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Full-Scale DELTA GEM MPS Demonstration May 11–12, 1999 AFRL/EAFB Rocket Laboratory

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13. ABSTRACT (*Maximum 200 words*)

A prototype Multiparameter Sensor System (MPS) is described for impact detection and environmental condition monitoring of graphite epoxy composite structures. This system is applied to a full-scale inert Delta-II solid rocket Graphite Epoxy Motor (GEM) casing. Microelectromechanical (MEMS) sensors are used in this demonstration, including those for 3-axis acceleration, temp-erature, pressure and humidity. All sensor measurements are made within a single package mounted at the center of mass of the test article. Sensor analog outputs are sampled with a National Instruments Inc. data acquisition PCMCIA card, and data is processed on a Pentium-II 200 MHz laptop computer. Sensor information collected during this demonstration was passed wirelessly to a remote user terminal for display and data storage. Data presented in this report includes peak acceleration for impacts just below damage threshold, environmental sensor trends, and wireless RF performance in a warehouse environment.

14. SUBJECT TERMS
Microelectromechanical sensors, MEMS, Multiparameter Sensor, Impact Detection, Delta-II, Health Monitoring, Graphite Epoxy Motor, Impact Monitor, Wireless Sensors, PCMCIA, LabView, graphite epoxy composite structures, condition based health monitoring.

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1. Introduction

Solid rocket Graphite Epoxy Motor (GEM) casings are susceptible to catastrophic damage due to blunt force impacts.[1] As an aftermath of the Delta 241 (IIR-1) explosion on January 17, 1997, field inspection of all GEM casings for damage just prior to launch was implemented. Subsequent investigations and feedback from industry have led to our proposal to instrument the entire fleet of GEMs from acceptance testing through erection on the launch pad with a continuous health monitoring system. This instrument would potentially monitor and record adverse impacts, accelerations, strains, or environments that may cause damage to the GEM casings.

The key requirements for such surveillance of GEMs are an unobtrusive system that does not interfere with normal rocket motor operations, direct-wire and wireless flexibility, very long-term surveillance capability in stand-alone wireless mode, low power, and the ability to identify normal operational signatures vs. unusual, serious events. Interest by the Medium Launch Vehicle (MLV) Program Office in the potential long-term application of such a system prompted this demonstration on a full-scale inert Delta GEM rocket motor as described in this report.

Technology developed under the Microelectromechanical (MEMS) Systems Corporate Research Initiative, Multiparameter Sensor (MPS) task was applied in the present demonstration.[2,3,4] This multi-year research program has led in this case to the creation of a system concept that would allow the unobtrusive, continuous health monitoring of Graphite Epoxy Motor casings and other impact-sensitive graphite epoxy structures. Our system concept uses a combination of MEMS sensors organized with a wireless network such that both impacts and environmental information can be collected, stored, and forwarded to a central computer via wireless radio frequency (RF) communication.

The purpose of this laboratory demonstration was twofold. First, to determine whether 3-axis accelerometers at a single location could detect impacts along the body of a full-scale, loaded, graphite-epoxy composite motor; and second, to demonstrate that this sensor could be implemented with a wireless networked MEMS multiparameter environmental monitor measuring 3-axis acceleration, temperature, pressure, and humidity. This report describes the multi-parameter sensor suite followed by presentation of results collected with the GEM MPS Health Monitoring System during a demonstration conducted at the Air Force Research Laboratory (AFRL), Rocket Laboratory at Edwards Air Force Base (EAFB).

2. MEMS Wireless Multiparameter Sensor System

A MEMS Wireless Multiparameter Sensor (MPS) is a combination of multiple microelectromechanical sensors measuring different environmental parameters integrated together with local computing, data storage, wireless communication, and power. The MPS is organized in a network such that hundreds of such nodes may communicate to a centralized data archiving computer (Figure 1). The need for such a sensor network is not limited to GEM health monitoring. The MPS system may be employed wherever high-value assets are stored, transported, or handled and where the past history of shock, acceleration, temperature, humidity, or pressure is of concern to the operation or reliability of that high value asset.

The present implementation of the MPS electronic hardware leverages off of commercially available technology to provide sensor data acquisition and processing, local memory storage, and networked RF communications. The design of the MPS is partitioned into an MPS sensor box and an MPS processor unit as shown in Figure 2. The partitioned design allows for customized arrangements of sensors to be tailored to a specific measurement, as well as to provide a common data collection, processing, storage, and communication infrastructure.

