of an inflatable module is an important factor in determining the feasibility of using such technologies for human habitat, especially in the presence of micrometeoroid and orbital debris (MMOD) threats. Flexible, hybrid Structural Health Monitoring (SHM) systems—which focus on the design, manufacturing, and integration of electronics and sensors—are essential for addressing some of the major impediments and challenges facing integration of multifunctional sensors and monitoring technologies into space habitat structures.

This project focuses on development of flexible multifunctional SHM systems for inflatable space habitat structures. The development will enable integration of sensing capabilities in inflatable softgoods material systems that are needed to monitor the structural performance of the material *in situ*, measure load/strain on softgoods components, detect damage, and predict further degradation/potential failures. The ability to acquire, process, and make use of this data in real time is an important risk mitigation for potential structural failure modes.

SENSOR DESIGN

The development of SHM sensors for inflatable space structures builds upon the development of previous SHM systems based around piezoelectric (PZT) transducers and strain-gauge sensors. Current SHM systems utilize flexible printed circuits but do not have the flexibility or the footprint to be stretched out over large areas for installation or embedded within materials. The uniqueness of the proposed development is that it includes an embeddable, state-of-the-art, ultra-thin actuator/sensor network with multiple sensing elements that can be integrated with an inflatable structure without affecting its structural integrity.

The primary goal was to identify and develop processes for integration of the sensor network with inflatable Vectran materials. This sensor network was to be designed to:

- Be flexible yet strong to conform to different shapes;
- Supply adequate sensor density to cover the entire area of the inflatable with high resolution;
- Be embeddable for integration with the inflatable materials;



Figure 1. Example of inflatable space habitats (courtesy of ILC Dover).

- Withstand mechanical and thermal environments experienced in fabrication, storage, and usage;
- Maintain overall network functionality if a local sensor/network failure occurs;
- Provide accurate sensor measurements;
- Be capable of hosting multiple types of sensors (e.g., PZT, strain, and temperature);
- Be scalable to commercial scale.

A conceptual design for a hybrid PZT and strain-gauge sensor package based on these criteria was developed as shown in Figure 2. The design assumes that built-in wiring can be used to connect to these sensors to the data-acquisition electronics for power and measurement. Once manufactured, the sensor packages can be sewn onto the Vectran fabric in any location, like a button.

