DEMONSTRATION OF A PARTICLE IMPACT MONITORING SYSTEM FOR CREWED SPACE EXPLORATION MODULES

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When micrometeorite or debris impacts occur on a space habitat, crew members need to be quickly informed of the likely extent of damage, and be directed to the impact location for possible repairs. The goal of the Habitat Particle Impact Monitoring System (HIMS) is to develop a fully automated, end-to-end particle impact detection system for crewed space exploration modules, both in space and on the surfaces of Solar System bodies. The HIMS uses multiple thin film piezo-polymer vibration sensors to detect impacts on a surface, and computer processing of the acoustical signals to characterize the impacts. Development and demonstration of the HIMS is proceeding in concert with NASA's Habitat Demonstration Unit (HDU) Project. The HDU Project is designed to develop and test various technologies, configurations, and operational concepts for exploration habitats.

This paper describes the HIMS development, initial testing, and HDU integration efforts. Initial tests of the system on the HDU were conducted at NASA's 2010 Desert Research and Technologies Studies (Desert-RATS). Four sensor locations were assigned near the corners of a rectangular pattern on the HDU module's wall. To study the influence of wall thickness, three sets of four sensors were installed at different layer depths: on the interior of the main module's wall, on the exterior of the same wall, and on the exterior of a layer of foam insulation applied to the exterior of the wall. Once the system was activated, particle impacts were periodically applied by firing a pneumatic pellet gun at the exterior wall section. Impact signals from the sensors were recognized by a data acquisition system when they occurred, and recorded on a computer for later analysis. Preliminary analysis of the results found that the HIMS system located the point of impact to within 8 cm, provided a measure of the impact energy / damage produced, and was insensitive to other acoustic events. Based on this success, a fully automated version of this system will be completed and demonstrated, along with a crew response procedure, as part of a crew "Caution/Warning" system at the 2011 Desert-RATS.

I. INTRODUCTION

The NASA Habitat Demonstration Unit (HDU) is a large-scale test bed designed for the testing and demonstration of technologies, processes, and operations that would be needed to support the future human exploration missions to the International Space Station, near-Earth asteroids, the Moon, or Mars. The HDU team is composed of architects, scientists, and engineers from multiple NASA centers. The 2010 configuration of the HDU included a Pressurized Excursion Module (PEM, the main module) and an airlock (see Figure 1). The PEM's circular floor space is divided into eight radial sections, labeled "A" through "H". Alternating sections contained either a workstation or a door. The airlock attached to one door, two rover vehicles could dock with two other doors, and the last door section was blocked and used for a workstation. The shell wall is a hard, resin-infused fiberglass composite with a thickness of about 1 cm and an exterior layer of 10-cm-thick foam insulation. The PEM has a 5-m inside diameter and 3.3-m height. The construction of HDU was completed at the NASA Johnson Space Center (JSC) in the summer of 2010. After a brief dry run at a

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Fig. 1: The Habitat Demonstration Unit at the 2010 NASA Desert Research and Technology Studies.

JSC "Rockyard" facility, HDU was shipped to the "SP Mountain" test site, approximately 40 miles north of Flagstaff, Arizona, where the HDU team participated in a very successful NASA Desert Research and Technology Studies (D-RATS) campaign for three weeks in late August.

One requirement to improve the safety of long-term habitat operations is the ability to monitor potentially damaging particle impacts on the structure. Sources of impacting particles include orbital debris and micrometeoroids, and secondary ejecta on the surface of a solar system body (e.g., planet or asteroid). The NASA Orbital Debris Program Office initiated an effort, with collaboration from the Naval Research Lab and Virginia Polytechnic Institute, to develop the Habitat particle Impact Monitoring System (HIMS) for HDU in April 2009. Twelve space-qualified polyvinylidene fluoride (PVDF) acoustic impact sensors (Figure 2) were installed at four different locations and three layers on the wall of Section D of

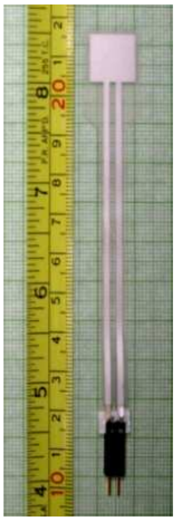


Fig. 2: A PVDF sensor of the type used by HIMS. The active area, about 1.2 cm square, is self-adhesive.

