SmartCan: Instrumentation, Meaurement, and Control at 70 Miles Up

An Engineering Education at the Edge of Space

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Abstract

The Sub-Orbital Mission Automation, Recording, and Tracking Canister (SmartCan) is a payload support platform that is being developed as part of a Senior Design course at the University's Department of Electrical & Computer Engineering. This two-semester course, a traditional capstone to an Engineering program at the University, began in August of 2008, and is, at the time of this writing, in its second and final semester.

Introduction

This project is the result of a cooperative collaboration between our senior design team and the (name of sponsoring agency), to develop an embedded control system and instrumentation package, to be included in a sub-orbital space mission in April, 2009. The goal of the project was to develop a space research platform which could be used to support future student projects with more traditional space-based scientific research. Our goal, then, was not to conduct experiments in space, but to design, build, and fly our payload support module as a proof of the concept.

The Project Team

This project has been designed and built by a group of five senior students from the electrical engineering and computer engineering programs at The University. Additional support for the project has been provided by our faculty advisors.

Key Organizations

Two key organizations have played significant roles in the furtherance of this project. All of the financial support for the SmartCan project has come from this organization, and our team has also received significant administrative and technical support and guidance from (names of agency contacts). UP Aerospace, the Denver, Colorado -based private commercial space launch company will conduct the sub-orbital space launch aboard which this payload will travel. The launch is tentatively scheduled for early May, 2009.

Our Mission

The overarching goal of the program of which this project is a part is the creation of series of small, cylindrical payload modules which will be included in a rocket launch from the facilities of Spaceport America, near the city of Truth or Consequences, New Mexico in May of 2009. The (name of sponsoring agency) Student Launch Program provides student groups with funding, direction, and a spot aboard the launch vehicle. UP Aerospace provides each team with a canister in which to house the group's project, which will be integrated into a single launch vehicle.

The specific mission that we were given at the outset of the project was to, in effect, “do something worthwhile”, and we believe that we have rendered a good-faith effort to fulfill this mission.

Our Approach

As with any new project, our team was given a very small set of constraints and some very loosely stipulated criteria. However, the general scope, capabilities, and design possibilities of our project were very broad at the outset.

Our approach to the specifics of the project, then, was to first decide what the project should do, and then decide how we could best bring it about.

In our talks with the project sponsors from NMSGC, we decided that the most useful thing that we, as electrical and computer engineering students, could contribute was to set aside the notion of conducting space research, and instead provide a platform upon which future students could build more traditional space-based research programs. This narrowing of the scope of the project provided a much-needed impetus toward establishing our vision for the remainder of the course.

A System Overview

In the following sections, I present the details of the electronic systems and components that form the heart of the SmartCan project.

Embedded Control/Acquisition System

At the heart of our project lies an embedded control system, which includes the computer and data acquisition hardware that allows our project to capture and record data from the instruments during the flight. This embedded control system is a PC/104 stack containing two boards, or modules: a single-board computer and a 32-channel, 16-

bit data acquisition module. A picture of the assembled PC/104 stack appears in Figure 1, below.

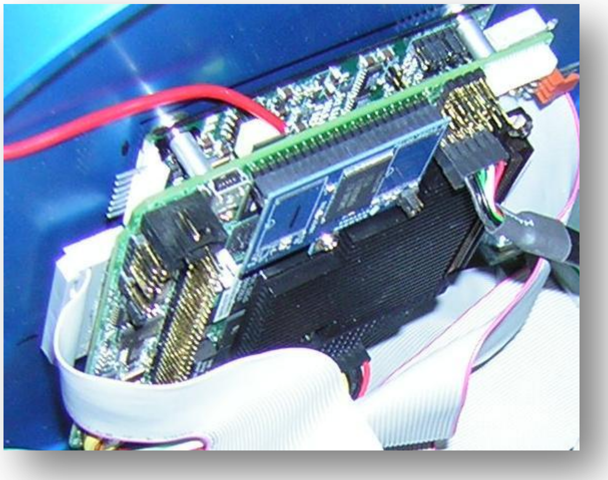


Figure 1: The heart of the system is this PC/104 Stack, containing a single-board computer and a data acquisition module.

During our initial discussions, we gave some preliminary consideration to the in-house development of an embedded control system, but summarily discounted it as being too technically complex for the time we had available and, ultimately, an unwarranted departure from the larger goals of the project. In the end, and in consultation with our technical advisors from NMSU, we agreed that a purchased system was a preferable use of the money and time we had available.