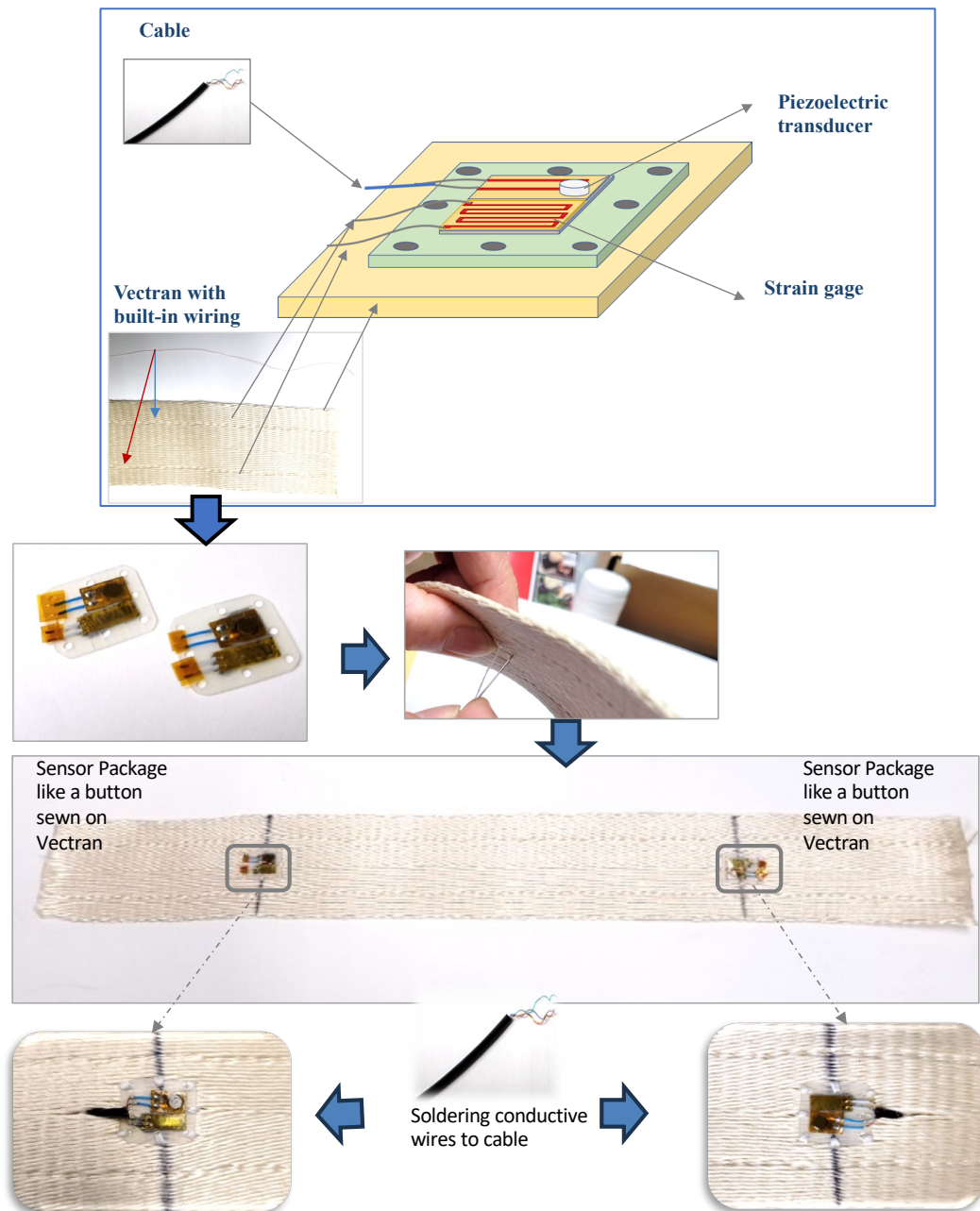


Figure 2. Preliminary design and integration of the sensor package with the Vectran webbing.

DATA ACQUISITION

Accellent's IMGenie Pro data-acquisition hardware was used throughout this project to provide impact detection and load/strain monitoring. It supports fully-simultaneous sampling from up to 32 PZT sensors at rates of 1,000 to 30,000 samples per second (sps), a resolution of 16 bits, an input range of ± 45 V, and integrated filtering. In addition to PZTs, the IMGenie Pro also supports acquiring data from up to 3 two-wire RTD sensors and up to 9 strain gauges, offering sampling rates of 2 to 4000 sps, 24 bits of resolution, gains of 1 to 128 dB, precision voltage and current sources for sensor excitation, and multiple filtering options. It is designed for continuous, automated operation and remote deployment, featuring an ARM Cortex-A9 CPU with 512 MB of RAM and 32 GB of flash memory that provides onboard data storage and processing capabilities along with a Gigabit Ethernet interface for communications (wireless interfaces, such as Wi-Fi and 4G LTE, are also available as build-to-order options). The IMGenie Pro is powered with 5 V_{DC}, housed in a rugged, lightweight composite enclosure that meets MIL-S-901D and MIL-STD-167 requirements, and fully operational from -40 to 85°C .



Figure 3. Accellent IMGenie Pro

Accellent has developed software that works together with the IMGenie Pro to provide a complete solution for impact detection on any type of structure. This software is called **Accellent Impact Monitor (AIM)**. It provides a user-friendly graphical interface for configuring the data-acquisition hardware, detecting impact events, localizing the impact relative to the position of the sensors on the structure, quantifying the force of the impact, and tracking impact events over time. AIM provides continuous, real-time monitoring of impact events, including configurable visual and audible alerts to the operator as well as tools for advanced users to investigate the underlying structural response (stress wave). AIM runs on all modern versions of the Windows operating system, from Windows Vista to Windows 11. All impact testing and demonstration throughout this project was conducted using AIM.

For strain/load monitoring, Accellent developed custom software as part of this project. The IMGenie Pro's firmware was modified to allow continuous, real-time capturing of the dynamic strain response from the PZT sensors (rather than stochastically in response to an impact trigger), storing the data locally. These data files were subsequently retrieved via SSH over Ethernet and processed manually. To record the static strain/loads, fully custom software was developed that ran on the IMGenie Pro and interfaced with the strain gauges, also saving the data locally for later retrieval and processing. An easy-to-use graphical interface is still under development for strain/load monitoring applications and will be customized specifically for inflatable softgoods structures, including calibration techniques to calculate the actual strain/load experienced by the Vectran itself (rather than the strain/load experienced by the sensor package, which is somewhat decoupled from the underlying material).