The primary goal of the MPS aspect of this demonstration was the development of a networked, wireless, MPS demonstration system capable of collecting and processing 3-axis acceleration, temperature, humidity, and pressure data from a MEMS sensor suite attached to the full-scale inert Delta GEM casing. This system can be scaled up such that up to fifty local area MPS sensor collection

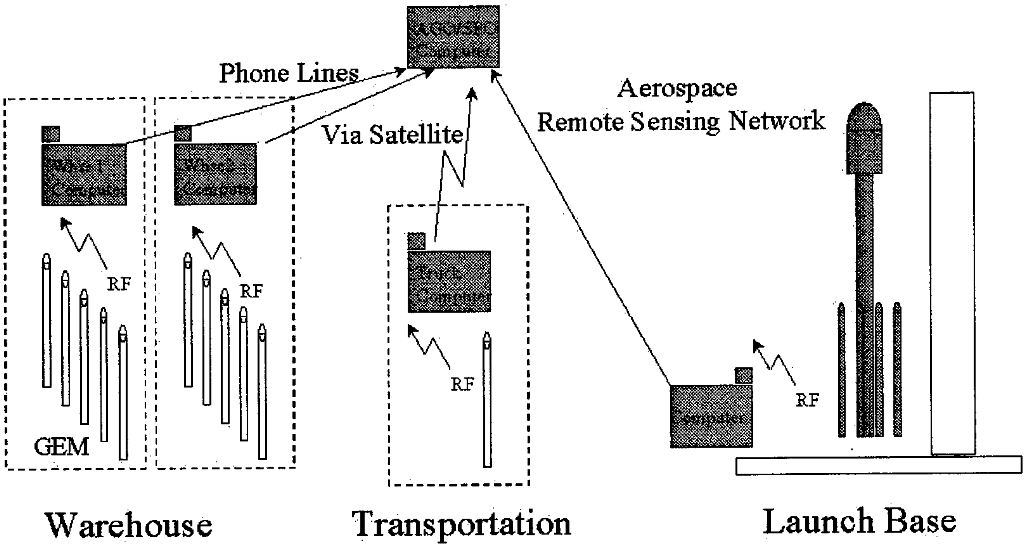

Figure 1. MPS Communication network concept showing coverage of high-value assets through storage, transportation, and pre-launch operations.

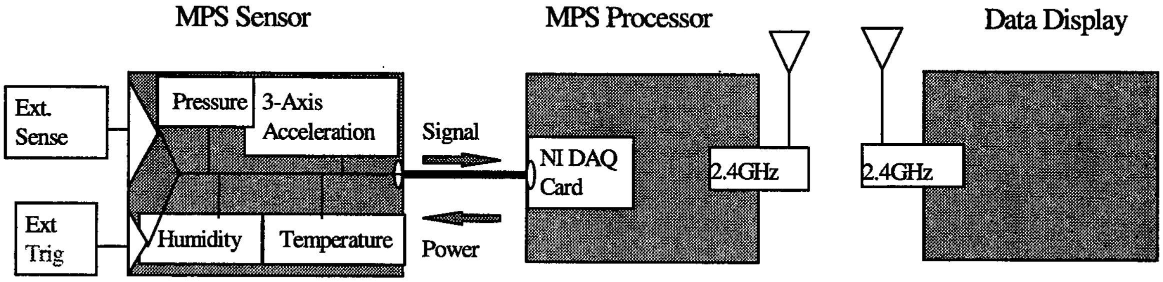

Figure 2. MPS signal acquisition and remote display block diagram showing the flow of information from the sensor front-end through the MPS data processor and wireless network to the remote user data display terminal.

sites can forward their data using a wireless network to a local data collection hub for data archiving or user display. Multiple local areas may be combined with a wired network such that hundreds to thousands of sensor nodes can be monitored over a large geographic area.

2.1 MPS MEMS Sensor Suite

In this demonstration, a 2 x 2 x 4 in. metal box, shown in Figure 3, housed the MPS environmental sensors in addition to a 3-axis accelerometer sensor. The environmental sensing package consisted of the Ohmic HC-700 humidity sensor, the Motorola MPX5100A pressure sensor, and the Analog Devices AD592 temperature sensor. The environments sensor package was rigidly fastened to the interior top of the sensor box, and holes were drilled to provide the sensors with exposure to the ambient environment.

The dynamic sensing package housed within the same sensor box was a three-axis accelerometer system consisting of one single-axis Analog Devices ADXL150 and one dual-axis ADXL250 accelerometer. To accurately capture the dynamic response of the test structure, it was necessary to decouple the acceleration response of the test structure from the acceleration response of the sensing

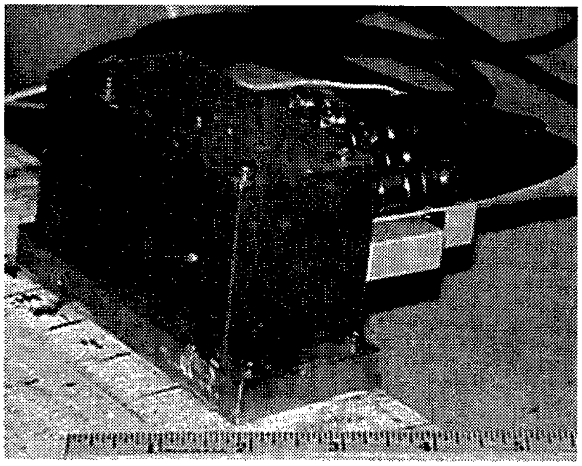

Figure 3. Multiparameter Sensor Package with 3-axis acceleration, temperature, pressure, and humidity sensors with optional interface to external sensors via BNC connections.

package. System requirements, in general, prevent the accelerometers from being mounted directly to the test article; our solution, in this case, was to provide a rigid path with known material characteristics between the sensors and the test article. The vibrational conduit connecting the sensor packaging to the test structure consists of a solid aluminum MPS sensor mount and an aluminum accelerometer mounting block (Figure 4).

