

Small Surface Probes for Solar System Exploration

J. C. Reddick¹, B. H. Kelsic, C. M. Cottingham, S. Roark, W. Tandy
Ball Aerospace & Technologies Corp.
1600 Commerce St., Boulder, CO 80306
¹(303) 939-7510, jreddick@ball.com

Abstract

Ball Aerospace & Technologies Corp. is developing miniature, robust, FPGA-based avionics systems for small science probes that are applicable to a wide range of solar system exploration missions. This system offers a new design solution for space systems that require motion control and high-speed sensor data acquisition and processing in a miniature, lightweight, low-power package. A modular architecture with standard interfaces provides versatility for a wide range of mission scenarios with minimal non-recurring engineering. The instrument functions are separated from the core functions, so the instrument suite can be selected for specific mission requirements without disrupting the overall avionics architecture. Additional IRAD activities have established and validated analysis methods for electronics in high-shock applications – allowing the assembly to be designed for the extreme environments expected in certain exploration missions. This paper will describe the development of rugged, miniature avionics and their implementation in a breadboard-level demonstration probe.

Keywords: aerospace, high-reliability, shock, probes, avionics

Introduction

Ball Aerospace & Technologies Corp. is increasing the technology readiness level of critical components for small science probes through a series of independent research and development (IRAD) projects. The projects involve development in the following areas:

- 1) miniature FPGA-based avionics that can be adapted to a range of small probe and instrument suite concepts. The avionics utilize standard interfaces for instrument control and data collection, and provide sufficient processing capability and memory for data management.
- 2) electronic packaging and analysis approaches for extreme environments, with a near-term focus on high shock and low temperature applications

Future developments will be directed at refining the communications system to operate at higher data rates, further reducing the size of the avionics, and integration of multiple instruments.

Background

In-situ measurements at the surface can provide unique, detailed information regarding the com-

position, structure, and characteristics of asteroids, comets, and planets and significantly increase the science return of numerous missions.

Small surface probes with relatively simple instrumentation could enable valuable in-situ science experiments without requiring a dedicated mission or severely impacting mission cost. Systems for controlling the descent and impact would not be needed, and the close proximity of an orbiting spacecraft simplifies the communications system and power requirements. However, since descent and impact controls are not used, certain missions may experience high shock levels as the probes are essentially dropped onto the surface.

Description of work

Ball Aerospace & Technologies Corp. has advanced the avionics architecture and the ability to design and analyze electronics for high-shock science missions. Together, these areas of development form the foundation for robust, miniature probes, that can be used for solar system exploration. The following sections will describe the development.

Architecture development for miniaturized, high reliability avionics

The avionics architecture is an FPGA-based Printed Circuit Board Assembly (PCBA), with standard interfaces to support numerous compact instruments for science data collection. The on-board memory is sufficiently large to allow for data storage and periodic uploading, as required by anticipated mission Concept of Operations (CONOPS). The packaging of the avionics is focused on miniaturization and scalability.

The electrical specifications of the avionics architecture are provided below:

Processor: 25 MHz LEON-3

Storage Capacity:

- SDRAM: 16 Mbytes
- FLASH ROM: Design supports 2 GBytes, board populated to 512 kByte

Data Interfaces:

- 2 Channel RS-422 Serial
- Space-wire
- 32 Channel 12 bit A/D -5 to 5 Volts
- 8 Channel 12 bit D/A -5 to 5 Volts
- 48-bits of general purpose digital I/O

The avionics Printed Circuit Board (PCB) is approximately 10 cm square. The construction utilizes embedded resistance and embedded capacitance, to achieve a minimal form-factor. Figure 1 shows the top-side parts placement for the PCBA.

The previous version of this architecture – with less memory and a larger form-factor - was successfully built and functionally tested. The architecture shown in Figure 1 reduced the previous PCB size by 50% by utilizing embedded passive components and a scalable interface. The design shown is presently being fabricated.