TESTING

The primary challenge of this project is ensuring that the sensor package sewn onto the Vectran fabric can survive and generate accurate data. To this end, survivability testing was conducted at ILC Dover using strips of Vectran webbing (pattern #699601000NA, natural “bake out”) procured from Bally Ribbon Mills. The sensor packages were manufactured by Acellent and integrated with the Vectran strips. Then, the Vectran strips were stretched to varying load levels in an Instron tensile testing machine, including to the point of failure. The test results sustained the following conclusions:

- The sensor packages were robust enough in their design and attachment to survive the stretching of the Vectran webbing strips to realistic load levels;
 - The sensor packages allowed precise and accurate measurements of the conditions of the Vectran webbing throughout the experiment, including the ability to determine the load/strain of the material and to detect, localize, and quantify impacts sustained by the material;
 - The attachment techniques used for the sensor packages did not result in a significant degradation in the performance (load tolerance) of the Vectran webbing.
- This testing therefore validated the design and attachment method for the sensor packages and showed that *in situ* monitoring of load/strain and impact events is possible.

The testing was conducted on five identical strips of 1-inch Vectran webbing in sequence. Two identical sensor packages, each consisting of a single PZT transducer (¼-inch diameter) and a single thin-foil metal strain gauge (3-mm active gauge length), were bonded to each Vectran strip. The sensor packages were positioned approximately 6 inches apart. Each strip was mounted vertically in the Instron machine, as shown in Figure 4, with a ruler positioned alongside in order to allow measurements of the elongation during the stretching process. The capstan and clamps used to hold the strip are also visible at the top and bottom. The distance between the grips (gauge length) was approximately 10 inches. The sensor packages can also be seen in Figure 4. Note that the sensor packages themselves are on the interior; behind each sensor package is an epoxy blob that serves to provide strain relief for the cabling, which is routed to the data-acquisition hardware. (In the final application, this wiring would be embedded within the Vectran webbing.)

For each strip, the test procedure involved a series of preconditioning stretches (starting at 50 lbf, increasing to 1375 lbf, holding for 5 seconds, decreasing back to 50 lbf, holding for 10 seconds, all repeated 5 times). On the first strip, a stretch rate of 3 in/min was configured; subsequently, this rate was lowered to 1 in/min. Data was collected continuously during preconditioning. The strain gauges were measured

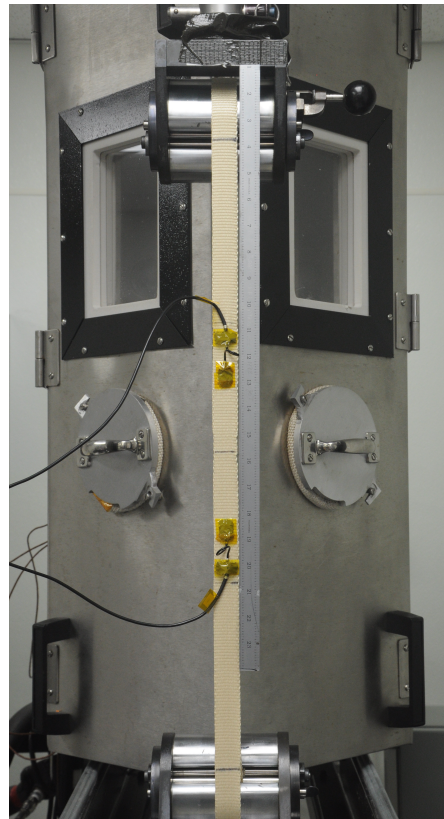


Figure 4. Representative example of a Vectran strip with two sensor packages mounted in the Instron machine.

alternately every 1.2 seconds (since there were 2 strain gauges, this amounted to a measurement from each strain gauge every 2.4 seconds), and the 2 PZT sensors were sampled simultaneously 30,000 times per second (30 ksp/s). After preconditioning was completed, the Vectran strip was being held in tension at 50 lbf. It was increased to the next tension level, and then held once more. During the hold, strain measurements were suspended and the impact-detection function (provided by the PZT sensors) was tested by softly tapping the strip in three locations: on top of sensor package 1, on top of sensor package 2, and in the middle between the two sensor packages). After tapping, strain measurement was resumed, the tension was increased to the next hold point, and the entire process was repeated. The complete test procedure is shown in Table 1. Note that only the first two strips were stretched to failure; for the remainder, the test was stopped after step 9 (at 2250 lbf).

