Device for Temporal Measurement of Loads in Parachute Suspension Systems

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In order to understand the distribution of loads in parachutes, the NASA Low Density Supersonic Decelerators (LDSD) project developed a wireless instrument to measure loads in the parachute suspension lines. The load cells are titanium links that are connected in the primary structural load path of the parachute system. Strain gages measure the elongation of the links and an onboard data acquisition system records the data to flash memory. The load cells have onboard power, and include a radio transceiver that is used to receive timing information. The load cells are designed to be interfaced with cordage, packed in a parachute bag, and deployed with a standard parachute deployment. The devices are triggered passively during the deployment of the parachute. Prototype devices with a mass of 100 grams and a load capability of 16,000 lbs were built as a proof of concept.

I. Introduction

Parachutes use suspension lines to connect the parachute canopy to the risers and bridles. The suspension lines are parallel load paths between the canopy and the payload. Typically, in parachute tests, the drag load of the parachute is measured by measuring the load at the interface of the payload. That load measurement only gives the total axial load of the parachute, but doesn't provide information about the distribution of load in the canopy. In order to verify design factors for suspension lines, the load in the suspension lines must be measured. Typically, the available load cells for measuring line loads are bulky and often require routing wires; most existing solutions are not low mass impact solutions to the parachute and typically cause restrictions on the test methods. For the NASA Low Density Supersonic Decelerators (LDSD) project, a 30.5 m diameter parachute was deployed in high altitude supersonic flow, with parachute inflation times less than one second. The packed density of that parachute and the inflation conditions were prohibitive for any existing methods of measuring line loads. Therefore, the LDSD team developed embedded miniature load cells with the objective of measuring in-situ the suspension line loads of a supersonic parachute inflation. The goal was to gather data on suspension line loads during canopy inflation in order to validate the estimated dynamic and asymmetric factors used in the predicted line loads.

I.A. Measurement Strategy

Despite the device being relatively small and lightweight, it still seems unrealistic to measure the individual load of every single suspension line. This is particularly impractical on a large parachute with many suspension lines. Therefore, there are two possible ways to implement suspension line load measurements; groups of lines can be measured or single lines can be measured. For the LDSD parachute, it was relatively simple to implement twelve devices because there are twelve joints connecting the suspension lines to the single riser. There are two approaches to using twelve devices to measure 96 suspension lines: measuring groups of lines or measuring individual lines. Measuring twelve groups of eight suspension lines gives a good indication of the overall load distribution in the lines and provides insight into circumferential load asymmetries in the canopy. Measuring twelve individual lines doesn't give a good indication of the overall load distribution, but

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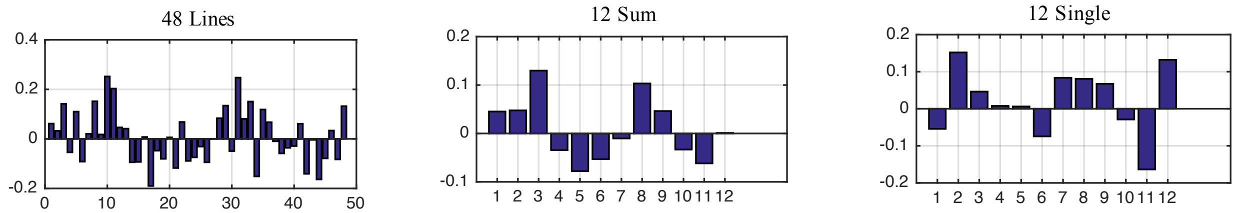
instead gives a better indication of the load variability among single lines. An example of this for twelve devices and 48 suspension lines is shown in Figure 1. This paper doesn't propose a correct strategy; this should be determined by the end-user of the load data.



(a) Total set of instantaneous line loads.

(b) Instantaneous loads for groups of 4 adjacent lines from the total set. The load variability is attenuated, but the load distribution is maintained.

(c) Instantaneous loads for evenly spaced individual lines from the total set.

Figure 1. Fictional data to demonstrate differences in measurement strategy. The suspension lines are shown on the x-axis. The y-axis shows the unitless deviation from the mean suspension line load. The sum method in (b) captures the overall load distribution better, but the single method in (c) captures the variability in load better.

I.B. Device Requirements

To this end, the load cell must have no detrimental performance impact on the parachute deployment, inflation, and structural capability and must be fully integrated into a supersonic parachute. This requirement translates to a design with a low volume, low mass, and a shape that wouldn't harm the surrounding softgoods. It must also be able to handle the high packing densities and large accelerations experienced during parachute deployment. A list of more complete design requirements and goals follows.