When assembled, the sensors are attached to adjacent sides of the accelerometer mounting block using a thin layer of epoxy. The mounting block was then rigidly fastened to the MPS sensor mount by two cap screws. The current GEM demonstrator incorporated a thin layer of epoxy as the fastener connecting the MPS sensor mount to the GEM test article. Shown in Figure 5 is the commercial-off-the-shelf (COTS) implementation of the MPS system with the sensor attached to the GEM casing, and the wireless laptop collecting information from the test article. Coordinates were chosen such that +X is along the axis from tail to nose, +Y is from right to left across the axis of the booster, with the origin at the Center-of-Mass on the top surface of the GEM casing. +Z is normal to the surface at the CM location. The MPS was mounted at the coordinate system origin and aligned to the chosen coordinate system.

In addition to the environmental and dynamic sensing packages, the complete sensor assembly contained five mini-BNC connectors that served as optional input ports for trigger and external sensor inputs. Although unused in this demonstration, these inputs may be used to support customized sensors for a particular application. The combined signals were channeled through a National Instruments 68-pin shielded cable to the MPS data acquisition laptop computer. Power for the MPS sensors was provided by the laptop computer.

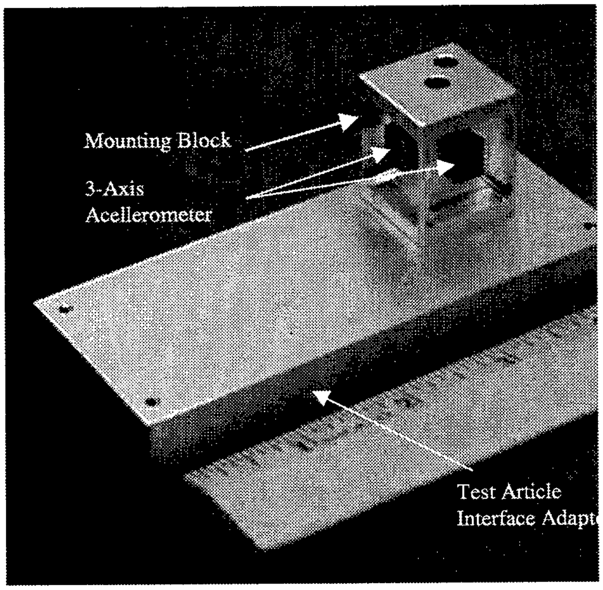

Figure 4. MPS sensor mounting adapter showing one single-axis MEMS accelerometer, one two-axis MEMS accelerometer, mounting block, and package interface to the GEM test article.

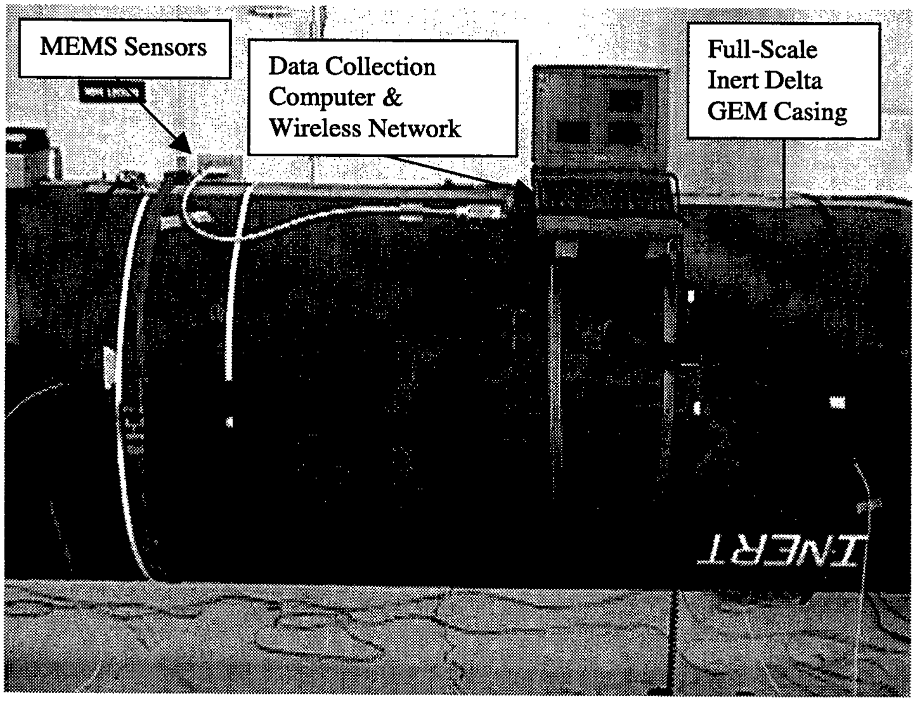

Figure 5. MPS sensor with data collection computer attached to Delta GEM during impact experiment testing. Data is collected at high speed, then forwarded wirelessly to a remote user display terminal.