Table I Test sequence for each strip

Preconditioning	5 times: 50 lbf → 1375 lbf → hold 5 sec → 50 lbf → hold 10 sec	
Step 1	50 lbf → 200 lbf	Impact 1, 2, 3
Step 2	200 lbf → 400 lbf	Impact 4, 5, 6
Step 3	400 lbf → 600 lbf	Impact 7, 8, 9
Step 4	600 lbf → 800 lbf	Impact 10, 11, 12
Step 5	800 lbf → 1000 lbf	Impact 13, 14, 15
Step 6	1000 lbf → 1400 lbf	Impact 16, 17, 18
Step 7	1400 lbf → 1800 lbf	Impact 19, 20, 21
Step 8	1800 lbf → 2000 lbf	Impact 22, 23, 24
Step 9	2000 lbf → 2250 lbf	Impact 24, 25, 26
Failure [optional]	2250 lbf → failure	

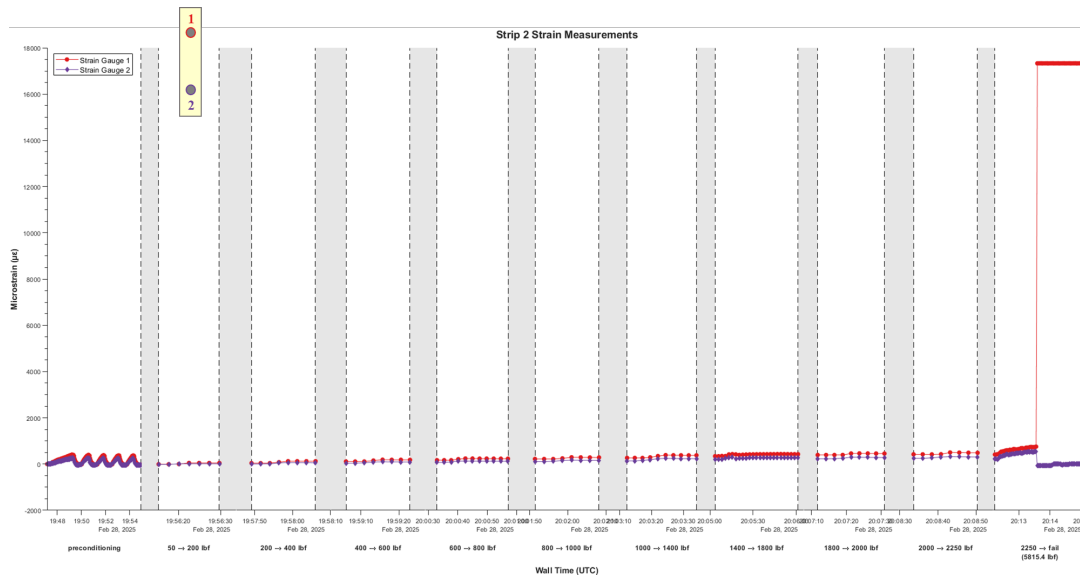


Figure 5A. Representative strain measurements from strip that was stretched to failure.

A representative set of strain measurements for one of the strips that was stretched to failure is shown as Figure 5A. The measurements from strain gauge 1 (on top) are shown in red; the measurements from strain gauge 2 (on bottom) are shown in purple. The horizontal axis is elapsed time, shown continuously. The breaks (gray sections) do not interrupt the horizontal axis (time continues to elapse) but represent the time periods during which strain measurements were disabled in order to perform the

impact tests. Note the oscillating strain pattern during the preconditioning step, and the roughly linear increase in strain during each of the subsequent steps. When the strip failed, the sensor package was damaged, which resulted in invalid, off-scale readings from the strain gauges. Figure 5B plots the same data as Figure 5A, except that the time (horizontal) axis is truncated to remove the invalid, off-scale readings, making it easier to see the trends within the measurements.