The computer board that we have selected is the Athena II 500-MHz Pentium-III class version from Diamond Systems Corporation, which is a slight variation of the PC/104 footprint. This SBC comes complete with a high-resolution SVGA display controller, a total of four USB ports, a complete cadre of traditional serial, parallel ports. Also included is a SoundBlaster-compatible stereo sound module, and an onboard Ethernet network controller.

Also included in the embedded controller system is a 32-channel, 16-bit data acquisition module. This full-feature device, also from Diamond Systems Corporation, includes an autocalibration system and a self-test feature.

Three Custom Boards

Owing to the highly specialized nature of the SmartCan, and the limited and cylindrical volume inside the canister, we found it necessary to design and assemble several key printed circuit boards (PCB's) to house our electronics and to provide interconnections for the power and signal routing that the SmartCan requires. These custom PCBs are described in the following sections.

Accelerometer Module (AM)

One of the key flight characteristics that we hope to capture and record is the effect that dynamic forces will have on the vehicle. These forces include the thrust which occurs during the launch, the separation and chute deployment, and the impact of touchdown. We also hope to capture other in-flight events such as wind shear, vibration, and attitudinal changes experienced by the vehicle.

To do this, we have included a set of surface-mounted (SM) MEMS accelerometers on a custom PC board that is mounted to the bottom lid of the SmartCan. Our goal was to include, for each of the three axes of motion, a high-G sensor for capturing large events and a low-G sensor for detecting smaller, unexpected dynamic effects.

This board consists of the accelerometers and, for each signal, a unity-gain buffer amplifier for driving the signal to the data acquisition system. Additional details about the accelerometers appear in the section on instrumentation later in this document.

Power Supply/Operator Interface Module (PS/OIM)

The primary consumer of power in the SmartCan is the SBC, which requires approximately 1.5A @ 5V during normal operation. Additionally, some of the sensors that we chose required excitation voltages of 3V and 10V. Given this, we decided that the cleanest and most effective power solution for the SmartCan was to design our own power supply board. This custom board contains three separate voltage regulators: a 5V switching power module (TI P/N: PTN78020) capable of providing up to 6A, and two LM317T adjustable linear regulators operating at 10V and 3V.

Because the SmartCan operates in a space environment, the use of electrolytic capacitors for power filtering and regulation is not permitted. Fortunately, because the SmartCan is totally battery powered, we did not have to contend with the heavy line regulation and ripple problems associated with AC power supply designs, and we are very satisfied with the performance that we achieved with a few tantalum and ceramic filter capacitors.

In addition to the supply of regulated operating voltages to the rest of the SmartCan, the Power Supply/Operator Interface Module also serves as the single source of operator access to the SmartCan's embedded control system. The module is oriented vertically in the canister, directly in front of a ¾"x2-1/2" access slot in the sidewall. This slot provides the only access to the interior of the SmartCan when the top and bottom lids are installed. As a result of this, we provided space on the power supply board for a pair of USB jacks for a keyboard and mouse and a VGA jack for the LCD monitor.

Also located on the PS/OIM is a Molex jack which provides a means to connect a battery charger for topping off the SmartCan's batteries without removing the lids.

(NOTE: We also included space on the PS/OIM for an RJ-45 panel-mounted jack which provides Ethernet access to the embedded control system.

However, the access opening proved to be just too small to permit adequate clearance for the connectors, and the team agreed to eliminate this option from our normal operation of the SmartCan. The Ethernet hardware is resident on the SBC, however, and this option is still a viable means by which future projects may wish to interact with the embedded control system.)

Mounted on the PS/OIM, and oriented toward the hatch opening are a set of three cadmium sulfide (CdS) photocells. More information on these photoresistive elements is discussed in the section on instrumentation.

Finally, the PS/OIM includes a main power switch and three LED indicators, providing the line technician a means of turning the SmartCan on and verifying proper operation prior to launch.

Sensor/Interface Module (S/IM)

The data acquisition module on the PC/104 stack is accessed through two ribbon-cable connections; a 50-pin header connector provides access to the analog inputs and outputs on the module, and a 34-pin header connector is used to access the digital (discrete) signals lines on the device.