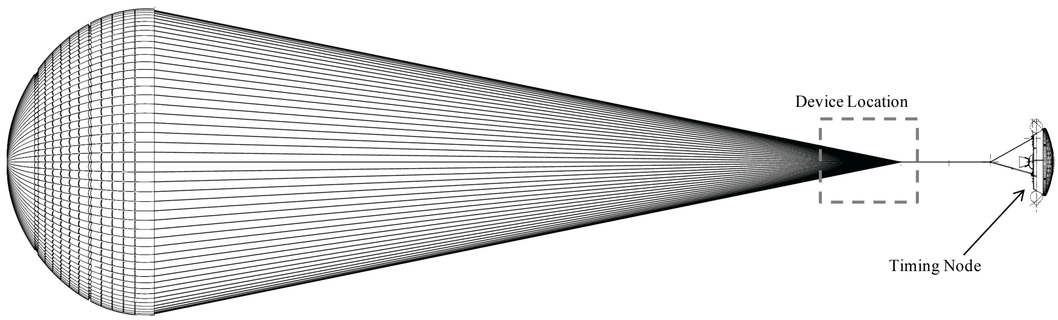
The device shall meet the following requirements:

1. Repeatably measure load up to 14,000 lbs (the full capability of the softgoods).
2. Measure load with an accuracy of $<3\%$ at loads > 500 lbs.
3. Load data shall be time tagged to accuracy of $<= 10$ msec with respect to a common time source.
4. Have a mass of less than 100 grams.
5. Passively trigger during parachute deployment.
6. Fully function after being packed in a pack with a density of 50 lbs/ft^3, or survive 120 psi of packing pressure.
7. Record for a minimum duration of 3 minutes.
8. Be designed for a maximum packed storage time of 12 months from parachute packing.
9. Meet all functional and performance requirements after being subjected to a max inertial load of 600 g for 20 ms.

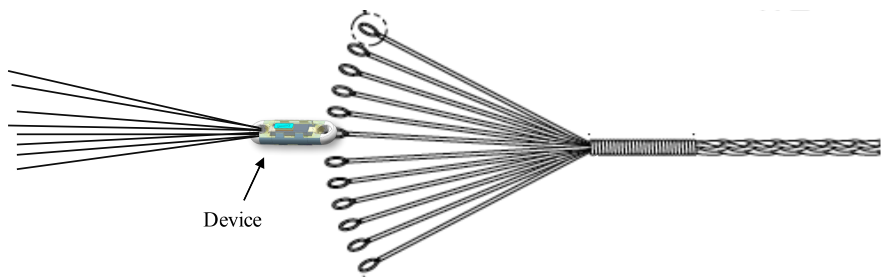
I.C. Device Overview

The devices were designed to connect the suspension lines to the riser lines at an existing joint location. One side of that joint is eight 1/8" Technora suspension lines, and the other side of that joint is a single 3/8" diameter Technora cord. Figure 2 shows the location of the devices in the canopy.

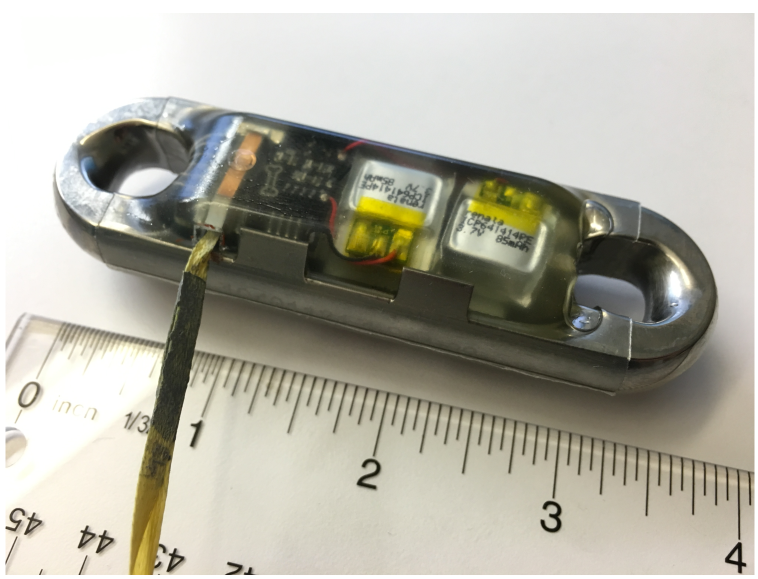
The device is a self-contained load cell and data acquisition system with a timing node radio to enable transmission of timing data from the parent spacecraft to the 'n' number devices. The load cell portion is a titanium link that is part of the primary structural load path of the parachute suspension system. Strain gages attached to the link measure the elongation and the onboard data acquisition system records the data to flash memory. Batteries are packaged internally and the device is turned on and triggered with a lanyard pull. The radio transceiver is capable of receiving timing information and transmitting data. The device



(a) Schematic of LDSD parachute and test vehicle.



(b) Detail of location of the device at an existing joint.



(c) Photograph of a functioning prototype of the device.

Figure 2. Location of the device in the parachute system.

is designed to interface with cordage, packed in a parachute bag, and deployed with a standard parachute deployment. Prototype devices with a mass of 100 grams and a load capability of 16,000 lbs were built as a proof of concept. The devices can be recharged and reused. A photo of a prototype device is shown in Figure 2(c) and a summary of the specifications is given in Table 1.

Table 1. Summary of device specifications. These are the design targets, not necessarily the limits of the device.