PEM. The four locations are indicated by the red circles in Figure 3a. Figure 3b depicts a cross-section through the wall at a sensor location. Sets of four HIMS sensors were first adhered to the interior and exterior of the fiberglass shell. Exterior sensor cables enter the PEM through a single penetration in the fiberglass shell. After spray-application of the insulation, a final set of four sensors was adhered to the outside of the insulation layer. Each set of four sensors is arranged with one sensor at each corner of a nearly rectangular pattern, and the three sets are aligned as closely as possible to "stack" the sensors.

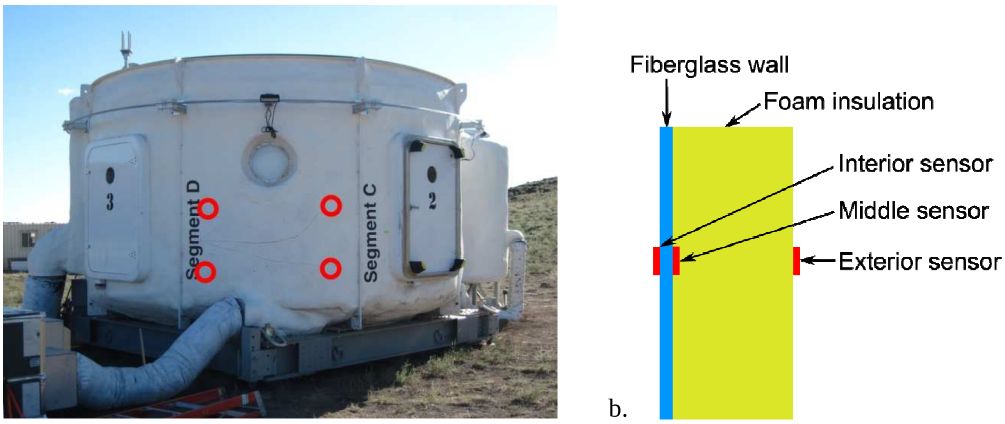
a.


Fig. 3: Locations of HIMS sensors on the PEM. (a) Red circles indicate sensors located at corners of a rectangular pattern. (b) PEM wall cross-section diagram shows locations of sensors in three layers.

The space-qualified HIMS sensors have been tested on different materials (aluminum plate, Kevlar, multi-layer insulation, etc.) subjected to hypervelocity impacts up to 7 km/sec. These low-mass transducers have a self-adhesive backing, so they can easily be attached to any suitable surface. Attaching the sensor to a large existing surface significantly increases the sensitive area. Since hypervelocity impacts on the HDU were not possible, a 10-pump air rifle was used to simulate particle impacts during the D-RATS campaign. The degree of projectile penetration was controlled by varying the number of compressions of the rifle pump handle. The speed of the projectile was also measured using a ballistic chronometer. Particle speed ranged from about 30 m/sec for 1 pump up to 150 m/sec for 10 pumps. The transition from partial to full penetration through the foam insulation of the structure occurred around 130 m/sec.

II. TEST

The objective of the project in 2009-2010 was to demonstrate the HIMS capability of detecting particle impact location and the degree of impact penetration. The former is achieved by multilateration analysis using differences in signal arrival times at the different sensor locations. The latter is achieved by analyzing signal strength as a function of time. Real-time data processing was not one of the objectives during this phase of the project. Impact signals (sensor output voltage as a function of time) were plotted on a computer screen, evaluated visually, and recorded for later analysis.

The HIMS, in its 2010 testing configuration, is shown pictorially in Figure 4. The system was portable and self-contained, with only the sensors attached permanently to the HDU-PEM. The data-acquisition card, compact personal computer, and data-analysis software are all off-the-shelf products. Since the preamplifier and data-acquisition card both supported four data channels, different sets of four sensors were used at different times during the tests. Analysis of the recorded signals would thus indicate which configuration of four sensors provided the best characterization of the impact.