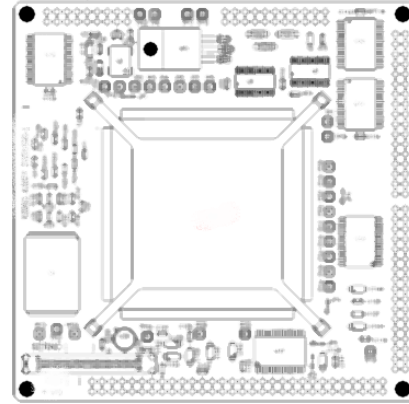


Figure 1 - Avionics PWA

Development for extreme environments – Analysis capabilities

The desire to keep the probe small, and relatively simple, precludes the use of controlled descent. Therefore, the probe is essentially dropped onto low gravity bodies such as the moon, asteroids, or planets. This CONOPS requires the avionics system within the probe to be able to withstand thousands of G's of drop shock. To be able to effectively design for high G applications, it is critical to perform reliable structural analysis at high G's. Ball Aerospace has developed custom analysis capabilities for this reason.

In order to shorten the design cycle, a custom analysis interface tool was developed to create finite element models of PCBAs directly from the PCBA design software, such as Mentor Graphics. The Board Analysis Tool (BANT) is written in Matlab and provides a graphical user interface for the automatic creation of detailed finite elements models (FEM). Component locations, board dimensions and more are imported from the industry standard IDF files and are used to generate the FEM.

The proprietary streamlined analysis process allows for a tighter design cycle and more precise analysis, which make designing for extreme environments more manageable. The analysis approach has been validated against previously utilized analysis techniques.

Development for extreme environments – Shock testing

In addition to the analysis methodology developed, shock testing was performed to better understand design variables in probe-sized PCBAs. Specific

variables that were included in testing include: PCB thickness, component type, component location, and component staking materials. Shock testing was performed at 500G, 1000G, 2000G, 5000G, and 10000G at the fixture input. Functional testing of each electrical component was conducted before and after each shock level. The specific variables and components are defined below.

Variables tested:

- PWA type (avionics and power supply components)
- PWB thickness (.093 and .125")
- Component placement (near edge and near center of PWA)
- Staking (various component staking materials and one full encapsulation material)

Component types tested:

- Stacked capacitors
- Tantulum capacitors
- Latching relays
- Oscillators
- Integrated circuits
- Diodes

Ten separate test vehicles were built and tested; four variations of the PCBA with avionics components, see Figure 2, and six variations of the PCBA with power supply components, see Figure 3. Each style of PCBA was built with varying PCB thickness and component staking methods.

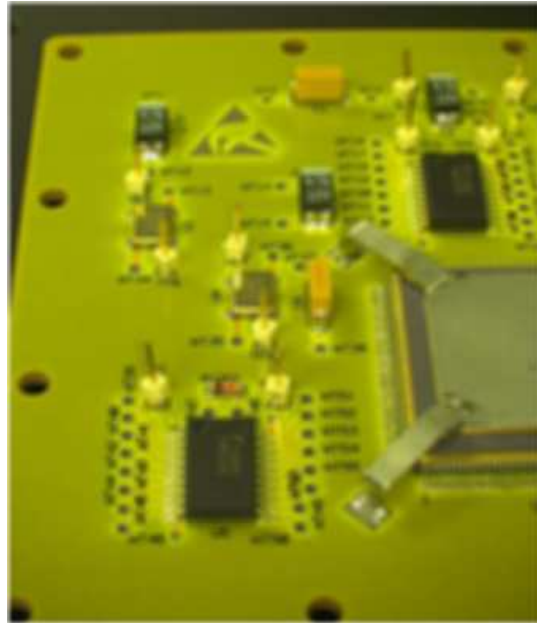


Figure 2 - Shock Test Vehicle: Avionics Components

Each component on each of the ten test vehicles was functionally tested before and after being exposed to a shock event. One exception is the large FPGA on the avionics PCBAs. The supporting circuitry was not included to provide electrical testing. The FPGA was only inspected for physical damage on the case, leads, and solder joints.

All test vehicles were then exposed to escalating levels of shock. The levels tested ranged from 500G to 10000G. These levels were calibrated at the test fixture. Actual board level responses were higher in some cases. The setup of the test vehicles on the shock beam is shown in Figure 4. All shock testing was performed in Ball Aerospace's environmental test facility.