Ultimate capability of softgood interface	14,000 lbs
Measurement linear range	Full interface capability
Analog to digital converter	16 bits
Record Time	minimum 20 mins
Flash memory	128 Mbit
Sample rate	1000 Hz
Timing knowledge	within 10 ms of reference time
Load accuracy	1.6% full scale
Mass	100 grams
Dimensions	3.9" x 1.2" x 0.8"
Operating temperature	0-40° C

I.D. Concept of Operation

The device triggers and powers on when a lanyard is pulled during parachute deployment. The device powers on and begins recording load data after 100 ms of initialization. The device records load data for a programmed amount of time. The device then transitions to recording the timing signal received from the radio. The timing signal is simply a counter that is broadcast from the payload. The payload initiates the counter at a known event, such as the initiation of parachute deployment, and the counter allows the load data to be synchronized back to the parachute inflation event.

II. Load Cell and Structure

The load cell of the device is simply a metal link that is instrumented with a full strain gage bridge. The metal load cell structure is the backbone of the device. The electronics are mounted on either side of the load cell structure. A cross section of the device packaging is shown in Figure 3. The structure was designed to a working load of 16,000 lbs with an ultimate factor of safety of 1.4. A prototype of the structure was proof loaded to 21,000 lbs, which exceeds the maximum capability of the softgood interface to the structure.

II.A. Load Cell Design

The load cell structure is a single machined titanium part (Figure 4). The structure is designed as a tensile link that can be connected to cordage on both sides. The prototype structure was designed to be used with 3/8" diameter Technora cordage, and despite the relatively tight radius, shows high tensile efficiency when attached to an eye loop. The structure cross section resembles a dogbone; most of the cross section area is located on the sides in the main load path, but there is a thin web between the sides that serves as the strain area. Cross-sections of the structure are shown in Figure 5. When the structure is loaded in tension, the web is thin enough that it experiences very uniform strain (Figure 6). The web is instrumented with tee rosette strain gages on both sides creating a full bridge.

II.B. Electrical Packaging

The electronics are nested in pockets on either side of the device and the whole assembly is cast with polyurethane to ruggedize the assembly. The electrical circuit boards have standoffs to separate them from the load cell structure, so the electronics are effectively "floating" in the polyurethane. The structure includes fingers that serve to create a concavity and mechanical stop to hold the polyurethane together as a back-up

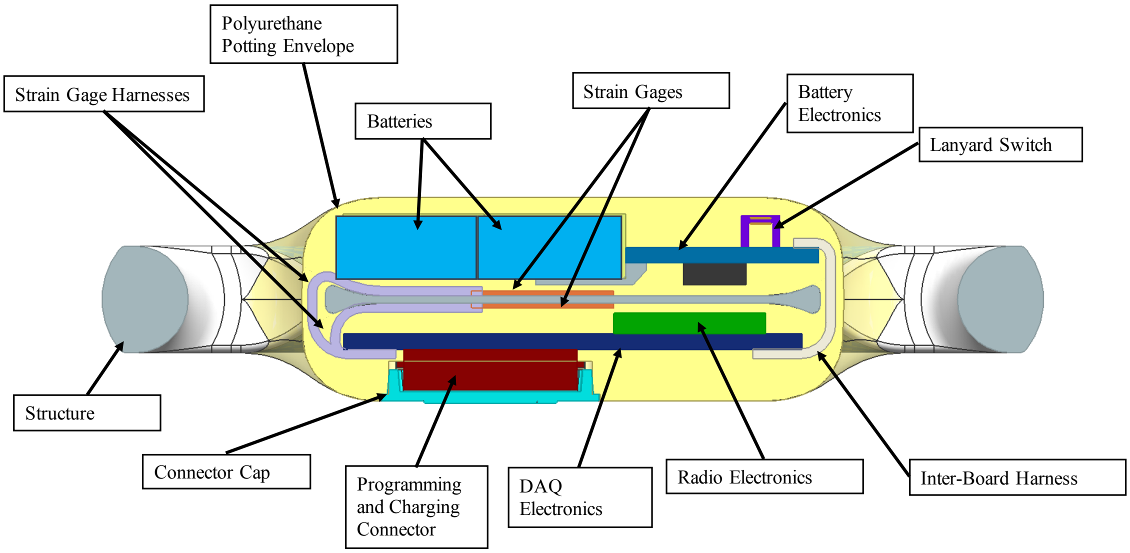


Figure 3. Schematic of a cross-section of the device package.

Figure 4. Photo of a machined titanium structure.