Initial tests were performed indoors at NASA's Johnson Space Center (JSC). For safety reasons and because the tests had to be essentially non-destructive, particle impacts were simulated using a CO_2-powered "airsoft" gun which fires 6-mm spherical plastic pellets. As testing progressed and the HDU was moved to an outdoor location at JSC, the airsoft gun

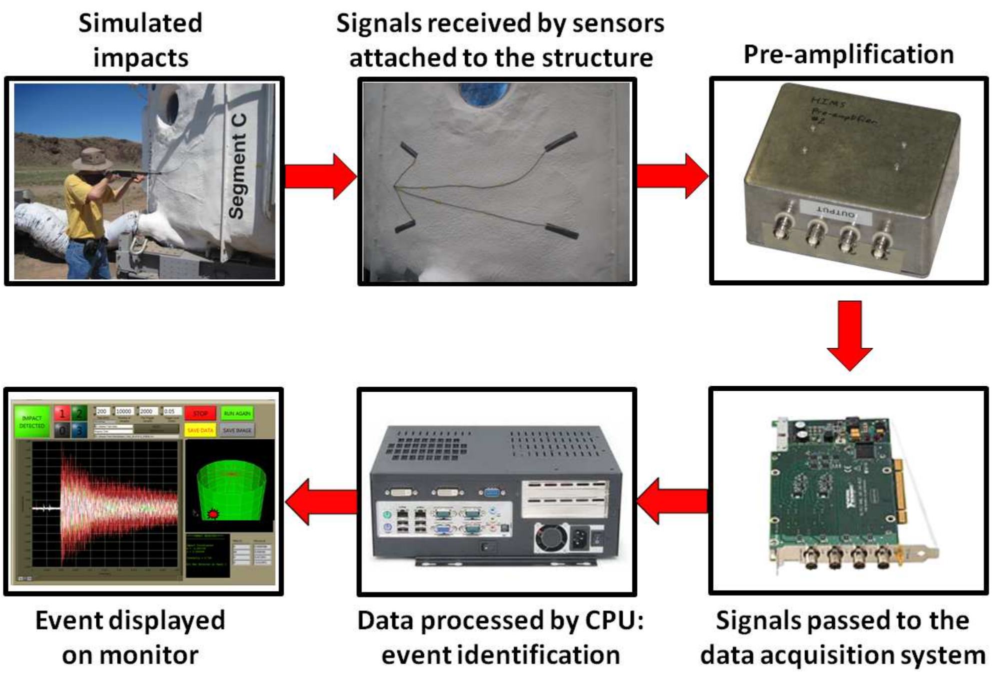


Fig. 4: Pictorial diagram of the Habitat Particle Impact Monitoring System (HIMS), 2010.

was replaced with a multi-pump pneumatic rifle firing 4.5-mm spherical steel "BB" pellets. For each test shot, the computer recorded the response from four impact sensors (see sample plot in Figure 5), and the air gun operators recorded the position of the impact relative to a reference point on the HDU exterior (see Figure 6). Initially the air gun operators also measured the depth of projectile penetration using a depth gauge. Due to the irregularities of the projectile's channel through the insulation, which tended to tear and close behind the projectile, the depth measurements were judged to be unreliable. These first two phases of the test program focused on verifying the operation of the hardware and software, and on characterizing the impact signals and system response.

The final phase of this test took place at NASA's 2010 D-RATS campaign. The HDU was moved to the outdoor SP Mountain test site north of Flagstaff, Arizona. These test shots used the air rifle exclusively. A total of 147 air rifle shots and 40 hours of HDU background acoustics data were collected. HIMS output data were recorded in the form of text files containing the sampled times and each sensor's output

