Flexible Multifunctional Structural Health Monitoring Systems for Inflatable Space Habitat Structures

FRANKLIN LI, SERENA WANG, ROSHAN JOSEPH
and AMRITA KUMAR

ABSTRACT

Space structures are one of the most critical components for any spacecraft, as they must 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 1950's and used in a number of spaceflight applications. Inflatable habitats, airlocks, and space stations can be used for in-space living spaces 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 the 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 of an inflatable module is an important factor in determining the feasibility of using inflatable technologies for habitat requirements, especially in the presence of micrometeoroid and orbital debris (MMOD) threats. There is therefore a need for Structural Health Monitoring (SHM) methods to perform detection, localization, and quantification of damage to structural layers throughout the structure's 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 basis or as a quick-response basis.

This paper discusses the development of an approach for SHM for inflatable softgoods, and testing a laboratory proof of concept of the preliminary design, which integrates the SHM approach into inflatable habitat test articles. An experimental test setup for performing the initial feasibility demonstration for impact detection using SMART Layer sensors. An initial test setup for testing was developed and testing performed for impact detection.

Franklin Li, Serena Wang, Roshan Joseph, Amrita Kumar, Acellent Technologies Inc., 835 Stewart Drive, Sunnyvale CA 94085.

It was identified that the SMART layer sensors can sense the signals due to impact. An experimental setup was also conceptualized for performing impact testing on the coupon with high tension on the Vectran layer. Test results demonstrate the feasibility of impact detection using the IMGenie DAQ hardware and AIM software on the inflatable materials.

INTRODUCTION

Space structures are one of the most critical components for any spacecraft, as they must 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 1950's and used in a number of spaceflight applications. Inflatable habitats, airlocks, and space stations can be used for in-space living spaces 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 (Figure 1). Many concepts by the 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 of an inflatable module is an important factor in determining the feasibility of using inflatable technologies for habitat requirements, especially in the presence of micrometeoroid and orbital debris (MMOD) threats. There is therefore a need for Structural Health Monitoring methods to perform detection, localization, and quantification of damage to structural layers throughout the structure's 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 basis or as a quick- response basis.

Flexible hybrid SHM systems which focus on the design, manufacturing and integration of electronics and sensors will address some of the impediments and challenges facing integration of multifunctional sensors and monitoring technologies into space habitat structures. Preliminary work was conducted to enable the manufacturing of integrated sensing capabilities into 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.

SHM SYSTEM FOR SPACE

The Structural Health Monitoring system utilizes the SMART Layer Technology that includes the three major components:

1. SMART Layer sensor network
2. Diagnostic hardware for impact detection
3. Diagnostic algorithms/software for identifying impact events and location

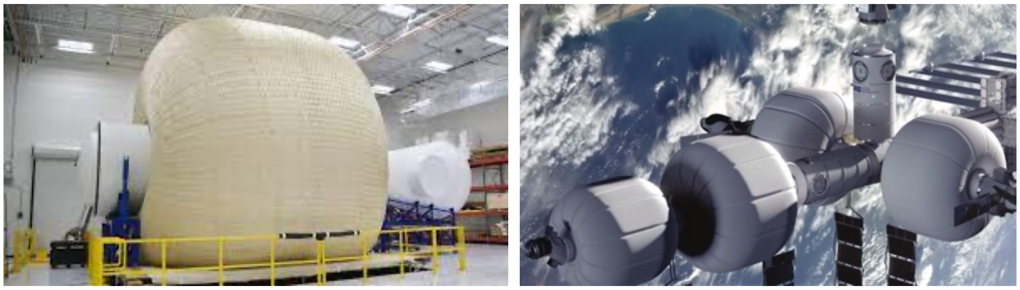

Figure 1: Inflatables for space

SMART Layers with 0.25” diameter PZT embedded in them were manufactured for use in the project. The SMART Layer is well established in the field of Structural Health Monitoring and is currently known for its unique ability to provide a large structural coverage for gathering data with its network of sensors/actuators embedded on a layer thus eliminating the need for each sensor to be installed individually. The layer consists of a network of embedded, distributed piezoelectric discs (PZT) acting as both sensors and actuators for monitoring structural condition in real time. The SMART Layer manufacturing process utilizes the printed circuit technique in order to connect a number of sensors and actuators embedded in the layer. The layer can be as thin as 4 mil, has almost negligible weight and provides excellent electrical insulation.

NASA provided the primary restraint material used in the inflatable structures called Vectran. NASA provided 12K Vectran webbing with a width of 1 inch. The material has a peak strain at failure of about 4%, but operationally is closer to 2% at 25% of ultimate. Creep strain can add another 0.5% to that over the duration of the mission. A key challenge was therefore to integrate the sensors with the Vectran material (Figure 2).