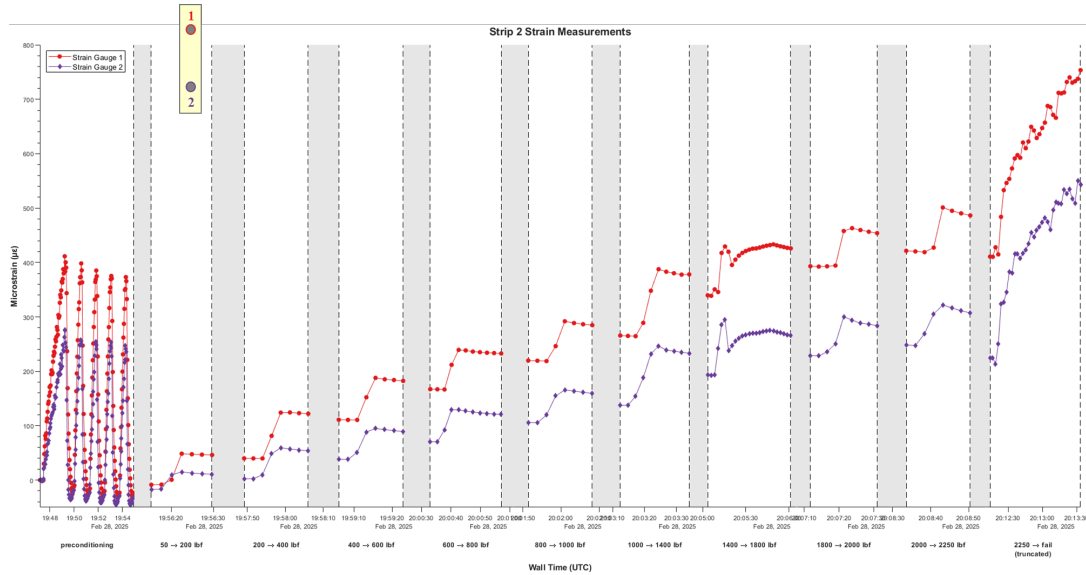


Figure 5B: Truncated view of representative strain measurements from strip that was stretched to failure.

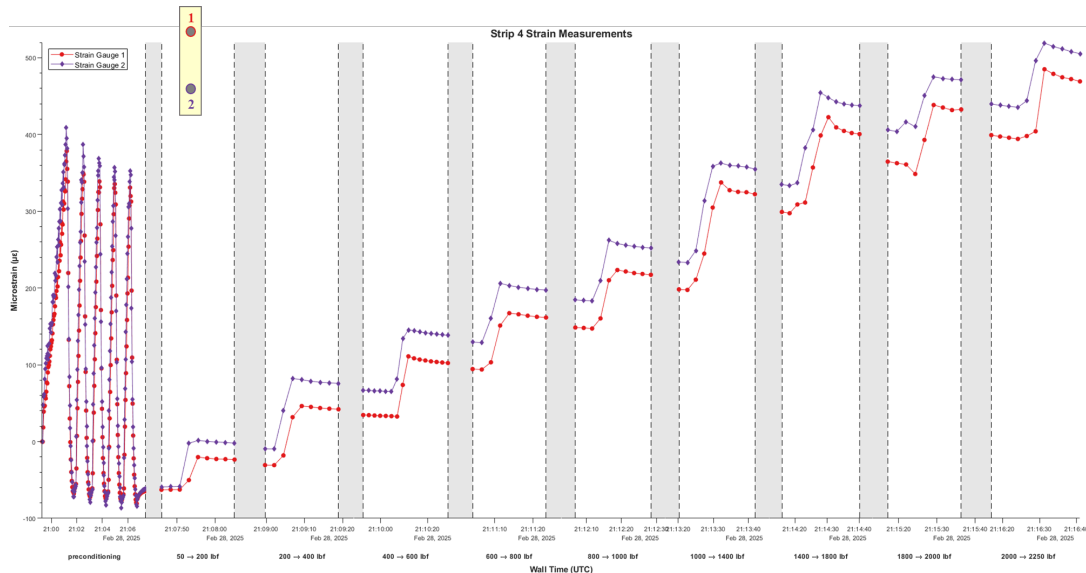


Figure 6. Representative strain measurements from strip that was not stretched to failure.