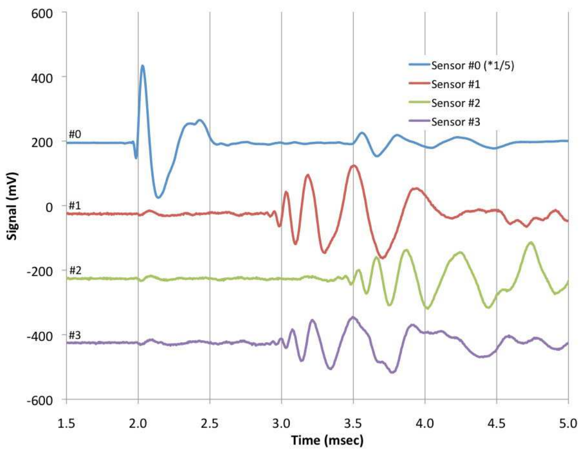


Fig. 5: Plot showing impact signals from four sensors on the HDU-PEM wall. (Note the signals are displaced from zero for clarity of the figure, and the output of Sensor 0 is scaled down to fit the plot scale.)

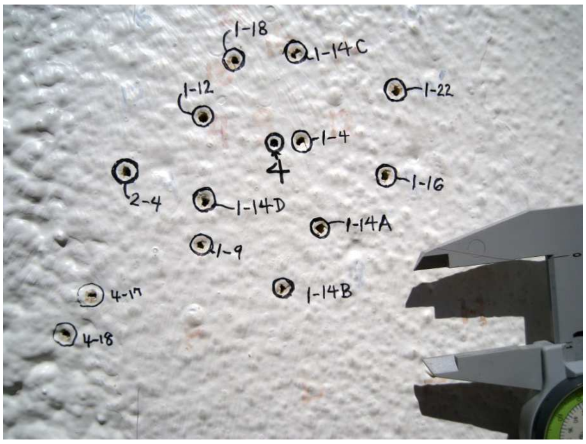


Fig. 6: Labeled impact points surrounding a reference point ("4") on the painted foam covering the exterior of the HDU-PEM.

voltage. Analysis of the pre-D-RATS tests allowed the HIMS team to set the input signal threshold that would trigger recording an "event," and to set the number of samples (pre- and post-trigger) to record per event. Background data were recorded by eliminating the trigger threshold and recording all sensor outputs during normal daytime and nighttime HDU operations.

Test shots were fired in several zones (the X's in Figure 7) distributed across the instrumented wall. Most of the test shots used the maximum of 10 pump compressions, and most were fired at an angle normal to the curved wall of the HDU-PEM. One series of shots used progressively fewer pump compressions, and a final set of shots was performed with the particle trajectory approximately 45 degrees from normal. After the test impacts were completed, the particle speeds were calibrated by firing the air gun through a "ballistic chronometer," which uses the projectile's time of flight between two light sensors to determine its speed. Several shots were measured at each step from 1 to 10 rifle pump compressions, yielding the average projectile speed at each energy level.