2.2 MPS Data Acquisition Computer

To reduce cost and effectively perform the GEM MPS demonstration with the most flexibility, we chose to implement the MPS data acquisition portion of the effort with a conventional COTS laptop computer and wireless LAN. As part of the MEMS CRI effort, we are developing custom palm-sized MPS hardware (Figure 6). This future version of the MPS will have 3-axis acceleration, tem-

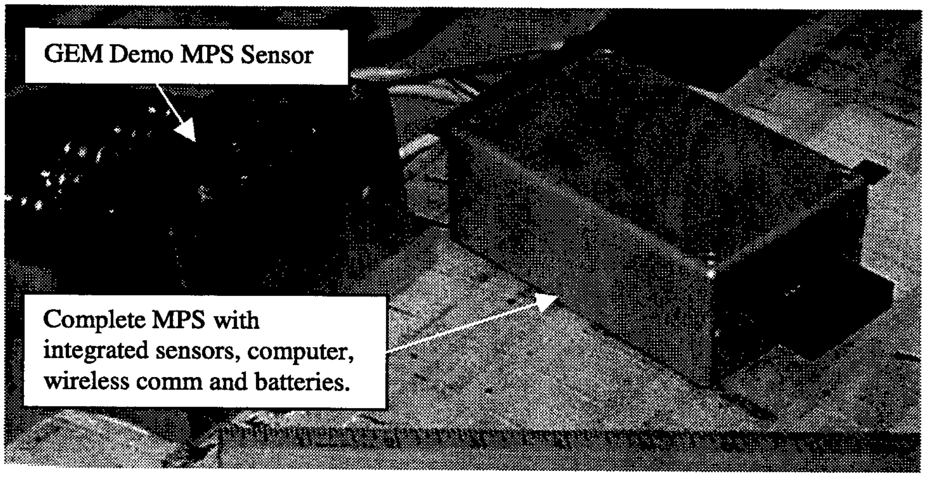

Figure 6. GEM MPS demo sensor (laptop computer not shown) and future palm-sized design of the complete multiparameter sensor.

perature, pressure, and humidity sensors, a micro-controller, event storage memory, time keeping, wireless communication, and power integrated into one miniaturized package.

A Hitachi VisionBook Plus 5000 with a National Instruments E-Series Data Acquisition Card processed the incoming analog sensor signals. The data sampling function of the MPS is provided by a commercially available 16-channel National Instruments DAQ PCMCIA card (AI-16XE-50) having 16-bit resolution. This card was configured for three high-speed channels, sampled at 25 ksamples/s, for accelerometer data collection, while three additional channels were used at a 500-Hz collection rates for non-environmental measurements (temperature, pressure, humidity). The software running the overall data acquisition process was developed in-house and based upon National Instruments LabView 5.0.

2.3 MPS Remote Data Display Computer

An important part of the demonstration was the wireless data exchange. A second Hitachi Laptop using a wireless local area network (LAN) served as the display computer. The hard drives of the two computers were cross-linked via the wireless network with both having shared file access. The remote computer also used LabView software to access files and plot MPS data. The MPS user screen displayed the three-axis accelerations, pressure, temperature, and humidity measurements. As each new information packet was stored on the remote display hard drive, the graphs of the MPS display were updated (Figure 7).

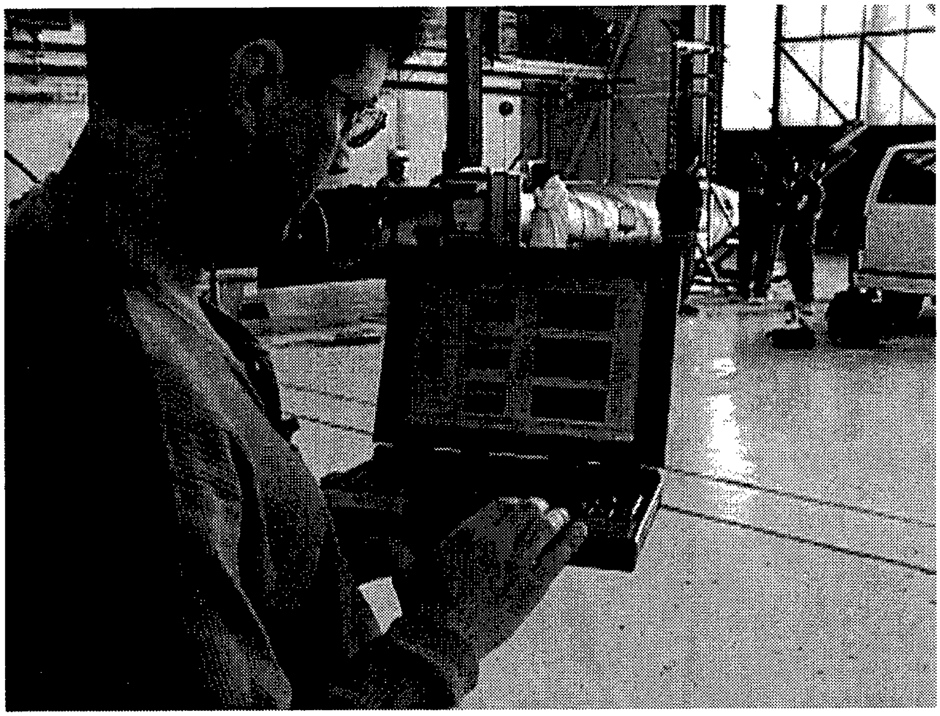

Figure 7. Remote user MPS display showing time sampled and Power Spectral Density (PSD) plots of accelerations for X, Y, and Z axes. Shown in background is the GEM test article with the wireless MPS sensor package mounted mid-ship.