The IMGenie Pro passive impact detection DAQ and AIM software was used for the impact detection (Figure 3). The system is set up to be continuously ‘listening’ for impacts at all times. When a sufficiently large force strikes the structure, the PZT sensors that are bonded onto the structure, pick up the stress waves traveling through the surface of the structure. A trigger mechanism is embedded in the code that enables software control to determine the trigger condition, which could be related to a specific set of feature(s) of the sensor measurements recorded by the network of PZT sensors.

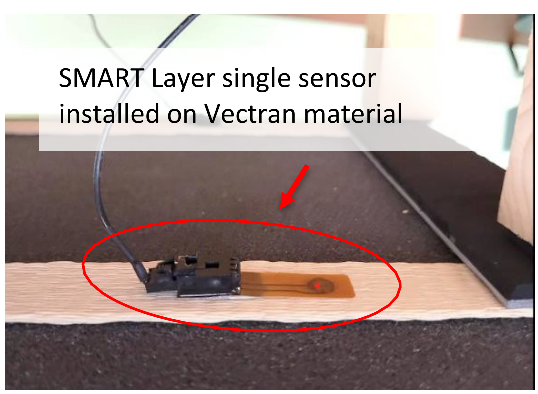

Figure 2: Sensors installed on Vectran material

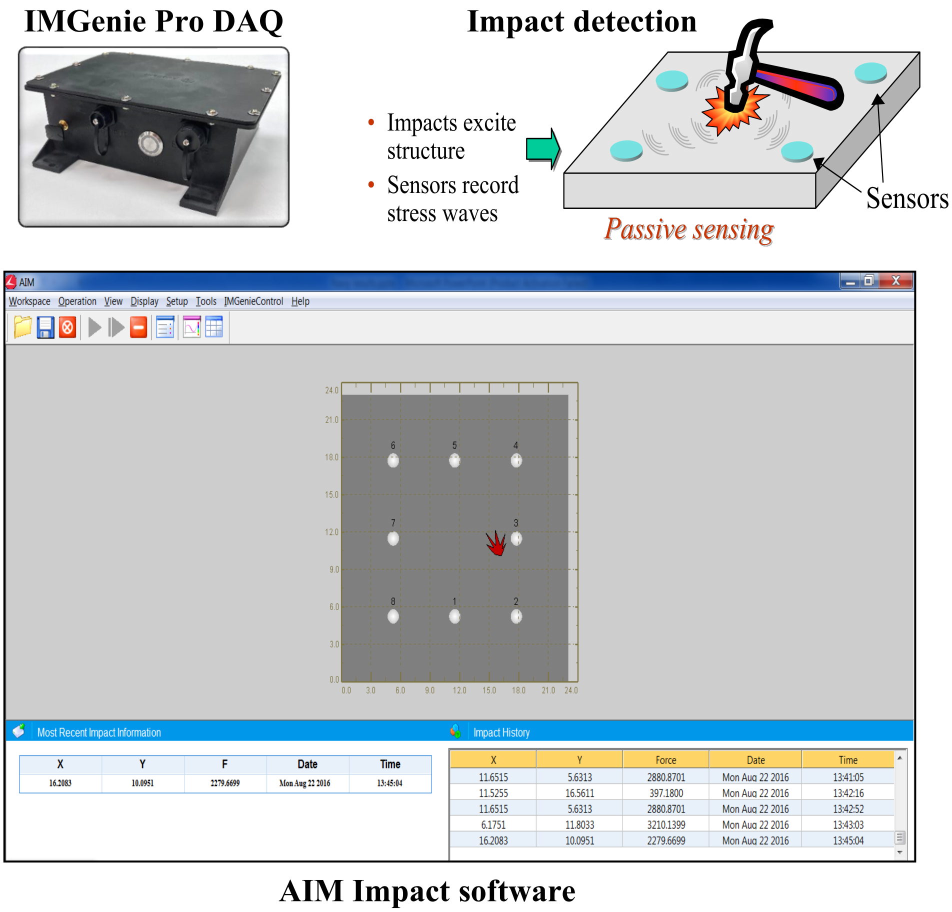

Figure 3: IMGenie Pro software and AIM software

To avoid false triggers by external noise, such as those from electromagnetic, acoustic or vibration, the signals used for triggering are filtered digitally. Upon triggering, all sensor measurements are recorded and stored in a data file for analysis. The data is immediately parsed to a signal-processing and interpretation algorithm, which analyzes the measurements to determine the location of the impact and also to estimate the energy and/or peak force level of the impact.