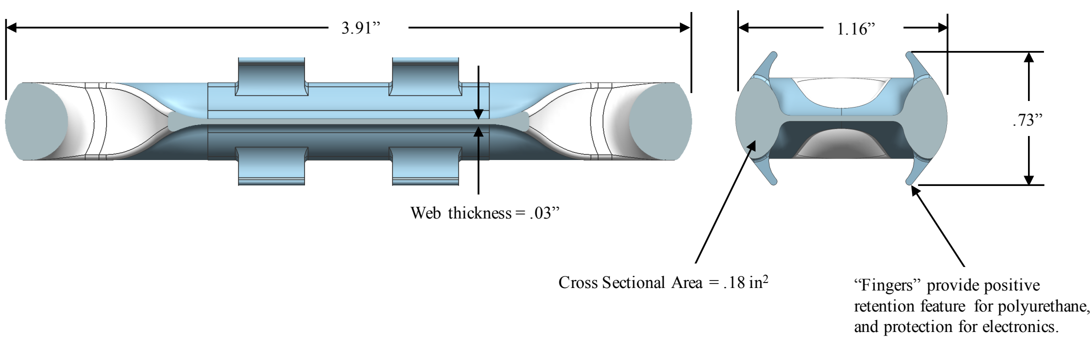


Figure 5. Cross-sections of the load cell structure showing the overall dimensions and the load-carrying area.

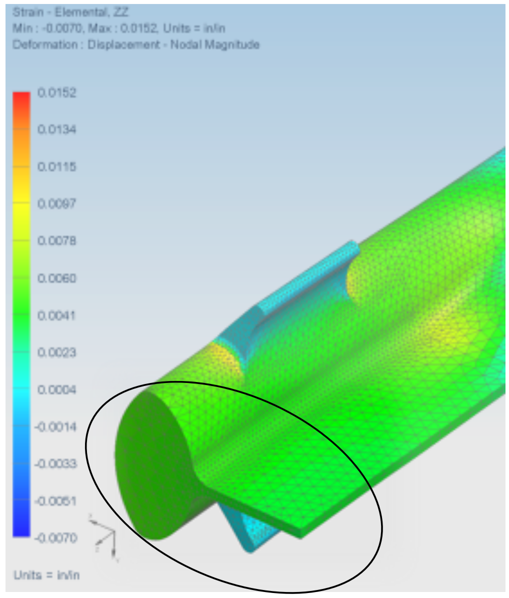


Figure 6. Finite element analysis results showing near constant axial strain highlighted in the cross section of the load cell structure.

to the bonded interfaces. The polyurethane used is Cytec CONATHANE® EN-11, which is a highly flexible polyurethane for molding and encapsulating electronic assemblies exposed to severe environmental extremes. The polyurethane is injected into a two-part mold that creates the outer shape of the assembly. Figure 13 shows a photo of the assembly prior to molding.

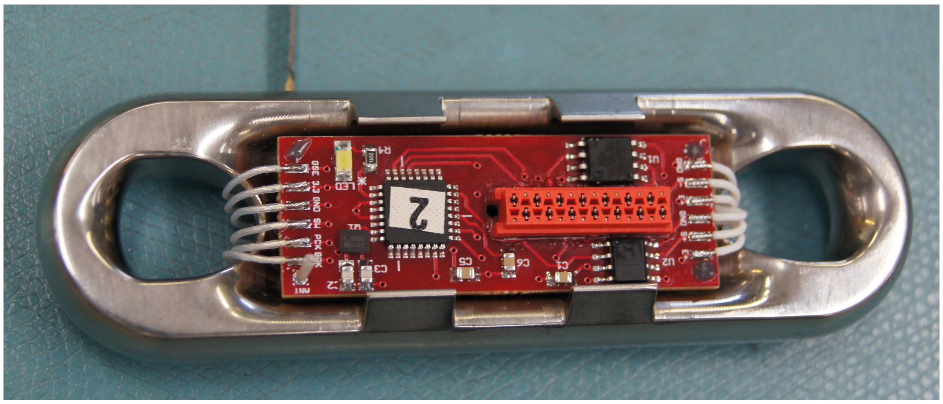
III. Data Acquisition System

The harsh environments the device could experience during parachute packing, inflation, and operation produced a unique set of requirements on the electrical hardware of the system. To survive the packing and acceleration environments, components had to be minimized, miniature, and reliable. The electrical hardware of the device consists of three key components, the Power Board, Data Acquisition (DAQ) Board and the Load Sensing Circuit. Figure 8 shows a block diagram of the entire data acquisition system. The subsequent sections describe the major component design details.