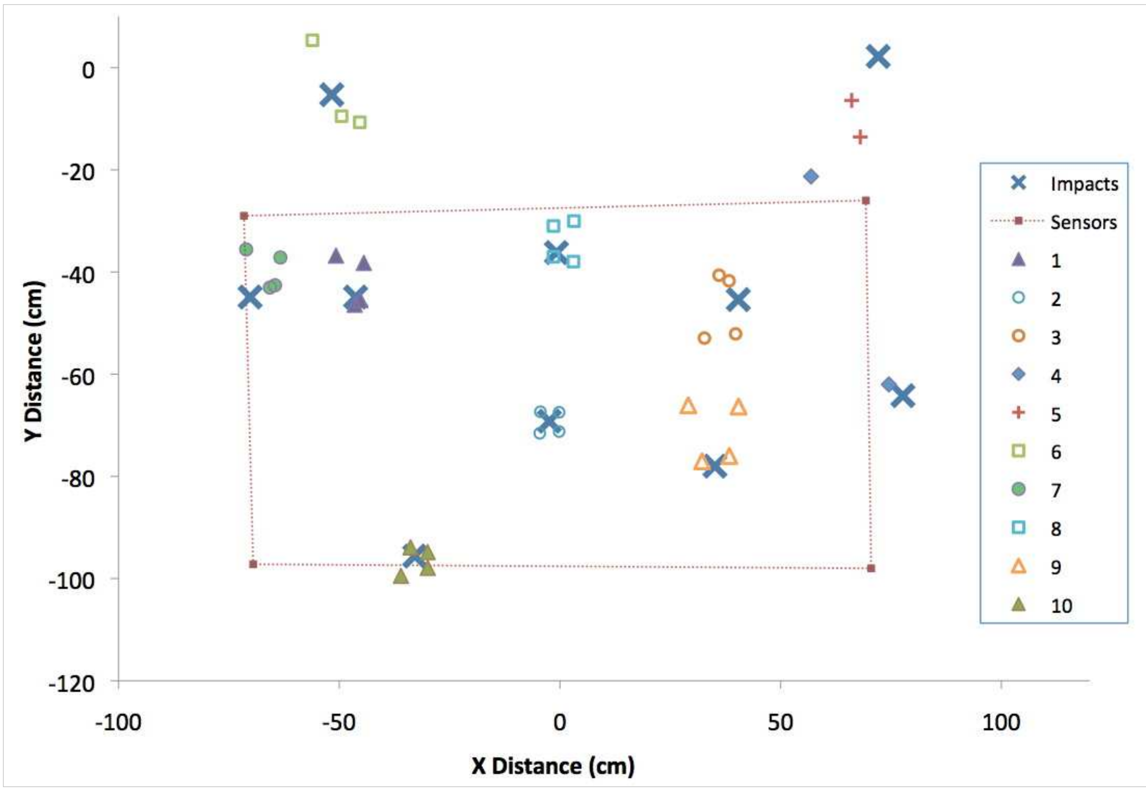


Fig. 7: Selected position results from the 2010 D-RATS HIMS test. Positions of the actual impacts and the sensors were measured. The computed impact positions are numbered in the plot key; the multilateration algorithm uses inputs from sets of three sensors, resulting in four possible location estimates.

III. DATA ANALYSIS

The system correctly identified all 147 projectile impacts. It determined the impact location of each to within 8 cm (see Figure 7), which is much higher accuracy than operationally required. Signal levels were also found to vary reproducibly with changes in projectile kinetic energy. It also captured 290 non-impact signals which were later identified by their very short duration as non-acoustic electrical spikes caused by the cycling of the habitat power generator. A simple waveform-duration criterion, based on the ratio of energy to peak voltage, was then applied to the data set, eliminating all but four of these false signals. Four additional false signals were acoustic and presumably due to noisy crew activities very near the sensors. These false signals had very low amplitudes and if interpreted as impacts, would have been categorized as inconsequential.

Analysis of the data with respect to the calibrated particle speeds (Figure 8) shows that the signal levels change reproducibly with changes in projectile kinetic energy. A short-duration signal (one having a shorter pulse width) is found to be a reliable indicator that the projectile penetrated through the foam insulation and impacted the hard fiberglass shell. As apparent from Figure 8, projectiles of this type with speeds less than about 130 m/s (energy of 2.8 J) stopped within the foam insulation and did not impact the fiberglass wall. The signal strength also increases dramatically when the projectile strikes the shell.

Comparing the response of the sensors on each of the three layers, it was determined that the interior and middle layer sensors provided almost identical signals and provided equally reliable results. This was not unexpected since the main sound propagation path to both of these sensors is through the relatively rigid inner shell material. However the signals arriving at the outer sensors were distorted and produced less reliable results. This is due to variations in the attenuation and dispersion of the sound wave as it traveled through the foam insulation.