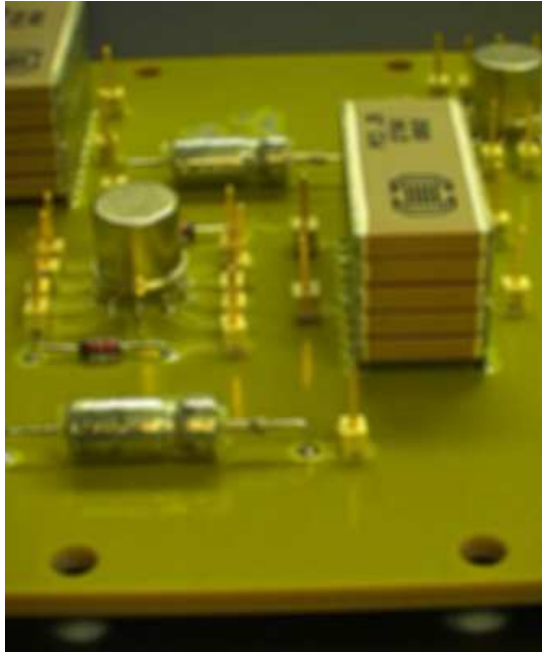


Figure 3 - Shock Test Vehicle: Power Supply Components

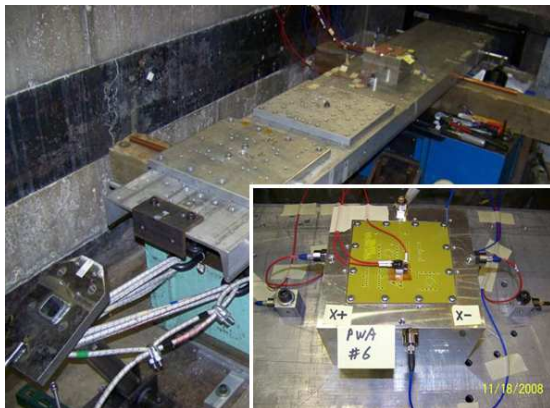


Figure 4 - Test Setup on Shock Beam

After the 500G, 1000G, and 2000G shock levels, all components operated successfully. One exception to this was a single relay, which malfunctioned after the first test. This condition was deemed to be a manufacturing defect, not a shock failure.

After the 10000G shock exposure, the latching relays that were placed near the edge of the PCBA either flipped or failed. The relays placed in the middle of the PCBA, and all other components, survived 5000G with no performance degradation. One possible explanation for this result is that the shock wave dissipates as it propagates through the board.

In general, the electronics components that were believed to be most susceptible to shock damage performed better than expected. The PCB thickness and staking variables were not a factor in the test results. This could be because the small board size of 10cm by 10cm drove the stiffness of the assembly more strongly than in larger board designs. However the board size was chosen because it was representative of the probe form-factor. Larger boards may exhibit different shock response characteristics.

Development for extreme environments – Material testing

Adhesives are commonly used in the aerospace industry to stake electrical components on PCBAs to help ensure they survive their vibration environments. These environments include ground testing, launch, deployment, and possibly intentional impact with other objects. The nonlinear response of these adhesives to vibration and temperature makes analysis difficult. Ball Aerospace investigated the static and dynamic properties of several materials to develop optimum staking solutions for several environments. Several adhesives were characterized for their response using Dynamic Mechanical Analysis in a frequency spectrum from 1 to 1000 Hz at discrete temperatures between -150C to 85C. The data were used to generate storage modulus Master Curves using Williams, Landel, and Ferry (WLF) Time Temperature Superposition software. These WLF Master Curves are then used in structural analysis to optimize PCBA design. Selected adhesives were used on representative PCBAs with shock-sensitive components. The shock testing described in the previous section was performed to demonstrate the material performance and validate the structural analysis, thereby enhancing the complex design capabilities of shock-tolerant electronics at Ball Aerospace.

Some mechanical properties for staking and encapsulating adhesives are available from their manufacturers. For most aerospace applications, more testing is usually required, for example at cryogenic temperatures, or in vacuum. In this study, the storage modulus of three urethane and one silicone were characterized over a wide temperature range. The test data are then used in our structural engineering analysis to predict board behavior in the vibration environment.

