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Compact, Lightweight Pressure Sensors for Aerodynamic Parachute Measurements

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Compact, lightweight sensors suitable for direct mounting onto parachute canopies are investigated to help verify and validate aerodynamic pressure and flow simulations for new parachute designs, and can provide real-time sensor data for airdrop studies and for parachute delivery systems having active control. Current efforts are focused on the development of a high accuracy, high dynamic-range pressure sensor for data extraction from experimental setups, real-time monitoring of conventional parachutes, and flight control for emerging decelerator systems. The present design is targeted at a full-scale pressure range of +/-100 Pa (+/-0.015 psi) having better than 1% accuracy while withstanding and measuring 200 kPa overpressure in either direction. A custom plastic package houses a custom sensor die having a pressure-deformable diaphragm with multiple optically coupled sealed-cavity resonant pickoffs. The sensor die is connected to an external interface circuit for signal extraction, formatting and data logging via a rugged, 1.0-mm diameter plastic optical fiber (including the jacket). The sensor package may be attached directly to the parachute fabric for differential pressure measurements. Fiber-tip versions of the sensor for absolute (barometric) pressure measurements are configurable for free-stream wind and water tunnel testing, which allows measurement of fluid pressure throughout the flow stream as the sensor probe is repositioned.

I. Introduction

ACCURATE monitoring of the aerodynamics and structural dynamics of variously sized and shaped parachutes is desired to verify and validate finite element analysis (FEA) tools used to predict the performance of the parachutes. Multiple sensors that are highly accurate, fast responding, lightweight, wireless, and attachable to a parachute canopy provide minimally intrusive real-time measurements for monitoring the transient airflow inside and outside the parachute, the structural dynamics of the canopy fabric, and the overall parachute shape and motion. Validation of computer-aided design and analysis techniques requires multiple-point measurements of temperature, airflow and pressure on and across fabric structures. Researchers in parachute technology recognize the need for small, accurate differential and absolute pressure sensors, temperature sensors, flow sensors, fabric stress monitors and strain sensors that can be used in small and large-scale test systems. These systems need to be able to accommodate rapid turnaround and a large number of sensor nodes without excessive setup and calibration requirements.

Currently, no sensor systems for low-pressure parachute measurements are available to accurately measure the low differential pressures across the parachute fabric during airdrop missions. While conventional technologies such as capacitance-based industrial pressure transmitters can provide the desired pressure range and resolution,

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these units are generally bulky, heavy and power-consumptive. Micromachined capacitive pressure sensors with integrated electronics offer an improved solution, although they typically fail to reach the low operating range requirements of 100 Pa (0.015 psi) or less and are not available in differential or gage pressure configurations. Low-cost piezoresistive pressure sensors, which comprise the majority of pressure sensors sold today, have limited signal-to-noise ratios that prevent them from giving accurate measurements of differential pressure at low operating ranges and have relatively high power consumption. Recent innovations by other researchers of integrated capacitive pressure sensors for tire pressure sensors have produced smaller devices that are typically configured as absolute pressure sensors and as such, do not have the capability of measuring small differential pressures that are of particular interest in parachute monitoring. Accommodations for wireless data communications, local data storage, batteries and an antenna add size and weight to the sensor node, which can alter the flow field and distort the structural response of the parachute.

A. Optically Coupled Resonant Sensor Probes

The issues with currently available sensors are being resolved with newly developed compact, lightweight, high-accuracy sensors that use precision pressure sensors based on optically coupled resonators combined with conventional silicon micromachined pressure-sensitive diaphragms in custom packages. The sensors are connected via a lightweight optical fiber from the parachute fabric to an external interface board that generates and stores pressure-sensor readings. The fiber-coupled sensor probe requires only a small package, with no batteries or onboard electronics that add weight or take additional space. Optical excitation and interrogation of the resonators with a single strand of plastic optical fiber, from less than a centimeter to a dozen meters or more in length, obviates the need for on-chip or in-package electronic circuitry, batteries, controllers and memory at the sensor probe that add appreciable size and weight. Developments on key parts of this system have included the resonant sensor die, the optical interface, controller interrogation of the resonator frequencies, a custom package, and application software to initiate and gather the data. Lightweight, plastic fiber connections to a canopy- or payload-mounted electronics and communications hub allow local data collection for real-time or delayed acquisition of data from one or more sensors. Each compact, lightweight sensor connects to the communications hub, which accommodates larger components including FLASH memory, a controller, a networkable wireless communication chip (e.g. ZigBee), antenna and batteries. One design of the sensor probe having a translucent package body and an optical fiber pigtail is shown in Fig. 1.