3. Results

The MPS system was used in this demonstration to detect impacts, record impact impulse temporal waveforms, monitor the ambient environmental conditions, and transmit these results wirelessly to a remote user terminal for data display and storage. The following section discusses a summary of results related to these activities.

3.1 GEM Impact Testing

MPS impact acceleration data were collected with a 3-axis accelerometer located at the center of mass of the GEM casing. Accelerations were sensed with the Analog Devices Inc. ADXL-150 single-axis and ADXL-250 dual-axis ±50G accelerometers. Accelerometer system noise for each of the three axes was measured to be 64 mG, 62 mG, and 69 mG for the X, Y, and Z accelerometers, respectively. Frequency responses of the accelerometers are specified to have a –3 dB roll-off at 5 kHz.

Calibrated impact energies of 1 ft-lb, 3 ft-lb, and 6 ft-lb were created by impacting the side of the GEM casing with a fixed mass swung from various heights. MPS data acquisition was triggered on the leading edge of the impact acceleration wave as it propagated along the GEM casing. The MPS system was configured to store 1000 points of the incoming wave at 25,000 samples per second.

Data for the 1, 3, and 6 ft-lb impacts for various positions away from the MPS are shown in Figure 8. In each plot, the absolute value of the peak detected acceleration is plotted versus the distance away from the MPS sensor for each axis. Additionally, the root-sum-of-squares total peak acceleration is plotted. Data collected for impacts fore and aft of the MPS as well as data collected for impacts on the right and left sides are combined here and plotted as impacts at an absolute distance from the MPS. Right-side or left-side peak MPS impact responses are identical in magnitude due to the circular symmetry of the booster, except for the phase of the impact wave. Fore/aft impact responses may, in fact, be slightly different due to an asymmetry along the booster from the thick-walled nozzle-end to the thin-walled nose cone end. Our MPS measurements did not detect this asymmetry since we were measuring impact-induced body accelerations, which are slightly affected by this fore/aft asymmetry.

Data shown in Figures 8 show that for impacts along the sides of the GEM casing, the majority of the accelerometer response was along the y-axis, across the GEM casing axial direction (i.e., along the direction of the impact). Accelerometer responses clearly dampen rapidly as the location of the impact is moved away from the MPS sensor. All impact energies were sensed when closer than 3.5 ft, while a 6 ft-lb impact transient wave could be sensed at a maximum distance of 10 ft. The maximum distance at which an impact could be detected was ultimately limited by the noise floor of the MPS sensor. Once the impact signal had decayed to less than twice the system noise (~100 mg typ.) the impact could not be detected.