The impact detection software was used to detect external impacts occurring on the inflatable material assembly. A number of key parameters were considered when building the algorithms:

- impact speed,
- material stiffness and dimensions,
- object stiffness, mass and size

An impact on the inflatable structure assembly produces transient stress waves that propagate, disperse, and dissipate along the load bearing material in both directions from the impact point. Each wave consists of a vibration component (standing wave) and a pure wave component (traveling wave). The vibration component consists of modes at fixed discrete frequencies that are determined by the material properties as well as the boundary conditions.

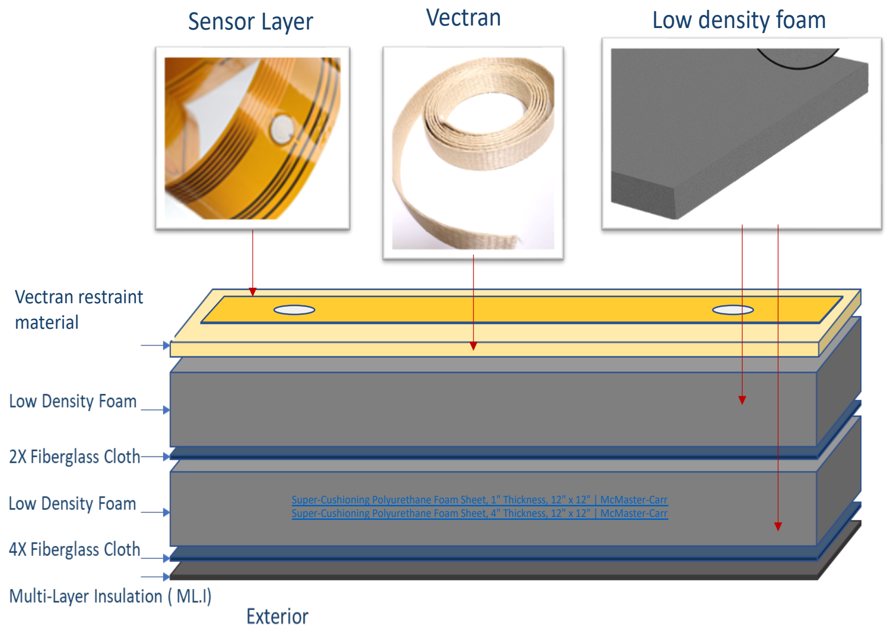

Figure 4: Cross-section of NASA habitat structure for testing

These frequencies are independent of the impact force characteristics and are not affected by the impact object characteristics, speed, or other impact parameters. In other words, the vibration components are a function of the structural properties of the material only. On the other hand, the pure wave component contains frequencies that are directly affected by the input force characteristics. For instance, an impact with a hard object will produce higher frequencies than a softer object. Likewise, a light object will excite higher frequency modes than a heavier object consisting of the same material.