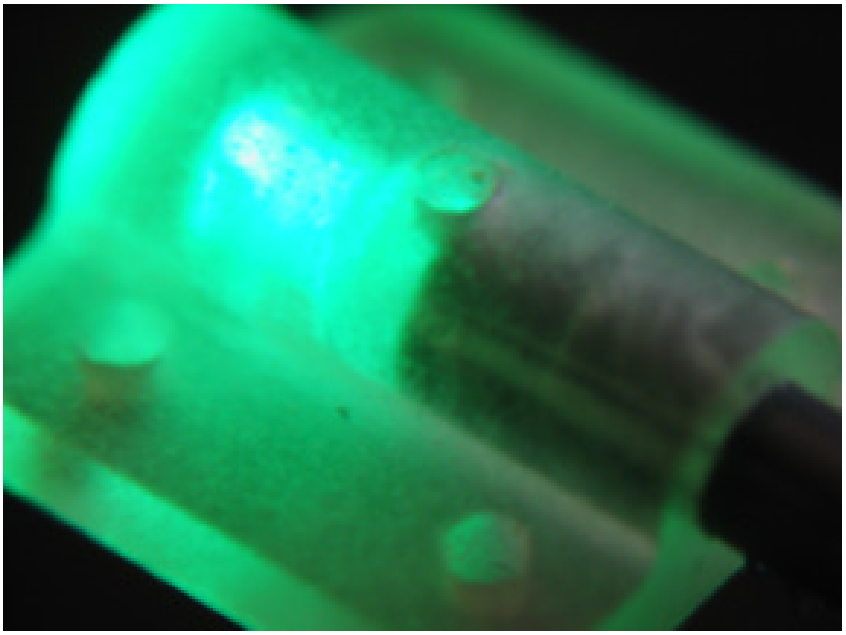

Figure 1. Differential pressure sensor package body with a 2.2-mm OD optical fiber, illuminated with light externally applied through the fiber from a green LED. The sensor die is not in the package for this photograph.

B. Program Objectives

Researchers need to instrument, monitor, verify and advance the performance of variously sized and shaped parachutes. This program addresses those needs by instrumenting a parachute with a plurality of small, high precision, optically coupled resonant pressure sensors attached to the canopy fabric, whereby one or more sensors are connected via an optical fiber to a controller board. Multiple sensors are connected via a star optical network or an ad hoc sensor network to a communications hub on the canopy or on the payload for data extraction and

accumulation. The resonant pressure sensors may be used with scaled-down versions of parachutes for wind- and water-tunnel testing.

Objectives of the program[1] include:

- Provide the ability to accurately monitor the aerodynamics and structural dynamics of variously sized and shaped parachutes
- Allow verification and validation of FEA
- Develop sensors that are highly accurate, fast responding, lightweight, and can be attached to the parachute fabric
- Specifically develop a sensor die and custom package for measuring small differential pressures across a parachute canopy
- Make provisions to accommodate wireless sensor connectivity.

C. Design Specifications

Definitions and performance specifications for the sensor, package, controller interface and GUI have been developed. A selected list of pertinent specifications including pressure range, package geometry, data rates and data storage requirements are listed in Table 1.

Table 1. System Definition and Performance Specifications for Differential Pressure Parachute Sensor Nodes

Parameter	Specification
Operating Pressure Range	0 to +/-100 Pa (+/-0.015 psi) differential or gage
Accuracy	1.0%
Resolution	0.1%
Repeatability	0.1%
Linearity	±0.5% FSO
Hysteresis	±0.5% FSO
Operating Temperature Range	-55°C to +70°C
Proof Pressure	1000x rated pressure
Burst Pressure	2000x rated pressure
Pressure Port	1 mm flush hole on gage (upper) side; 1 mm OD metal tube extending 2.0 mm on lower pressure port side
Package Attachment	Attachable to 1.1 oz/yd ripstop Nylon fabric via penetration of the fabric with a protruding metal tube and retainable with a stitchable retainer covering and flush with the tube tip
Package Weight	<0.4 gms
Package Size	Package body: 10 mm x 10 mm x 4 mm high not including the protruding tube Retainer: 10 x 10 mm x 1.5 mm high Tube: flush with retainer outer surface
Sensor Excitation	Optical
Sensor Output	Intensity and frequency-modulated raw signals from sensor probe, ratiometric or formatted output from hub-embedded controller
Fiber Weight	1.0 grams/meter (1.0-mm OD POF)
Fiber Bend Radius	> 15 mm (1.0-mm OD POF)
Data Update Rate	< 1000 per second peak (sampling rate can be much less during off-peak periods; data may be stored locally for downloading at a later time; higher data rates may have lower accuracy)
Local Data Storage	> 10,000 data points including time/date stamp

II. Sensor Die and Package Development

Key parts of the sensor system include the sensor die, sensor package, optical interface, controller software, incorporation of radio transceiver components allowing wireless communication, and application software to initiate and gather the data. One goal of the present program is the design, fabrication and assembly of an optically coupled

resonant pressure sensor for operating ranges as low as +/- 100 Pa, with overpressure capability well in excess of 100 kPa (1 atm) that can be utilized for instrumenting Army-designed parachutes. A custom package, an optical interface, controller software, and a suitable GUI have been developed or are currently being developed that allow single-point instrumentation of test parachutes. A radio interface such as ZigBee™ can be incorporated using off-the-shelf components and software utilities to demonstrate an ad hoc wireless sensor network. The target for the wireless sensor network includes at least eight sensor nodes mountable on the parachute canopy. With a properly implemented ZigBee™ network, several hundred sensor nodes can be accommodated. Rather than having a large network of sensors, production versions of the instrumentation nodes may have only one or a few carefully placed sensor nodes to provide the necessary guidance and control.