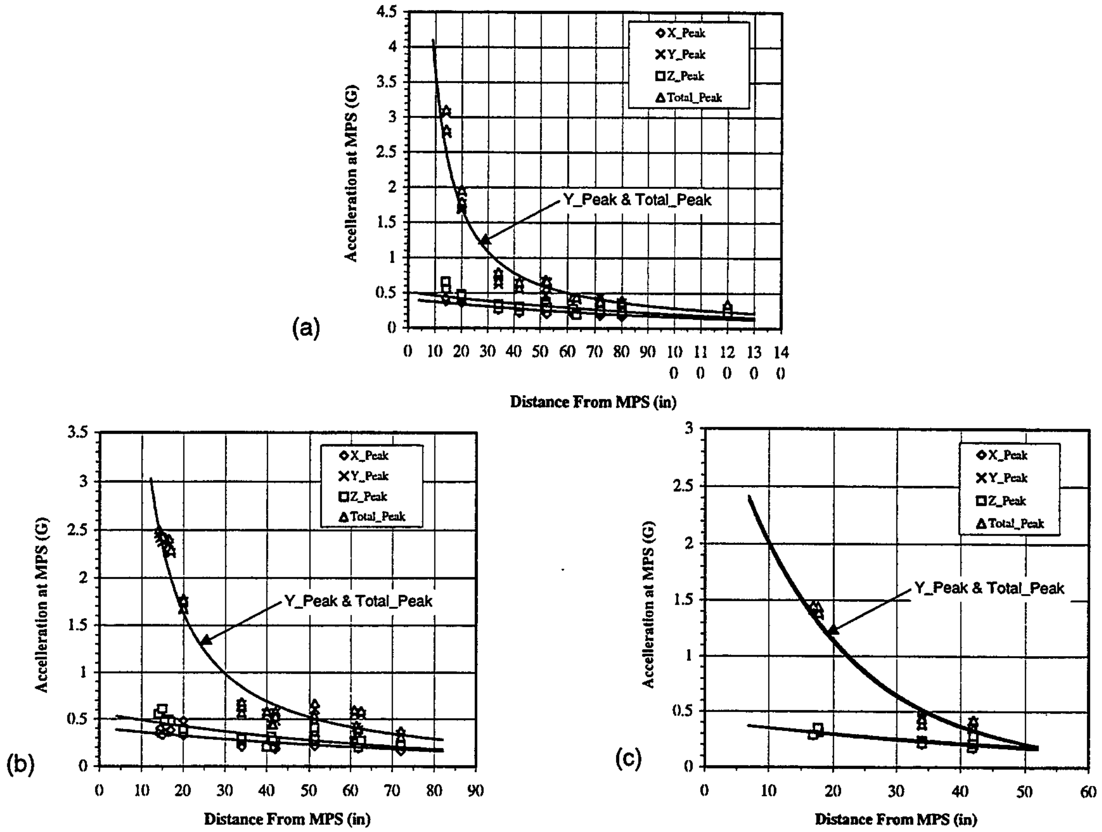

Figure 8. Peak impact acceleration vs. position from MPS for (a) 6 ft-lb impact energy; (b) 3 ft-lb impact energy; (c) 1 ft-lb impact energy.

From this data, one can conclude that to develop a low-cost, minimal, distributed accelerometer network, capable of detecting an impact energy equal to or greater than 6 ft-lb anywhere along the GEM, would require as a minimum, a string of four single-axis accelerometers. These sensors would be located along the axis of the GEM, placed every 10 ft. This could be accomplished by simply distributing along the body of the casing, in a single string, the existing three MPS accelerometers and using an additional internal MPS accelerometer. This spacing would cover a 40-ft-long casing, potentially more, allowing for detection of any side impact energy greater than or equal to the 6 ft-lb damage threshold, anywhere along the GEM. The main short-coming of this approach is that impacts lower than 6 ft-lb at a close-in distance may trigger the system, creating false impact alerts. This short-coming would only alert operators to small impacts that were falsely identified as damaging; true damaging events would still be recorded as well. Due to the simplicity and ease of implementation, this short-coming may be considered acceptable.

Performance of the MPS accelerometer sensor may additionally be improved to increase sensitivity and to reduce the sensor noise floor. The present MPS design uses a ±50 G accelerometer. A ±5 G accelerometer would have been preferable for impact detection. Since the noise, in this case, is largely due to the read-out system, use of the higher sensitivity accelerometer would proportionately lower the noise floor, potentially allowing for 10 mG trigger threshold operation. Both of these sensor improvements would increase the detection distance range of the MPS impact monitor.

3.2 Environmental Sensor Data

Multiparameter environmental sensor data was derived from commercial MEMS and conventional sensors. MPS sensor performance data are shown in Table 1. In this demonstration, MPS data were sampled, averaged, and stored at the time of impact; however, it is expected that in actual use the environmental portion of the data stream would be continuously data logged at a low rate to detect hazardous environments during storage and/or transportation. All MPS data were wirelessly transmitted to a roving remote laptop computer that stored the impact accelerations and environmental data.

Figure 9 shows the general trends in ambient temperature, atmospheric pressure, and relative humidity during the course of the test day. Increasing temperature during the day with a reduction in atmospheric pressure and a decrease in relative humidity were observed. In the data plots for temperature and pressure, there are anomalous data points early in the day and later in the afternoon. These data points are suspected to be due to changes in our test set-up stemming from differing power sources. Differing potentials from laptop battery, auxiliary battery, or AC line adapter resulted in DC offsets in the sensor electronics of a few tens of millivolts. These differences resulted in the offset measurements and can be corrected in the future by the addition of improved line regulators.

From the environments data shown, we demonstrated an ability to measure changes of better than 0.1°C in temperature, 0.1 kPa in pressure, and 0.5% in humidity. Based on manufacturer datasheet information, our absolute knowledge was limited to ±0.8°C in temperature, ±3 kPa in pressure, and ±2% in humidity. For this application, the MPS environmental monitors have more than sufficient resolution to detect and record most, if not all, storage, transportation, and launch base environments.

Table 1. MPS Sensor Performance

Sensor Type	Model	Data Range	Power Requirements
Temperature	Analog Devices AD592	–25°C to +105°C, ±0.8°C	4–30 VDC, 120 uA
Pressure	Motorola MPX5100A	15-115 kPa, ±3 kPa	4.75–5.25 VDC, 5–10 mA
Humidity	Ohmic HC-700	0-100%RH, ±2%RH	4–9 VDC, 0.2 to 2.0 mA
1-Axis Acceleration	Analog Devices ADXL150	±50 g	4.75–5.25 VDC, 1.8 mA
2-Axis Acceleration	Analog Devices ADXL250	±50 g	4.75–5.25 VDC, 3.6 mA

3.3 RF Datarates and Datapacket Loss Measurement

During our impact and handling test exercises, an additional experiment was conducted to determine the approximate datarate and datapacket error rate of the wireless network portion of the MPS system. Currently, all MPS data is collected in RAM on the data acquisition computer and then stored to a remote hard disk via wireless at the user data terminal. In the GEM impact detection application, real-time data streaming is not required, although local high-bandwidth data collection is paramount. In other applications, such as remote control, process control, or battlefield sensor networks, real-time streaming data may be required. These wireless real-time intensive applications will have their datarate impacted by the local rf transmission environment.