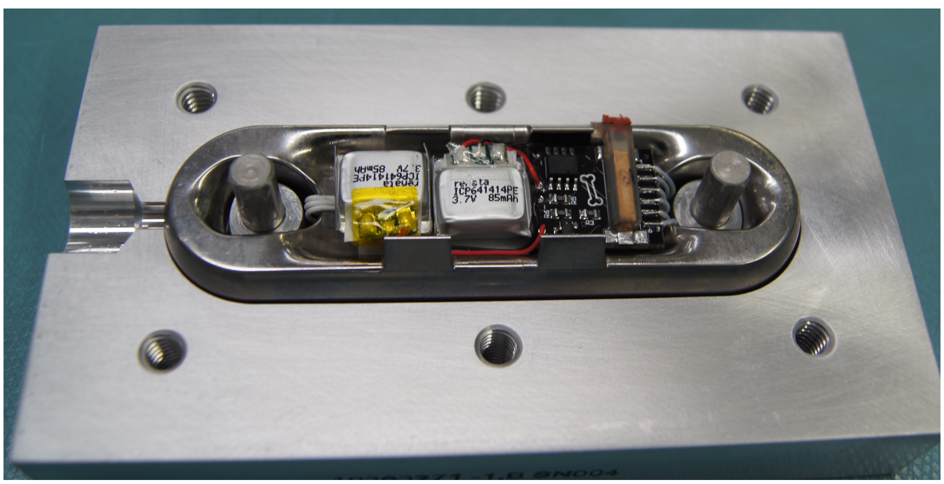
III.A. Power and Batteries

III.A.1. Batteries

The battery pack consists of two rechargeable Lithium-polymer prismatic cells, each with a nominal voltage of 3.7 V and a capacity of 95 mAh. The total nominal battery pack voltage is 7.4 V, but can fluctuate between 6.0 - 8.4 V depending on state of charge. Lithium-polymer cells were chosen because of their high rate of discharge (1-2 x C), which enabled a battery pack of very low capacity that could provide the required power for a short period of time. With the batteries at a full state of charge, the device is expected to run for an hour. The battery cells are allowed to fully discharge to a cell voltage of 3 V in order to maximize on-time. The total number of battery cycles wasn't a factor in the design, so there was no constraint on depth of discharge. The capacity of the batteries provides enough margin to tolerate a reduced state of charge and performance from storage and thermal effects, allowing the device to be packed for up to 12 months without battery charging. Each battery cell contains a protection circuit that protects the battery from overcharging, prevents discharge below 3.0 V, and limits the current in the case of a short. The battery cells can be charged individually through the connector in order to maintain a balanced pack. Each battery cell weighs approximately 2 grams.



(a) DAQ electronics and connector assembled prior to molding.



(b) Assembly in mold prior to molding. Batteries and lanyard switch visible on top.

Figure 7. Photos of the electronics assembled to the load cell prior to molding with polyurethane.

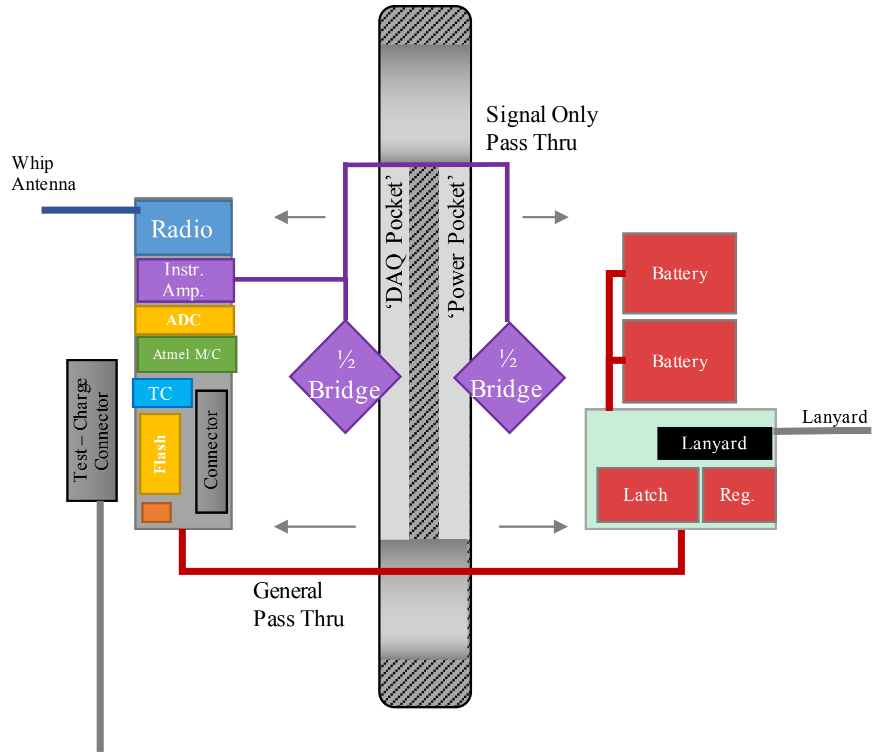


Figure 8. Block diagram of the entire data acquisition system, including the power board, the data acquisition board, and the load sensing circuit.

III.A.2. Lanyard Switch

The power board contains a small mechanical switch that is connected to the primary leads of the batteries. The switch has two thin metal plates that are separated by a lanyard made of Kevlar lacing tape (Figure 9). The lanyard is secured to the device with break-ties and is attached to the parachute lines, so that when the lines are pulled during deployment the lanyard is pulled. When the lanyard is pulled the two plates make contact and close the circuit. The lanyard switch is the component of the latching circuit that when closed connects the battery voltage to the gate of the thyristor. The two conductive plates of the lanyard switch could potentially separate in dynamic environments, which would results in intermittent power to the system. This required the design of a simple latching circuit, which would be insensitive to the connection of the switch and would keep the device powered on if the lanyard switch were reopened.