Materials Testing: Tensile Modulus Using DMA

Modulus testing using a MtraviB Dynamic Mechanical Analyzer (DMA) model 150 was used to conduct the tests at Akron Rubber Development Laboratory (ARDL). These types of modulus experiments are routine at ARDL since their focus is on testing elastomeric materials (Ball Aerospace's DMA tester can only test up to 200 Hz). Dr. Edward Therrill from ARDL was our chief engineer for the testing.

Materials Testing: Frequency Sweeps Using DMA for Storage Modulus

Frequency sweeps and temperature sweeps were conducted per ASTM Test Method D5992. The frequency sweeps were used to produce the WLF storage modulus master curves. For these tests, the temperature and input load were held constant and the oscillating frequency input was run for 20 frequencies over the range of 1 to 1000 Hz. This test was repeated for 34 temperatures between -150°C and 80°C, in increments of 5 to 10 degrees. From this data, the WLF time temperature superposition technique was used to create master curves for the storage modulus (equivalent to the tensile modulus) for each material over a wide frequency range. These master curves can be used to show how the materials respond to an input dynamic strain while at any reference temperature.

As an example, the temperature curves and the generated master curve for Material A are shown in Figures 5 and 6.

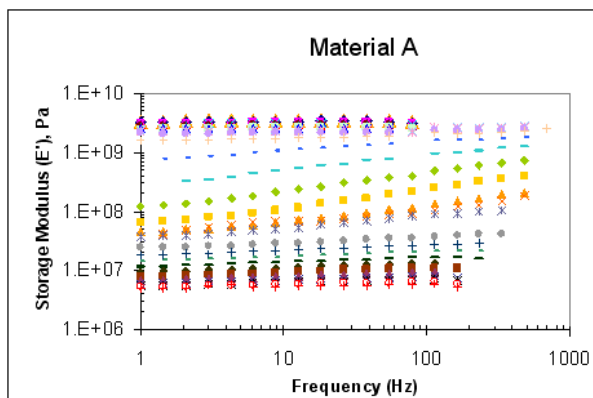


Figure 5 - Storage Modulus versus temperature and frequency for Material A

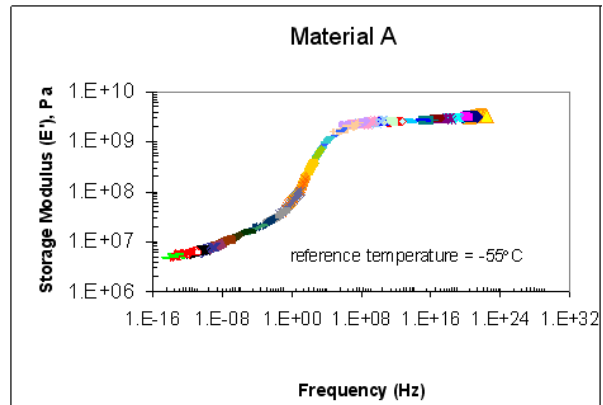


Figure 6 - Storage Modulus master curve for Material A at -55°C

Materials Testing: Temperature Sweeps Using DMA for Storage Modulus and Tangent Delta

In this test set, temperature sweeps were conducted while the dynamic input frequency was held constant. Storage modulus, Loss modulus, and Tangent Delta were calculated. This data allows more precise evaluation of the effect of a specific frequency on a material. For example, some elastomers, when moved very slowly, take on a new permanent set or new shape. An extreme example of this phenomenon is the creep or sag of glass over a long time period, even at room temperature. On the other end of the spectrum, some elastomers fracture when moved at high frequencies. A rubber band can support more weight when loaded slowly than when pulled rapidly since it has time to realign its molecules.

Test parameters for temperature sweeps: The instrument was used in the tensile mode. While oscillating at a fixed frequency, temperature was ramped from -150°C to 80°C at a rate of 1°C/minute. Four frequencies were run: 1, 10, 100, and 1000 Hz.

As an example, the storage modulus, loss modulus, and tangent delta for Material A are shown in Figure 7.

Understanding how commonly used staking materials behave over wide temperature and frequency ranges is important in being able to reliably model the structural behavior of probes used in harsh environments. The material property characterization allows for informed design choices and reliable analysis inputs.