To provide a clean and straightforward system of interconnects between this data acquisition module and the sensors and signals elsewhere in the SmartCan, we elected to create a custom PCB called the Sensor/Interface Module, or S/IM, which provides a central interface between the data acquisition hardware and the instrumentation package. This board consists primary of a set of 5 header connectors, to which are connected the ribbon cables from the data acquisition module, the PS/OIM, the AM, and a wiring harness carrying signals from a set of thermistors and strain gauges (these are discussed in greater detail in a later section on the instrumentation package).

Also located on the S/IM is a pressure transducer and several op-amps for signal conditioning.

The S/IM acts, then, as the nerve center for the SmartCan, and is situated vertically near the back wall of the sensor.

These three modules were designed by our team, using schematic capture software and autorouting layout tools, the boards were manufactured by third-party companies, and we complete the assembly in-house (with the exception of the SM components on the AM. For this, we solicited the assistance of the students and staff of a local community college). On balance, we were very pleased with the results of this process, and found the exercise interesting and rewarding.

(NOTE: One additional circuit board, a small off-the shelf perforated board from Radio Shack, was hastily assembled and included in the SmartCan in the final days of assembly and testing, to accommodate a revision in the design of the pre-amplifier stage for the pressure transducer. For further information, see the sidebar on the preceding page).

Powering the Canister

The self-contained nature of the SmartCan project meant that all the power required for the unit to operate must be carried inside. The batteries that we chose for our project are 6-cell, 7.2-volt nickel-metal hydride (NiMH) batteries designed for radio-controlled cars and trucks.

(NOTE: Our initial design called for the use of lithium (either Li-Ion or the newer and lighter LiPo) batteries; however, we were informed early in the project that, generally, the use of lithium batteries in space is not allowed and that the few commercially available space-rated lithium batteries on the market were prohibitively expensive. So we opted for the use of the heavier, but acceptable, NiMH batteries instead.)

Instrumentation Package

The SmartCan's purpose is to measure and record data during the 15-minute space flight. Therefore, a major element in our design was the inclusion of the required sensors and the signal conditioning requirements for each sensor.

We chose to focus on the following types of measurements:

- Temperatures
- Atmospheric pressures
- Vibration
- Canister stress/strain
- Ambient light levels
- Battery and power supply voltages

(We had initially hoped to incorporate an on-board GPS system for recording precise positional data throughout the flight; however, as we soon learned, the use of GPS devices for operation above altitudes of 60,000 feet is considered a sensitive issue of national security, and is highly regulated and prohibitively expensive. So we scrubbed this idea, and set about finding other ways to determine our altitude, attitude, and phase of flight).

We settled on the use of thermistors for the temperature measurements, as they are relatively straightforward and easy to integrate into a data acquisition system. Thermistors require no special voltages, amplification, or signal conditioning, and their transfer characteristics are well-understood and conversion back to engineering units in software is a simple matter.

The front and rear (with respect to the access opening) wall temperatures use a 5kOhm (nom.), surface-mounted thermistor. Near the center of the canister volume is a 5-

kOhm (nom.) stud-mounted thermistor.

Attached to the side walls of the canister, space 90° apart, are four strain gauges. They are oriented vertically, so as to sense minute changes in the height of the sidewalls, reflecting mechanical stresses occurring in the vehicle as it encounters differential dynamic forces associated with wind shear conditions.

(NOTE: We, as a team, will readily admit that we do not know what, if anything, to expect from the strain gauge data. We have very little in the way of technical data on the ultimate construction of the vehicle, and no real way of knowing if there will be sufficient sideward loading of the vehicle to result in any measureable perturbations by the strain gauges. We are interested in seeing the results, but recognize that this is, ultimately, an educational experience, and we have learned a great deal about the use of strain gauges as a result of including them in our design).

The lead wires for the thermistors and strain gauges are bundled together and terminated by a connector which attaches to the S/IM.

As mentioned earlier, another primary sensor is the atmospheric pressure sensor that is mounted on the S/IM and will be used to provide elevation data during the initial launch phase and the several minutes of reentry and impact. The sensor, shown here, is a 4-active-arm piezoelectric sensor on a glass substrate, which permits it to withstand very high g-forces without failing. We received a strong recommendation to include this sensor from our technical advisor, and we have a high degree of confidence that the sensor will survive any large-magnitude acceleration or deceleration encountered during the flight.

Onboard the sensor is a 1.2-kOhm thermistor for enabling temperature-compensated pressure measurements. This thermistor is incorporated into the data acquisition system similar to the other thermistors mentioned earlier.