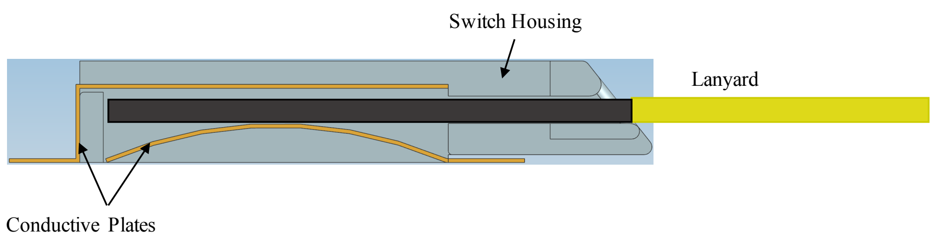


Figure 9. Cross-section schematic of the lanyard switch. When the lanyard is pulled, the conductive plates are able to touch and power on the device.

III.A.3. Latching Circuit

A simple latching circuit is used to allow the battery voltage to be isolated from the regulator and rest of the electronics during storage. The latching circuit acts as a physical trigger to begin the operation of the entire device. A thyristor is used to control flow of current from the battery to the rest of the system. When the lanyard switch closes, battery voltage pulls high the gate of the thyristor, which allows current to flow through to the system. The properties of this type of rectifier are such that once current is allowed to flow through the thyristor, the system is “latched’ and becomes insensitive to the change in gate voltage (actions of the lanyard switch).

III.B. Data Acquisition and Signal Processing

III.B.1. Overview

The electrical components are mounted on two printed circuit boards, with one board mounted on each side of the structure in the concave section. On one side is the DAQ board, which contains the micro-processor, instrumentation amplifier, analog to digital converter, temperature sensor, flash memory, radio, and connector. On the opposite side is the power board and the batteries. The batteries are held to the power board for alignment in the mold with a plastic battery cradle. Power and data signals are passed between the boards at the throat of the interface holes in the structure opposite from the softgoods interface. The external connector is on the outside of the DAQ board and is exposed after molding and has a cap to cover it for flight. The DAQ board is the device’s interface with the other supporting sensors and power, where all data and power signals are passed through. The connector enables the charging, external power, programming, calibration and retrieval of the acquired data. Communication is done through interface with the ATMEL micro-controller, although SPI communication can be done independently with the onboard 128 Mbit flash storage. The micro-controller is responsible for the command and retrieval of data to and from the rest of the components on board. The load data is sensed by the strain gage bridge, amplified by a Texas Instruments Instrumentation Amplifier, digitized by a 16-bit ADC, read by the micro-controller, and written to the onboard flash. During this signal acquisition, DAQ Board temperature data is being recorded from a temperature sensor located next to the Instrumentation Amplifier to account for any temperature drift of the amplifier. The final timing signal that is tagged to the data written to the flash storage is a PPS signal that is received via the onboard RF transceiver operating on the 915 MHz frequency band. The data acquisition architecture is enabled by three technology elements including a high-resolution 16-bit analog to digital circuit (ADC), a low latency flash memory chip, and a miniature transmitter-receiver radio. Each of these elements is coupled with both a design constrain and the concept of flight operations. For example, the ADC resolution and it’s related 1000 Hz sample rate drove the total data rate higher and subsequently the need to record data locally and recovered post-test. Details of each of these critical element design features are summarized below.

III.B.2. Load Signal Processing

Tensile load is sensed via the 350 ohm full bridge transducer circuit on the strain area of the load structure (Figure 10). To complete the full bridge, each side of the structure has a Vishay half-bridge two-element 90 tee rosette in a 3-wire configuration. The bridge excitation is provided by the +3.3-volt output of the voltage regulator located on the power board. The load signal is amplified with an instrumentation amplifier located on the DAQ Board. The configuration produces a load cell with a sensitivity of 9.1 mV/V @ 20,000 lbs.

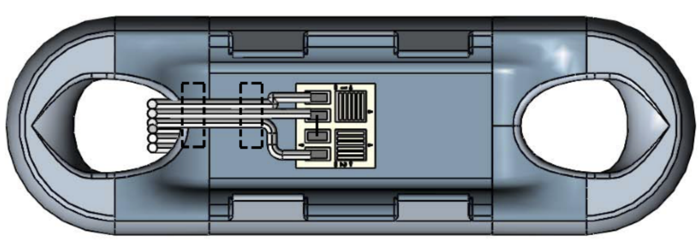


Figure 10. Picture showing the location and configuration of the strain gages on the load cell structure. The dashed boxes show where the wires are staked.

III.B.3. ADC

Leveraging the Arduino-class miniature low-power Atmel chips was a consideration for this design due to code reuse for open source code. An Atmel 328P series microcontroller was selected as the primary embedded controller. Of the micro controllers surveyed, most of the native analog inputs provided 10-bit or 12-bit resolution. For this application additional load resolution was needed. A 16-bit ADC chip was selected based on its compatible standard SPI bus protocol. The SPI protocol is also the same protocol used for reading local temperature and writing to onboard flash.