The present test was performed inside the warehouse/hangar where the GEM motor was located. The warehouse enclosure was approximately 100 ft wide by 200 ft long by 50 ft tall. The optimum direction of the MPS antennas was determined to be in the plane of the laptop keyboard, to the left of

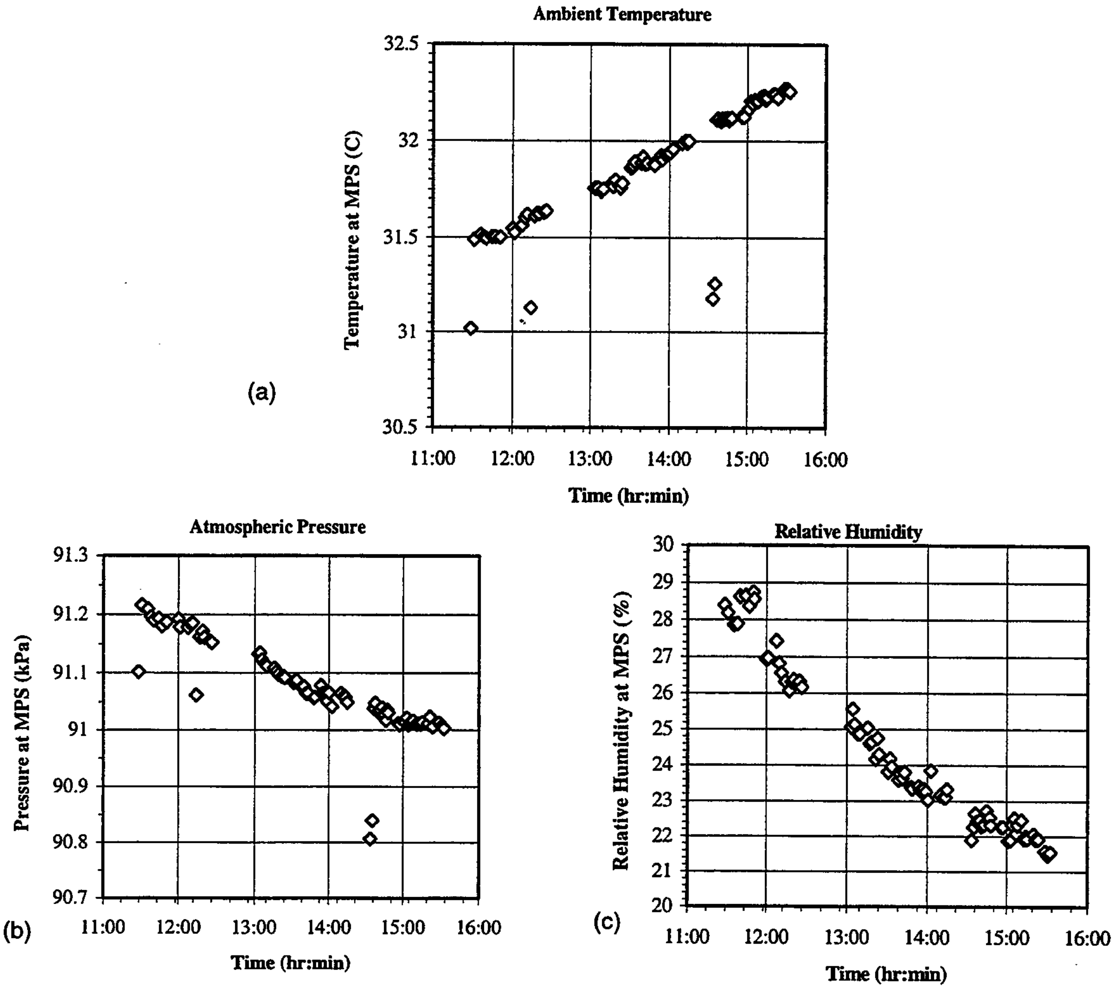

Figure 9. MPS (a) ambient temperature, (b) atmospheric pressure, and (c) relative humidity during impact testing at AFRL/EAFB rocket laboratory. Panel (c) shows drying trend during the test day.

the operator. As part of the GEM MPS demonstration, the remote user data display computer was moved around the interior of the warehouse while datarate and datapacket error rates were determined. This experiment used a custom program that continuously broadcasts fixed data packets from the MPS data collection system, while the remote user terminal logged wireless communication channel performance statistics.

Shown in Figures 10 and 11are the results of this test. Figure 10 shows that the user terminal can expect to receive no less than 200 kb/s nor more than 400 kb/s. These values are to be compared with the maximum measured datarate of 1 Mb/s observed when outside and far away from all sources of interference. The wireless communication channel uses the same basic bit rate to communicate all the time, the effective datarate is lowered when, due to interference, datapackets are lost. Figure 11 shows the packet error rate plot of the warehouse environment. This figure shows that packet error rates range from 40% to 73% throughout the warehouse.

Although these rates will be different for any particular application, the results suggest that it is critical to survey the proposed application site to determine whether the desired wireless datarate performance can be achieved. Simple differences in configuration can have a dramatic effect on the resulting datarate, as seen in this case. One example of this can be seen in Figure10. On the right side of the figure, the warehouse metal bay door was closed, while on the left side the bay door was open. The resulting multipath RF reflections off of the closed door resulted in an approximate 30% loss of datarate between the ends of the warehouse.