Each of our accelerometers is a MEMS device in a surface-mounted package from Freescale Semiconductor, Inc. For the fine measurements, we are using an MMA-7330 triaxial, dual-range (4g/16g) with the range select line hardwired to select the 16g range. For the coarse measurements, we are using two devices, an MMA-1213 Z-axis accelerometer, and an MMA-3201, dual-axis device for measurements in the X and Y vectors (for reference, we consider the Z axis to be parallel to the vehicle's axis of thrust).

Additional sensors for measuring ambient and directional light levels are mounted on three of the four edges of the PS/OIM and are angled toward the access opening. The electrical resistance of these 5mm x 7mm CdS photocells (see Figure 3) bears an inverse relation to the amount of light which is incident to the surface of the detector. By placing these sensors in series with fixed resistor, a corresponding (and proportional) voltage is supplied to the data acquisition system. The phase and magnitude relationships between the signals from these sensors provide such attitudinal data as the rotational speed and pitch of the vehicle.

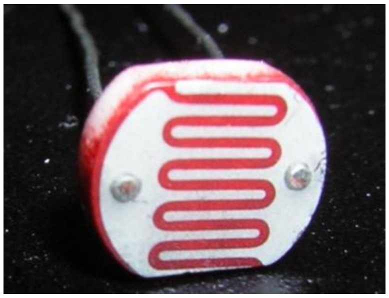


Figure 2: Cadmium Sulfide (CdS) photocells are used to sense vehicle roll rate and attitude

Putting It All Together: Mechanical Construction

Of all the work that we have put into this project, none has been so challenging and gratifying as the final stages of assembly, of committing each of the carefully crafted subassemblies to their place in the canister interior.

Although we had created many sketches of our intended design, and completed a somewhat rudimentary but fairly helpful 3D CAD model of our intended design, we knew that we would discover a number of glitches and unforeseen bumps in the road. And, true to our expectations, we spent a good deal of time trimming, cutting, and coming up with alternatives when our design proved unworkable is some way.

The nature of the cylinder, and of the overall design of the launch vehicle itself, prohibited us from causing any changes in the cylindrical outer surface of the canister wall (to do so would prevent the vehicle's skin from fitting properly, which is, naturally, unacceptable). So all mounting holes needed to be located in the top and bottom cover plates of the canister. The canister, pictured in figure 3, looks a little "busy" with all the cables in the way. The batteries can be seen at the bottom of the canister, while the two vertically mounted PCBs can be seen on the right and left sides of the image.

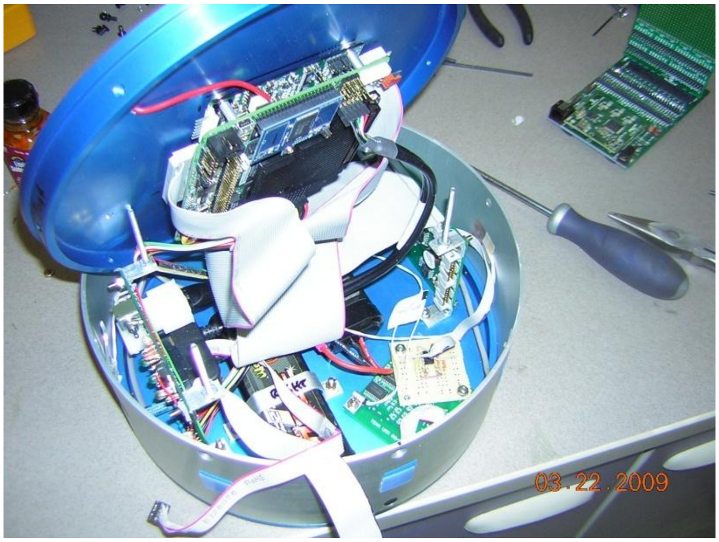


Figure 3: The rat's nest of cables and parts inside the SmartCan (shown here with the upper lid removed)

On the left is the PS/OIM, which faces the access opening, while on the right, the edge of the S/IM can be seen with two of the cable connectors unplugged. (The small, tan board contains the modifications mentioned in the earlier sidebar).

Another requirement we needed to consider was the mechanical balance. The specifications for the project required that the center of gravity (CG) remain at the center of the volume of the cylinder. We developed a strategy of using the placement of the battery mounting straps as a convenient way of managing the CG without the curse of having to add dead weight to the canister to achieve the proper balance.

After many hours of measuring, cutting, and drilling, the final assembly was very like what we had envisioned from the outset of the project, and, as a team, we found it a very fulfilling sight.