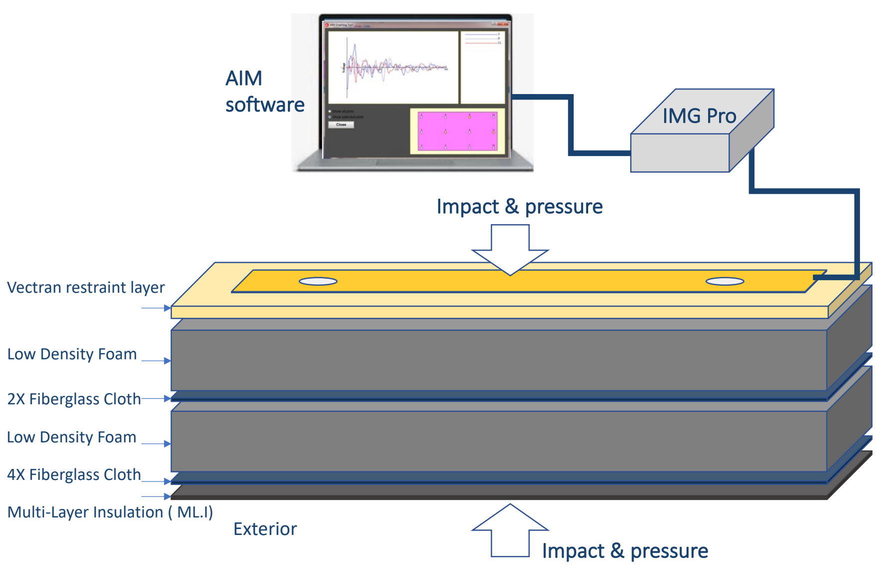

Figure 5: Structure with instrumentation for recording the impact signals

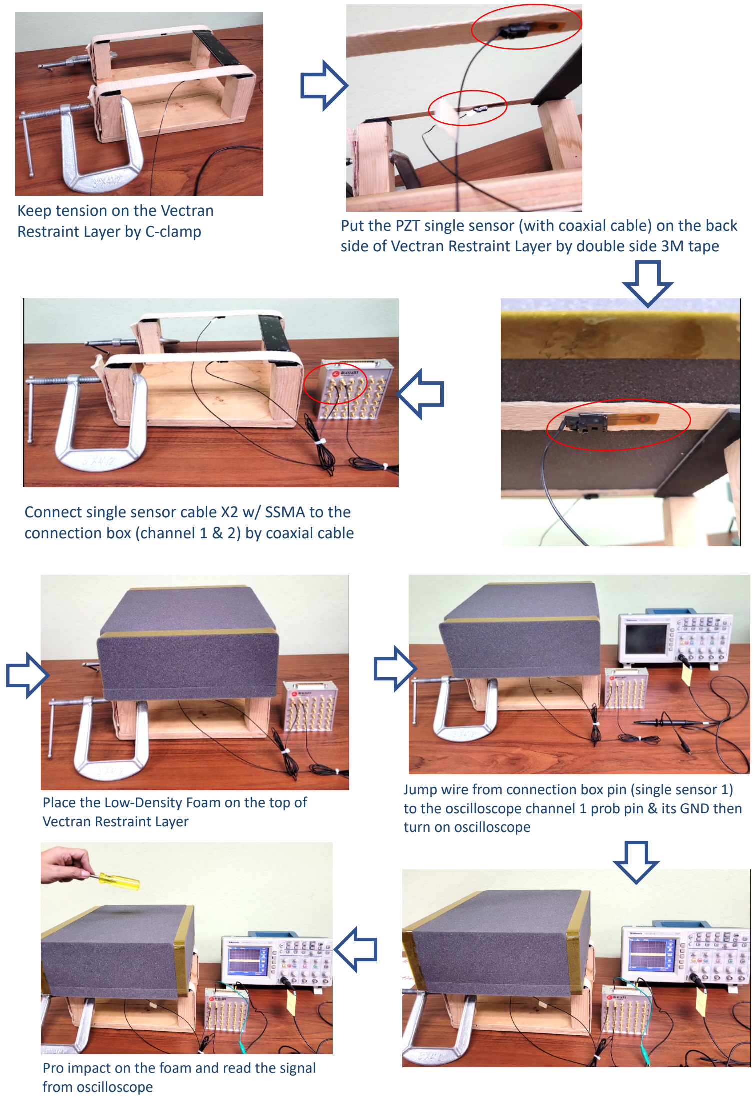

Figure 6: Preliminary testing with sensors

If such a wave frequency feature, or dominant frequency, exists and can be quickly extracted from the sensor signals, then this can be used as a method of rapidly identifying impact events for the inflatable materials.

TESTING ON INFLATABLE MATERIALS

In order to demonstrate the SHM system use for high-speed impact detection, the Vectran material was procured from NASA and low-density foam was obtained from McMaster Carr Super-Cushioning Polyurethane Foam Sheet, 1" Thickness, 12" x 12". The foam that would be used for a large habitat would be 4-in thick, and is an open cell polyurethane. The materials procured were setup as shown in figure 4.

The proposed test cross section of the habitat wall is shown in Figure 4. The structure consists of multi-layer insulation, above which a fiberglass cloth will be placed. Above the fiberglass cloth, two low-density foams separated by fiberglass cloth will be placed. Above the low-density form, the woven Vectran restraint layer will be installed. The piezoelectric sensor smart layers will be bonded on the Vectran restraint layer for sensing the impact signals. The structure installed with SMART layer sensors and connected to the impact detection hardware is shown in Figure 5.

After the installation of the sensors on the Vectran restraint material, the instrumentation for recording the impact signals was connected to the sensor layer. The IMGenie Pro hardware for recording the signal will be connected to the smart layer using a cable connection. The hardware was connected to the laptop using an ethernet cable. The laptop was installed with the AIM software for controlling the hardware for the impact signal recording. The software has several options for convenient recording and post-processing of the impact signals and impact source localization.