III.B.4. Flash Memory

A serial flash memory chip was selected based on it?s compatible data rate, capacity, low power consumption, and standard SPI data interface. The device's required data sample rate of 1000 Hz and the limited microcontroller memory together created the need for using the flash controller's 256-byte page buffer in combination with the chip's hold pin. All system counters, load, temperature, and timing data was passed as a data packet incrementally to the flash page buffer until a single page was filled and written to the flash memory. During the periodic page write cycle a few sample packets would be held in the microcontroller's SRAM before resuming to fill the flash page buffer. The related code base design and testing was kept simple by using timing characterizations and functional testing as the primary validation approach. A simple state machine was used to initialize the system, record primary load data, record timing sync data (from radio), and gracefully safe the system via a lower power condition. An overview of the software states is provided in Figure 11.

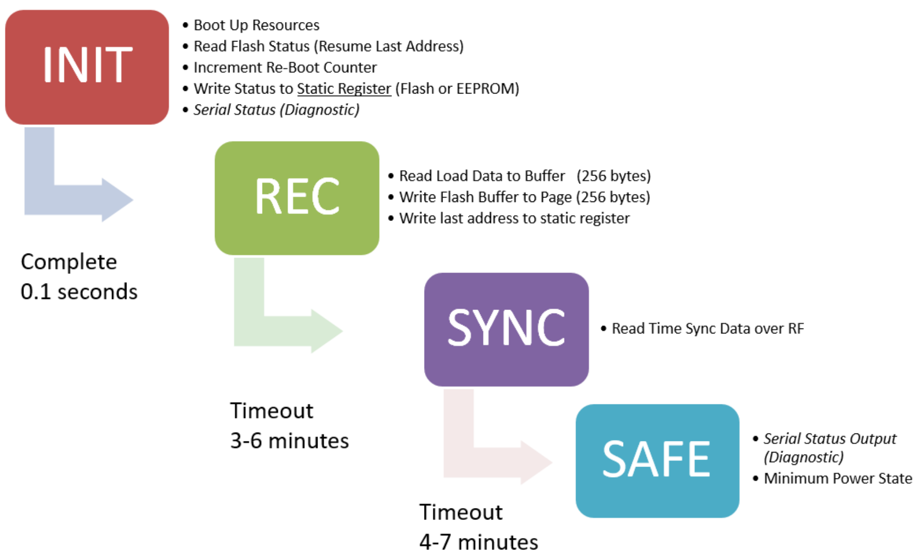


Figure 11. Block diagram showing the programmed states of the device. The four states are initialization, recording, synchronization, and safeing.

III.B.5. Wireless Time Sync

On-board load data is not particularly relevant or useful without a timing correlation to the parent spacecraft. Timing knowledge was provided based on a miniature hobby-grade radio data signal. The parent spacecraft would include a single timing node to translate absolute GPS time knowledge into a 1 pulse per second timing signal. This relative signal would be packetize with other counters and transmitted to all other embedded DAQ Device receivers. The miniature radio transceiver was selected based on its small size, lower power consumption, 500 mW capable transmitted power, and existing open source code libraries for use with our microcontroller. A simple whip antenna was trimmed to be a fractional division of the related 915 Mhz wavelength. This antenna design presented considerable power loss however was able to meet the 40-50 meter line of sight requirement with adequate margin above loss of signal threshold. This determination was based on a combination of functional drop-out tests out doors and power measurements tests inside of an anechoic chamber.

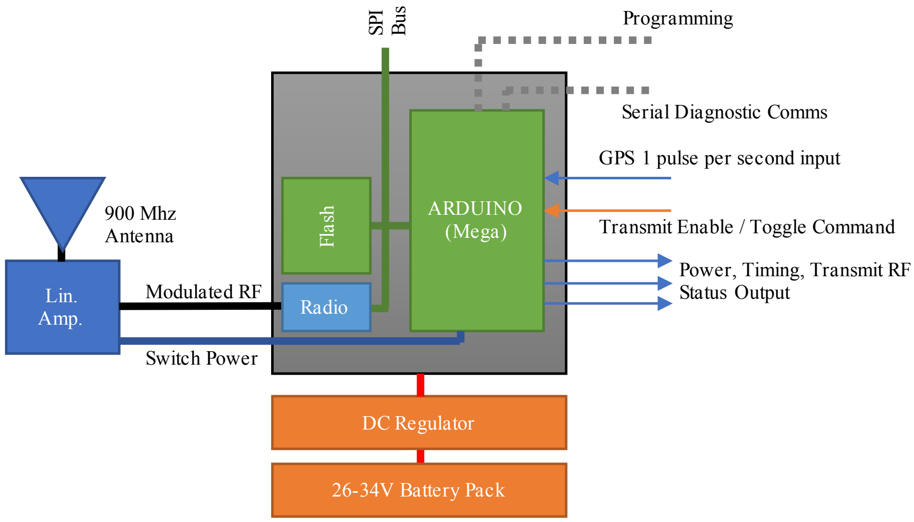


Figure 12. Block diagram showing the timing node located on the payload.