Software Philosophy and Design

The primary role of the embedded control system is to acquire, condition, and record sensor data. To accomplish this, we are using National Instrument's LabVIEW graphical programming suite running on the Windows 2000 operating system. (We are using Win2k due to its stability and relatively small footprint on the 4GB flashdisk).

As the vehicle is being prepared for the launch, a line technician turns on the power switch and observes the LED indicators through the access opening. As there is no user interface attached to the SBC during the normal operation of the SmartCan, our primary data collection program contains little or no visual elements. We simply initialize the data acquisition hardware, complete a self-calibration procedure, run a series of self-tests on the accelerometer devices, and provide the appropriate indications on the LEDs to indicate the status of the SmartCan. LabVIEW then commences data collection until the vehicle is recovered or the batteries become exhausted.

Measurements are captured at sample rates appropriate to what is being measured. The fastest sample rate that we are using is 1 ms per sample for our accelerometer signals.

Power supply measurements, as an example, are much more stable and slow-changing and are sampled at the slower rate of once every second.

Post-flight data collection involves reading the binary data files containing the data captured during the flight, and displaying that data on the screen and storing formatted ASCII data files that can be used by subsequent processing and analysis tools.

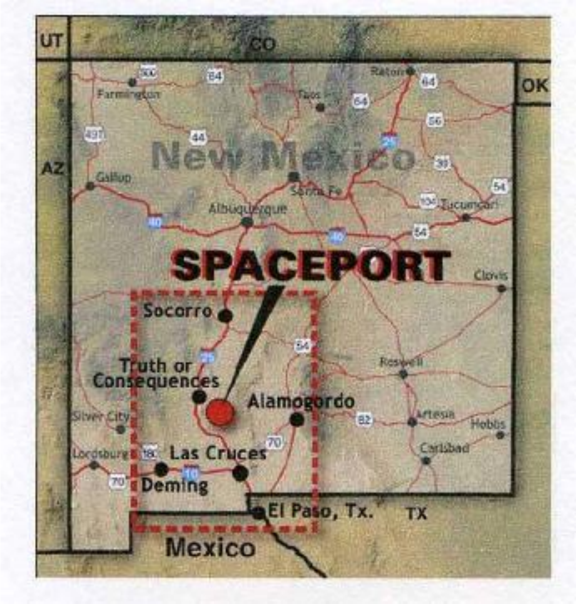


Figure 4: Our mission will launch from Spaceport America (its location shown here) on May 2, 2009

Source: UP Aerospace (http://www.upaerospace.com)

A Little about the Space Flight…

The space flight itself is scheduled to occur on Saturday, May 2, 2009. The facilities of the Spaceport America launch site are located in the desert southeast of the city of Truth or Consequences, New Mexico (see the map in figure 4), just over a range of mountains from the White Sands Missile Range (WSMR), to the east. Several WSMR telemetry and launch support capabilities are made available for the launch. Up Aerospace, based in Denver, Colorado, is the private space launch company that conducts the launch. Their flagship vehicle, which appears below, is 10” in diameter and the length depends upon the launch configuration.

The canister that was provided for our project is called the PTS-4 (see the photo in figure 5 below), and is approximately 10" in diameter. It has an overall height of 4" (the useful inside height is closer to 3.25"). In the days before the launch, the trailer which carries the launch rail will be placed in a horizontal orientation, and the SpaceLoft XL vehicle will be, literally, assembled in place, with the nose cone first, progressing through the parachute storage compartment and each payload canister is placed into it proper place on the rail. Finally, the propulsion system is installed and the vehicle is complete.

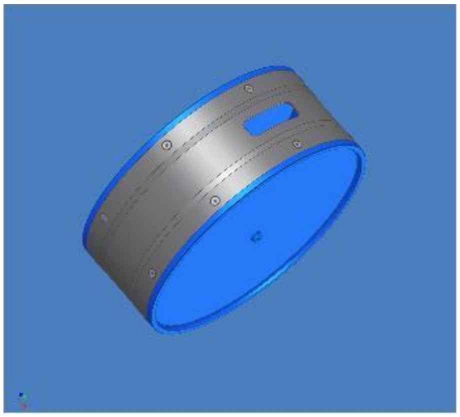


Figure 5: The PTS-4 canister, supplied by UP Aerospace, houses the systems and components that make up the SmartCan project

Source: UP Aerospace (http://www.upaerospace.com)

The flight itself will last approximately 15 minutes, and is projected to reach a maximum altitude of 74 miles, or about 390,000 feet. Following a 13-second rocket motor burn, at which time the vehicle will have reached a height of some 39,000 feet and traveling at its maximum velocity, it will continue its trajectory as its speed and energy bleed off. The total residence time in the space environment (that is, beyond a height of 100 km) is in the neighborhood of 4 minutes. Touchdown is projected to occur within a 30-mile radius of the launch site, and the process of tracking the vehicle and recovering it will commence. Our payload will be located, removed from the vehicle, and returned to us as soon as is practical.