Figure 7: Test setup using 2% strain

Based on the proposed test setup, an initial test setup was developed as presented in Figure 6. The figure presents the installation of the Vectran restraint on a wooden frame using a C-clamp in tension. Two SMART Layer single sensors were installed on the restraint layer using a double side 3M tape. The single sensors are connected to the single sensor connection box using single sensor coaxial cables. Figure 7 presents the placement of the low-density foam on the Restraint Layer and the connection to the Oscilloscope for recording the signals. The low-density foam was placed on top of the Vectran layers. The jump wire from the connection box is connected to the oscilloscope. After establishing the connection, the oscilloscope was turned on for sensing the impact signals. An impact was applied on the foam and the signal due to the impact was sensed by the oscilloscope.

Figure 6 shows preliminary test results when impacted with a hammer. The oscilloscope shows a clear signal change when impacted. This initial test demonstrates the functioning of the sensors. However more testing was needed to demonstrate the impact detection using the DAQ hardware and software.

To perform these impact tests on the test coupon an experimental setup as presented in Figure 7 was conceptualized.

Figure 8: Impact test setup using a paintball gun for impacts

The test was conducted as follows:

- Keep Woven Vectran Restraint Layer 2% strain tension for impact test by bench vise tool machine
- Install single sensor on the 2% strain tension restraint layer by 3M adhesive film
- Connect the coaxial cables from sensors to the connection box
- Connect the cable to the IMGenie Pro DAQ HW
- Attach the foam on the other side of restraint layers without sensors mounted
- Turn on the DAQ HW
- Shoot paint ball projectile on the foam side using paint ball gun
- Take data

The test setup is shown in figure 7. 2% strain was mechanically induced. The assembled inflatable was impacted using a paint gun and the results clearly demonstrated that the sensors can detect the impact event (Figure 8).

The testing was then repeated with data collected and processed using the IMGenie pro DAQ hardware from Acellent along with the impact software (Figure 9). The software clearly identifies the impact event and location on the assembly.

CONCLUSIONS

Inflatable structures are being pursued as candidates for long-term habitats in space. The ability to monitor and assess the structural health of an inflatable module is an important factor in determining the feasibility of using inflatable technologies for habitat requirements, especially in the presence of micrometeoroid and orbital debris (MMOD) threats. There is therefore a need for Structural Health Monitoring methods to perform detection, localization, and quantification of damage to structural layers throughout the structure's mission.

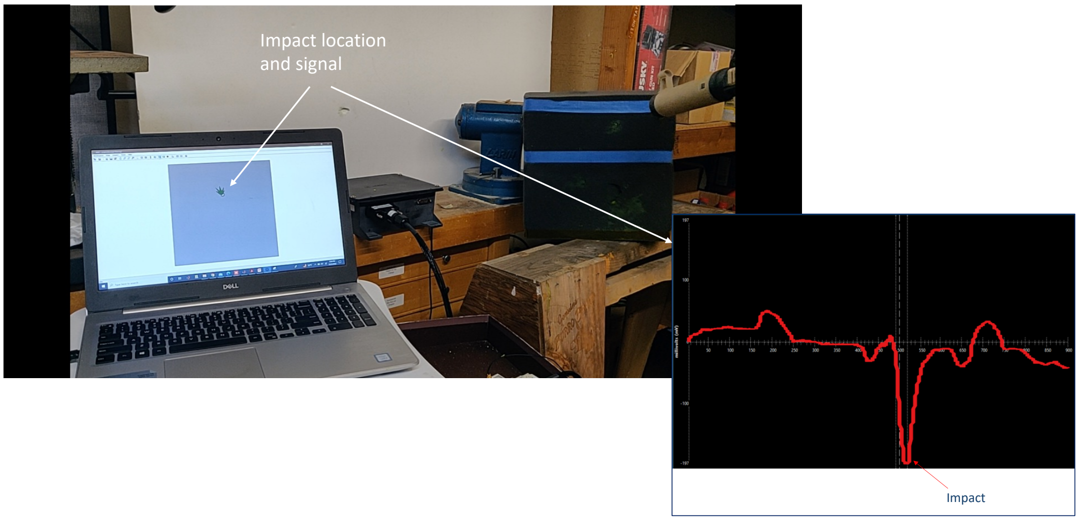

Figure 9: Impact detected using IMGenie hardware and AIM software

An experimental test setup for performing the feasibility demonstration for impact detection was proposed. Based on the proposed feasibility demonstration, an initial test setup for testing was developed, and initial testing performed for impact detection. We have identified that the SMART layer sensors can sense the signals due to impact. An experimental setup was also conceptualized for performing impact testing on the coupon with high tension on the Vectran layer. Test results demonstrate the feasibility of impact detection using the IMGenie DAQ hardware and AIM software.

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