Figure 6 is a representative plot of strain measurements from a strip that was not stretched to failure (strip 4). Because this strip was not stretched to failure, the full time-series produces a plot that looks just like Figure 5B. Note that two strain gauges show good agreement with one other (although there is some offset, which is to be expected, since this is “raw” data with no calibration or offset factors applied), and the strain measurements are quite repeatable across Figures 5B and 6. This trend of high repeatability was observed across the measurements for all five Vectran strips.



Figure 7A. Broken Vectran strip after pulling to failure.

Within each section (the white regions in-between the gray dividers), the strain measurement can be clearly seen to increase, then subsequently begin to decrease gradually. The sustained increase represents the period of active stretching/elongation; the gradual decay represents the “hold” period, during which the Vectran relaxed, resulting in an observed decrease in the strain. In fact, if one interpolates visually across the gray regions, it is clear that the Vectran continues to relax slightly during the impact tests, such that the next set of measurements starts at a slightly lower strain level than the previous set of measurements ended. Note that these sub-durations (periods of sustained elongation, followed by gradual relaxation) are not consistent or repeatable because the timing (starting and stopping of the strain measurement) was done manually and not synchronized to the same clock used to control the Instron machine. Still, it is clear that the strain measurements are reasonable and consistent with what would be expected based on the experimental procedure. This confirms that the sensor package is working well (i.e., that it is sensitive to the strain experienced by the underlying Vectran strip as a result of the increased load/stretching) and that the sensor package survived throughout the entire stretching process, up until the point where the Vectran strip failed.

When the Vectran strip was stretched to the point of failure, it generally ripped at or around the sensor package, causing damage to the sensors themselves, the wiring, or both, as previously noted when explaining the out-of-range measurements at the end of Figure 5A. Figure 7A is a photograph of one of the Vectran strips still loaded in the Instron machine after it was pulled to failure; Figure 7B is a close-up photograph of a failed strap around the sensor package. In both photos, the frayed threads reveal an obvious failure mode. Strip 1 failed at a load of 5823.2 lbf, and strip 2 failed at 5815.4 lbf. By way of comparison, a sixth strip, which was identical except without any sensor package bonded to it, failed at 6300.4 lbf. Therefore, while the sensor package clearly weakens the Vectran webbing at the location where it is installed, reducing its load-bearing capacity from greater than 6000 lbf to less than 6000 lbf, these strips of webbing are only rated up to a tensile strength of 5500 lbf, which is well below even the reduced failure point.

In addition to the static strain/load measurements that were obtained from the two strain gauges during stretching (Figures 5–6), a series of extremely high-speed measurements were also recorded from the two co-located PZT sensors during stretching, representing high-fidelity dynamic strain measurements. A representative example of these measurements is shown as Figure 8 (in this case, strip #1, when stretched from 1000 to 1400 lbf). The ground noise of approximately ± 0.01 V is plainly visible throughout the entire measurement interval, as are a few small spikes extending below the noise in the region of time where the strip was being stretched continuously by the Instron machine, presumably due to some vibration or non-uniform stretching (resulting in jerkiness) by the machine. Under these particular test conditions, this dynamic strain data is not especially useful, but the tests nevertheless demonstrate that it can be successfully collected.



Figure 7B. Close-up of frayed and broken Vectran fibers around sensor package after pulling to failure.