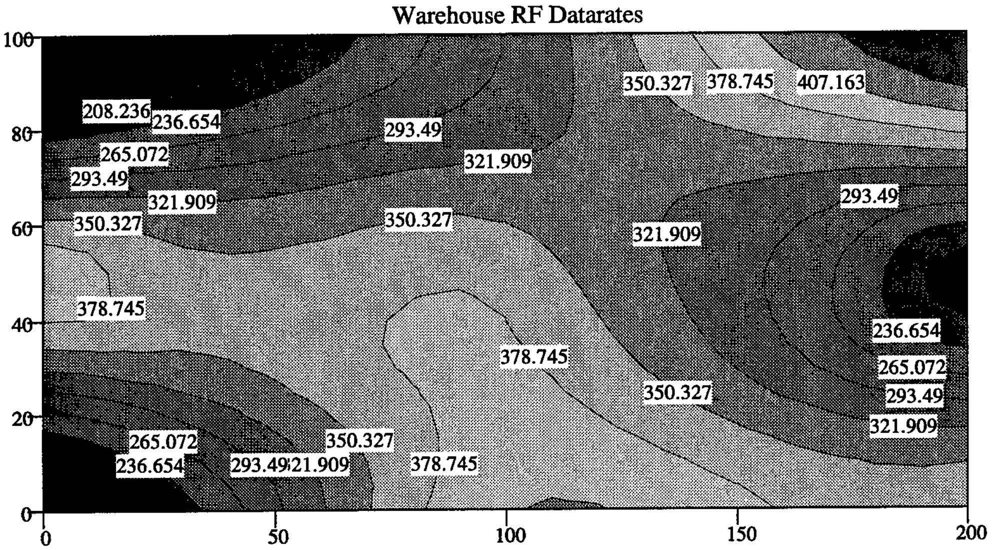

Figure 10. MPS wireless datarates in positional relationship to the GEM casing. GEM casing is located in upper left corner. X-Y positions are in feet, datarates are in kb/s.

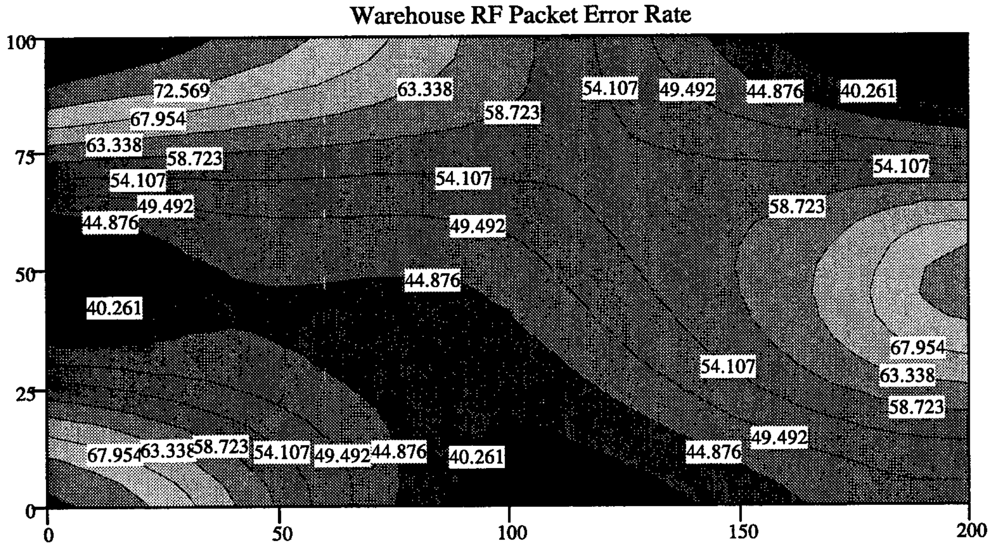

Figure 11. MPS wireless datapacket error rates in positional relationship to the GEM casing. GEM casing is located in upper left corner. X-Y positions are in feet, error rates are in percent.

4. Conclusion

We have successfully demonstrated a prototype Delta GEM impact and environments health monitor using the Aerospace Corporate Research Initiative MEMS Multiparameter Sensor (MPS) system. Impacts slightly below the damage threshold were detected up to 10 ft away from the MPS system, leading to the possibility of developing a simple, low-cost, distributed impact detector based on the MPS with a distributed chain of accelerometers mounted along the body of the GEM casing. This impact monitor would not determine absolute impact magnitude or precise impact location, but would alert the user that an impact above a predetermined threshold had occurred and within which 10-ft segment of the GEM the impact was located.

The MEMS sensors used in this demonstration provided a multi-parameter measurement of temperature, pressure, humidity, and three-axis acceleration. The environmental data collected showed normal daily trends in temperature, pressure, and humidity during the experiment run. This information could be used, in practice, to determine that GEM casings were stored properly and not exposed to excessive temperature, atmospheric humidity, or surface dew.

Finally, our wireless system was exercised in a typical warehouse environment and showed data rates sufficient to support 8-bit sampling at 25 ksamples/s. This level of performance would be sufficient for many wireless applications requiring real-time wireless data streaming from remote MPS sensors.

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