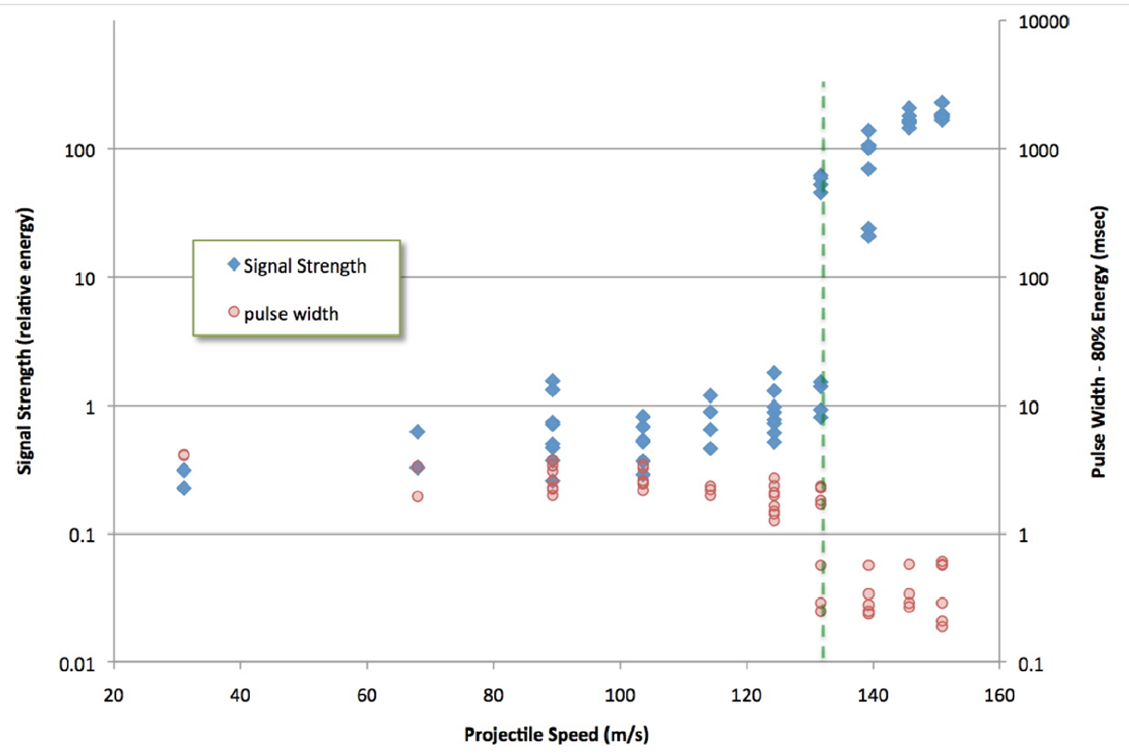


Fig. 8: Impact signal levels changed reproducibly with changes in projectile kinetic energy. The dotted vertical line (at about 130 m/s) highlights the clear division between lower speeds where the projectile stops in the foam insulation before striking the fiberglass wall, and higher speeds where the projectile impacts the wall.

IV. CURRENT AND FUTURE WORK

To reflect the change in focus in late 2010-2011, the HDU Pressurized Excursion Module has been renamed the Deep Space Habitat (DSH). Key objectives for the HIMS project in 2010-2011 are to develop a three-dimensional graphical console to display impact time, location, and severity information in real time, to develop an impact response procedure for crew members in preparation for the integrated 2011 D-RATS campaign, and to fully integrate the HIMS hardware and software into the existing infrastructure of the HDU. The software, which in 2010 ran on a portable computer and only detected and recorded impact events, has been upgraded with the impact location and characterization algorithms, and runs on an HDU computer located under the floor of the DSH. The data acquisition modules are also integrated into DSH support systems. The signal preamplifier is similar to the previous unit and is attached to a workstation inside Section D.

The primary goal of the HIMS team for the 2011 D-RATS campaign is to test the end-to-end detection capability of the system. When a suspect event occurs at any time during the exercise, the HIMS will automatically log the time and signal waveforms received, calculate the impact location, evaluate the energy associated with the event, and use the waveform shape to calculate the probability that the event is an impact rather than extraneous noise. If the event is judged to be an impact, the integrated system will signal an alarm on an HDU Crew Display. Personnel inside the DSH will then select the alarm in order to display specific information, including the impact coordinates, severity, and a measure of confidence (to distinguish non-impact electrical interference). The crew will then locate the point of impact and assess the damage based on the Crew Display output.

A secondary goal for 2011 is to demonstrate the potential applications of HIMS to other habitat structures, such as a multi-layer inflatable. Inflatable structures are becoming more important in the planning of long-duration space missions both in and beyond Earth orbit. The HDU project's "X-Hab" inflatable loft

provides the opportunity for testing the HIMS on a flexible, inflatable structure.

V. ACKNOWLEDGEMENTS

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