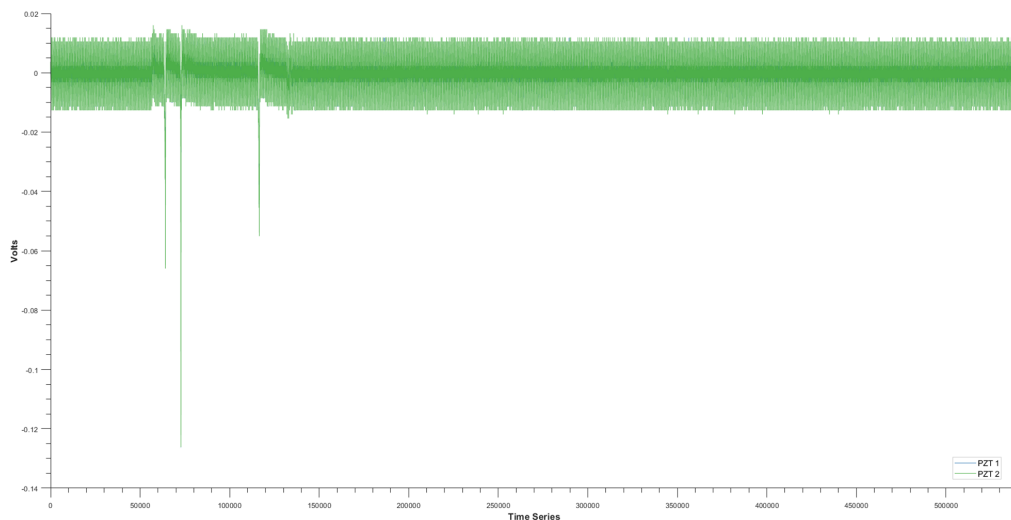
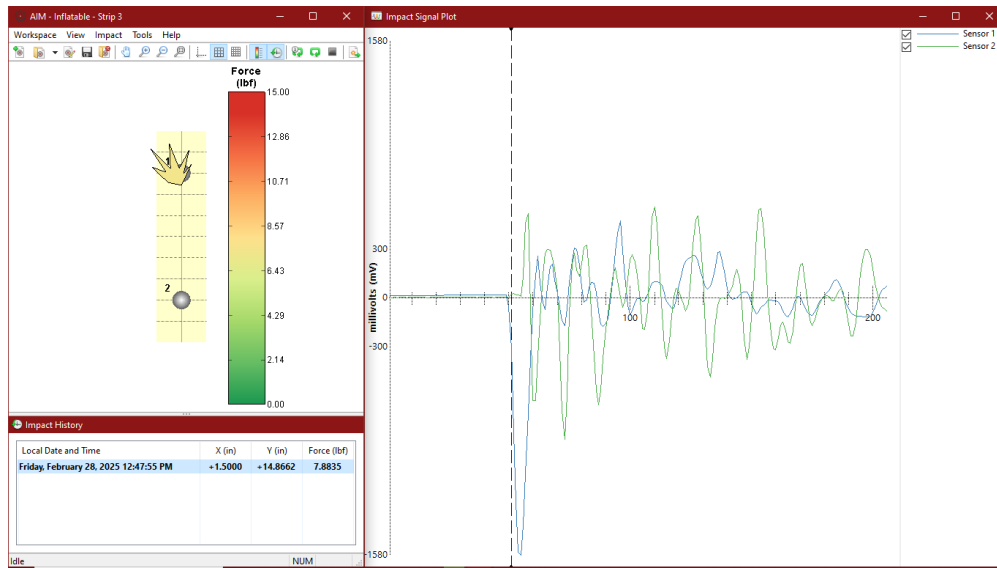


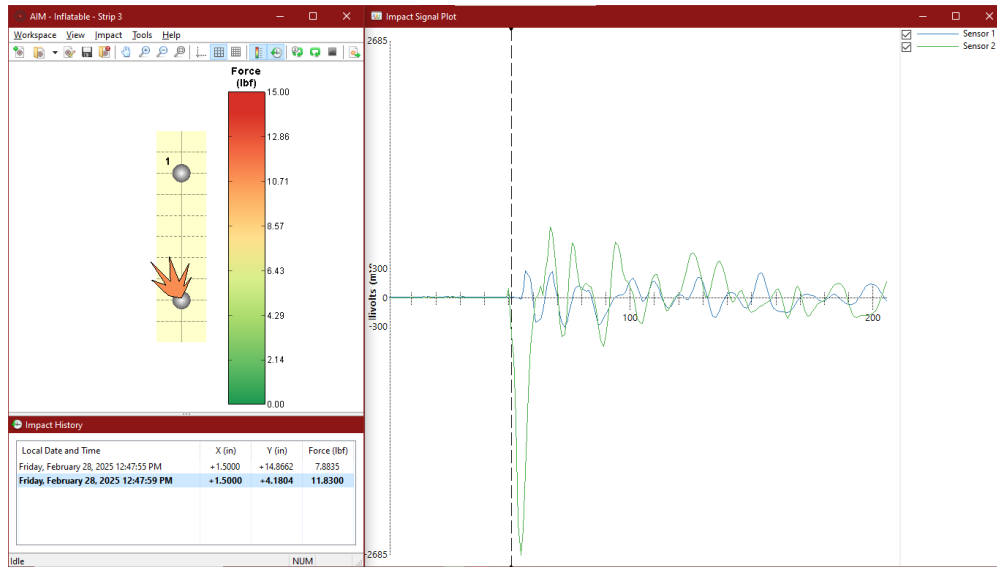
Figure 8. A representative set of dynamic strain measurements from PZT sensors during one particular stretch-and-hold interval.