Conclusion

The SmartCan project represents an opportunity for the members of our team to expand their knowledge and experience in a number of important arenas. We have been given a nebulous and largely undefined mandate and turned it into a useful and working system. We have learned a great deal about the design and manufacture of printed circuit boards, mechanical construction of a system, how to research and select the appropriate sensor for a given application, and, perhaps most importantly, we have learned to work together, as members of a team, to solve real-world problems.

This experience has provided us with a powerful platform of understanding from which to launch our engineering careers and, in the process, has permitted us to see a practical side of engineering that is difficult to reproduce in the classroom.

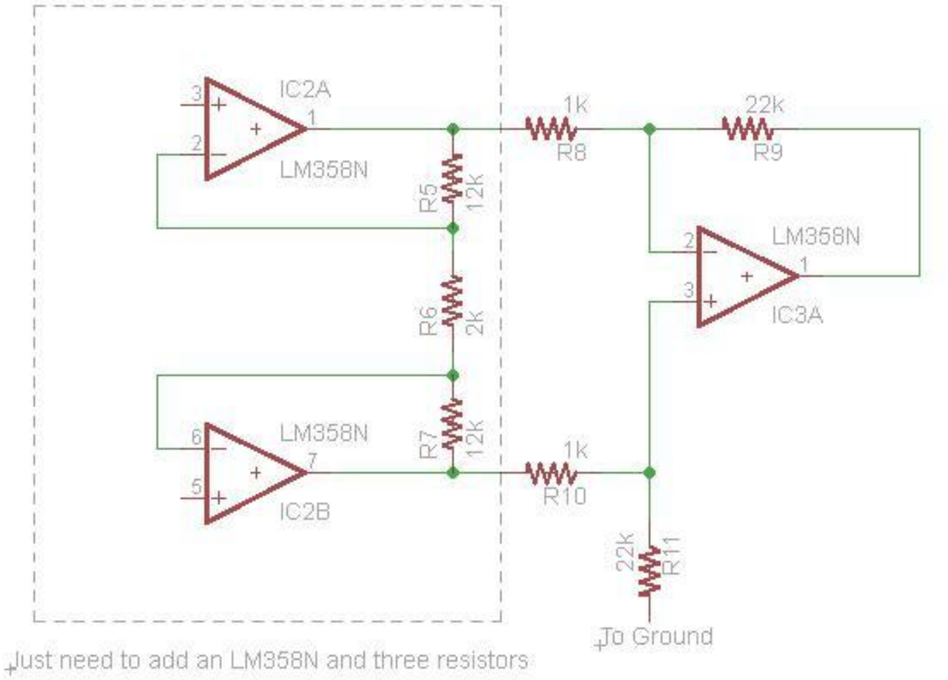
Appendix A: Lessons Learned

Oops! Back to the Drawing Board…

During final testing of the SmartCan's sensors prior to assembling the unit and shipping it off to UP Aerospace for integration, we discovered that we were getting no signal from the pressure transducer. The pressure transducer we had chosen for flight was a $250 high-reliability quartz unit (Omega P/N PX4600) with a full scale output of 30 mV with a 10Vdc excitation, which was slightly lower than the sensor that we had been using to test the system previously. What we failed to realize was that, unlike the cheaper sensor, whose output was expressed in mV/psi per volt of excitation, the PX4600's *total output* was 30 mV, an order of magnitude lower than the results we were getting from the cheaper device. Additionally, impedance matching became a problem with our original amplifier stage (see figure 6), and the result was an unresponsive sensor.

The schematic in figure 6 illustrates the conversion from our original difference amplifier to the classic 3-op-amp instrumentation amplifier shown. With a total gain of approximately 250, and the dramatic increase in the input impedance, the device began to work exactly as expected.

Figure 6: This schematic shows the changes (inside the dotted line) to the preamplifier for the pressure transducer.



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