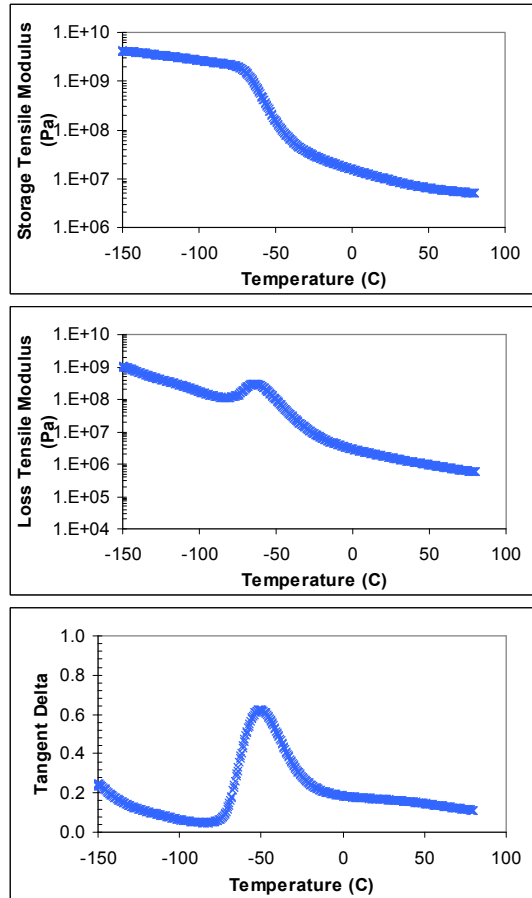


Figure 7 (a) Storage Modulus, (b) Loss Modulus, and (c) Tangent Delta for Material A at 1 Hz

Conclusion

This work involves multiple discrete activities, all supporting the development of small probes intended to collect data in support of the science goals of numerous space missions. The conclusions of each activity will be provided in this section.

Electronics architecture: the FPGA-based avionics development has been proven functionally with a breadboard PCBA. The design has gone through a second iteration to enhance memory capacity and decrease the size. The avionics subassembly now fits on a single 10cm square PCBA and can be used as a module in various probe applications, allowing interfaces for various instruments. The avionics PCBA still needs to be hardened for harsh environments.

Structural analysis of electronics in high-shock applications: analysis techniques were streamlined and correlated with expected results. Improved

(a) analytical methods allow for more complex designs to be analyzed quickly and reliably.

Shock testing: key conclusions from the shock testing are as follows:

- PCB thickness and staking were not observed to have a strong impact on component survivability when the boards are small. Relays aside, shock levels were not high enough to truly test these variables
- Latching relays are more robust than expected but appear to be the limiting component for shock applications. Solid state relays should be investigated for high-shock applications
- Capacitors, ICs, oscillators, and diodes showed no performance degradation. They may degrade if used on larger boards (hence larger PWB displacements)

(c)

Material characterization: material property testing was deemed to be an important element in designing for extreme environments. DMA testing from 1 to 1000Hz, and over varying temperatures, was proven to be a valuable design and analysis aid. Material properties of common materials were determined, but just as important, the process to test additional materials was established.

Summary

Developing a robust electrical architecture and developing the ability to design and analyze electronic assemblies for extreme environments are believed to be the foundation for miniature space-science probes. Materials, component selection, assembly design, and analysis for extreme environments are the building blocks for this development.

Ball Aerospace & Technologies Corp. has increased the technology readiness level of these critical components for small science probes through a series of development projects. The projects involve development in miniature FPGA-based avionics that can be adapted to a range of small probe and instrument suite concepts. The avionics utilize standard interfaces for instrument control and data collection, and provide sufficient processing capability and memory for data management.

Additional development involved the electronic packaging and analysis approaches for extreme environments; with a primarily near-term focus on high-shock and low temperature applications. The work included proprietary enhancements of analytical methods, empirical shock testing, and material characterization - all of which are tools in the ability to successfully design for extreme environments.

Future developments will be directed at refining the communications and power subsystems of the probe architecture. Additional work will also be directed at merging all functional subsystems with the shock-tolerant work to provide a fully operation probe architecture for use in extreme space environments.