Finally, in between each stretch-and-hold interval (corresponding to the gray vertical regions in Figures 5–6), the Vectran strip was lightly tapped three times while it was being held under tension in order to test the impact detection capabilities of the SHM system. Each of the three taps were at a different location: the first on top of sensor 1, the second on top of sensor 2, and the third between the two sensors. Even with only two sensors, the system was able to accurately determine the location of the impact (whether it was on top of a sensor or between the two sensors), as well as quantify the force level of the impact. Both the location and force level estimates can be made more accurate by calibration (and, of course, by adding more sensors). Figures 9A–C are screenshots from AIM showing the estimated location of the impact relative to the structure and sensors (starburst pattern), the estimated force of the impact (color of the starburst pattern), and the plot of the signals from both PZT sensors.

A



B



C

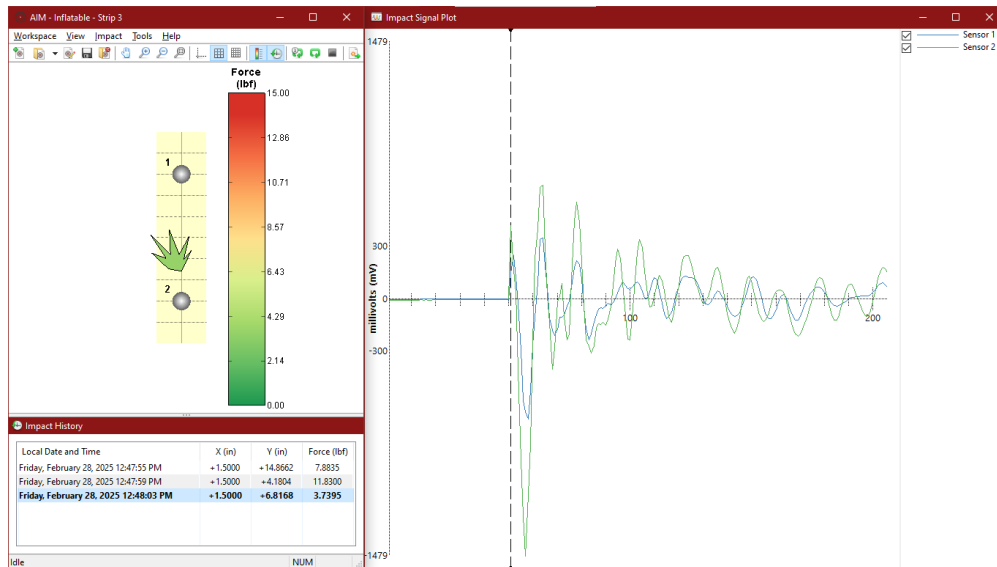


Figure 9. Screenshot of AIM main window and plot window after tapping on strip 3 (A) on top of sensor 1, (B) on top of sensor 2, (C) between sensors 1 and 2.

SUMMARY

Accellent has developed a novel sensor appliqué containing co-located PZT and strain gauges that is designed for use with softgoods materials. The sensor package is an integral part of a Structural Health Monitoring (SHM) system, which also included Accellent's IMGenie Pro data-acquisition hardware and served to provide static strain/load measurements, dynamic strain sensing, and impact detection. As an initial proof of this system's functionality and durability, five Vectran strips were instrumented with Accellent's sensors and then stretched under carefully controlled conditions using an Instron tensile testing machine. The sensor package not only survived but was able to capture accurate data throughout the entire process, up to the point of material failure. Although the sensor package did slightly weaken the Vectran, the failure point across multiple tests was still significantly above the rated tensile strength of the webbing (> 5800 lbf, as compared to 5500 lbf). This represents a significant innovation: to the best of our knowledge, it is the first time that a network of sensors has been successfully attached to a Vectran softgood and survived that structure being subjected to load. It shows that an integrated SHM system capable of monitoring both load/strain and impacts is a viable and essential component of any inflatable space habitat.

The next steps will be to test on a subscale inflatable test article to see if the sensors can survive the inflation and are able to function accurately.

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