IV. Testing and Results of Prototype

IV.A. Strength Testing

The load cell structures were subjected to tensile testing to validate their structural integrity and the joint efficiency of the cordage to the structure. First, the structures were proof loaded with metal interfaces to a load of 21,000 lbs to validate the structural analysis. No yielding or damage was observed during this test. Next, a piece of 3/8” diameter Technora cordage was spliced to the structure with an eye loop and pulled to failure. The minimum specified strength of the cordage is 16,300 lbs, and the minimum strength of the samples spliced to the structure was 14,000 lbs, yielding a joint efficiency of just over 85%. This was adequate strength for the application. Additional testing was done with four representative Technora suspension lines eye spliced to one end of the load cell structure. Limited samples of that configuration were tested, but joint efficiencies above 85% were also achieved in that configuration.

IV.B. Device Calibration

To verify the capability of the device, a calibration plan was developed to validate the mechanical design of the device as well as the electrical configuration of the system. A large amount of initial testing was done to determine the strain properties of the mechanical link. Several iterations of strain gage and mechanical link configuration were required to settle on the device’s load sense system. Once the mechanical load sensing system was validated, a matured calibration process for a parachute suspension line had been developed. The calibration process is standard for a load cell with the exception of additional loading to for soft-good excitation. Calibration was done on an Instron Tensile Test System. The device was powered externally through the connector with a simulated battery voltage (7 volts) and loaded up to 12,000 lbs (75% of Full-Scale). An external data acquisition system was used to measure the analog output of the Instron load cell, the load signal from the device’s instrument amplifier, and the serial data stream from the device. The calibration of the device was done with a soft interface to simulate a flight-like connection, using Technora cordage as the interface to the link. The calibration of the first flight prototype system produced informative data for the configuration of the device as well as of the calibration system. The device produced repeatable results and linear voltage output during loading, with a typical sensitivity of 3.171 mV/V at 10,000 lbs. The results obtained from the calibration of the flight prototype devices gave confidence in the feasibility and capability of the design.

Table 2. Device calibration error sources for the prototype device.

Linearity Error	1.51	%FS
Hysteresis Error	0.40	%FS
Repeatability Error	0.32	%FS
Total Accuracy (Measured)	1.56	%FS
Sensitivity	3.171	mV/V @ 10k lbs

IV.C. Data Acquisition Functional Testing

The device functional testing was segmented based on each of its functions. The initial phase focused on the load cell sensor data as compared to the calibrated pull test load. This testing used a simple code base that published conditioned load cell voltage data out of the programming-test connector interface. After the sensor data was validated the function testing focused on the power sub-system.

Functional testing of the fast lanyard deployment and it's related latch circuit were tested with a representative structure and power board. Battery cell and pack level charge characterization were also an important portion of the power functional tests due to the relatively significant discharge period while the device remained in the packed configuration.

One of the more challenging portions of the functional testing was related to validating existing code libraries and custom libraries developed for interleaving flash memory buffer and page write management operations. The limited microcontroller working memory and timing constrains made were validated with numerous concise test code deployments. Some of the timing characterizations became so tedious that programming cross compilers were evaluated to more quickly develop the requisite deployed ANSI C code from other more manageable scripting and abstracted languages.

A full system deployment test was not completed due to other external schedule constraints; however, a high speed parachute extraction test or a drop test was planned as a full system verification test prior to use on a supersonic parachute test.

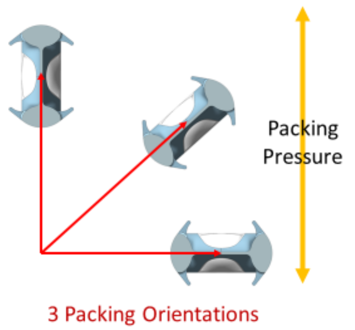
IV.D. Packing Testing

In order to demonstrate that the device can survive the parachute packing process, two prototype devices were packed into a mockup packing fixture with Technora suspension lines. The packing fixture was 12 in diameter and 10 tons of force was applied to the pack with a hydraulic press. Multiple packing orientations were tested to determine how damage might occur. Figure 13(a) shows the multiple packing orientations that were tested and Figure 13(b) shows the two devices after being packed. The polyurethane held up well with no noticeable peeling or tearing. Early prototypes experienced damage to wiring that was too close to the surface of the polyurethane, so later prototypes were designed with a minimum thickness of polyurethane. The later prototypes had no damage to the electronics boards after being packed repeatedly.

V. Conclusion

An embedded load measurement device was developed in order to measure suspension line loads during a supersonic parachute deployment. The prototype device has a mass of 100 grams and is ruggedized to be packed and deployed with a parachute. The device is initiated passively with a lanyard pull during parachute deployment and can measure tensile loads up to 16,000 lbs at a 1000 Hz rate. The load cell had a measured accuracy of 1.56% of full scale. The device receives a timing signal from a radio located on the payload that enables time synchronization across multiple devices and to a common timing signal. Data is stored locally, so the device must be recovered in order to recover the data.

Functional testing and calibration was performed at the component level to verify the load cell design and data acquisition system design. Hardware and software were iterated through multiple prototypes and a final design configuration was created. Bench testing of the data acquisition system was used to verify component layouts and software implementation. Unfortunately, for programatic reasons, full system functional testing was never performed and the devices were not used for any parachute tests.



(a) Device orientations that were tested in the packing test.

(b) Photo of two devices after being packed.

Figure 13. Details of packing test.

Acknowledgments

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