D. CAD Tools and FEA Analysis for Sensor Design

Preliminary closed-form analyses aided the design of a low-pressure resonant pressure sensor capable of high resolution for pressure range requirements of +/- 100 Pa with high overpressure protection in excess of one atmosphere. The analytical results showed that multiple resonators on a micromachined pressure-sensitive deformable diaphragm provide adequate pressure and temperature outputs.

Load cases were run for exemplary diaphragm and resonator dimensions. Plots of frequency output allowed refinement of values to avoid frequency overlaps and achieve sufficient sensitivity. Using the fracture strain for silicon with a safety margin of 10x, the die stresses comfortably meet the overpressure and burst pressure specifications. The simulation results show that the sensors can measure pressure in excess of +/- 100,000 Pa as well as in the +/- 100 Pa range.

To validate the closed form analysis, finite element analysis (FEA) with ANSYS® was used to determine the resonator and diaphragm resonant frequencies, frequency response and stress levels, and the pressure sensitivities for each resonator. Load cases were run over pressure ranges between –100 and +100 Pa and between –100,000 Pa and +100,000 Pa applied to the diaphragm topside. The pressure sensitivity was slightly reduced compared to the analytic calculations. Locating the edge resonator closer to the edge of the diaphragm increased the pressure sensitivity of the edge resonator and improved the correlation between the analytic results and finite element analysis. The diaphragm resonant frequency computed using FEA is higher than expected, although it can be explained by the sparseness (with resulting increase in stiffness) of the diaphragm elements. Stress analysis validates closed-form results, which indicate that the die stresses comfortably meet the overpressure and burst pressure specifications.

Coventor® software – a design and analysis software tool used in the MEMS field for layout, solid modeling, and FEM modeling capability – was used for CAD design, additional modeling, and layout of the low-pressure sensor. The Coventor process editor helped set up process steps that emulate clean-room processing steps. The materials database associated with the process editor contributed relevant information on sensor-fabrication materials and their associated properties. The Coventor solid modeler combined a user-specified material database file, a user-modified process file, and a user-designed layout file to produce a solid model of the pressure sensor that approximated the resulting device as if it had been through all the clean room processing. The solid models were examined for intended and undesirable constructions. The meshing of the solid models provided for various analyses including mechanical deformation, stress determination, and resonant frequency calculations.

A customized materials database was generated with specific values for Young's modulus, Poisson's ratio, internal stress, thermal expansion coefficients and the like associated with each material used in the sensor fabrication process. The low-pressure sensor designed previously with the aid of closed-form analysis, SolidWorks® 3-D CAD tools and ANSYS finite element modeling software was inserted into the 2-D layout editor of the CoventorWare® software, built into a solid model with a device-specific process flow generated with the process editor, meshed with the meshing tool, and verified using various solvers including co-solved mechanical and electrostatic analyses.

A number of analyses were run with the Coventor software package, resulting in verification of the sensor die design and expected sensitivity to applied pressure. Other analyses included:

- study of resonator actuation and performance
- deflection of cantilevered and doubly supported beams
- cursory damping analysis of cantilevered and doubly supported beams
- buckling analysis of strain diagnostic test structures

Additional FEM modeling including modal analysis was completed on each sensor die in the primary and test chip arrays to help guide the testing effort to be performed after the completion of die fabrication.

E. Sensor Die Development

The low-pressure resonant sensor was designed, modeled, simulated and laid out with CAD design, modeling, simulation and layout tools. Layouts of the pressure-sensor cell were generated from the die, diaphragm and resonator dimensions. The pressure sensor cell was arrayed over a 100-mm wafer to determine sensor die and test die placement. Design rule checks for minimum spacing, minimum width, self-intersection and other considerations were run. Supporting structures such as additional test structures, process diagnostic structures and investigatory structures were added to the mask set, culminating in mask-set data ready for a photomask vendor.

The sensor die, optically coupled via an optical fiber, are very small and require no metal interconnects or metal lead frame, thereby reducing package size and complexity. While absolute-pressure versions of the die are readily configurable, the die is accommodated by the current differential-pressure sensor package that measures pressure differences across the canopy fabric. Gage-pressure sensors with one side referenced to the local, static environment are also configurable. Deformations of the pressure-sensitive diaphragm are detected via shifts in frequency of the on-chip resonators, providing high accuracy, high dynamic range, and high resolution.

The mask set includes a primary die array and a test chip array. The mask set contains several optically coupled, low-pressure resonant sensor designs and other devices, along with a series of process monitoring structures. Individual primary die are placed in an arrangement to fill in the wafer. The primary die include multiple copies of a low-pressure sensor design and other devices and structures. A majority of the primary die contain a sealed-cavity three-beam low-pressure resonant pressure sensor.

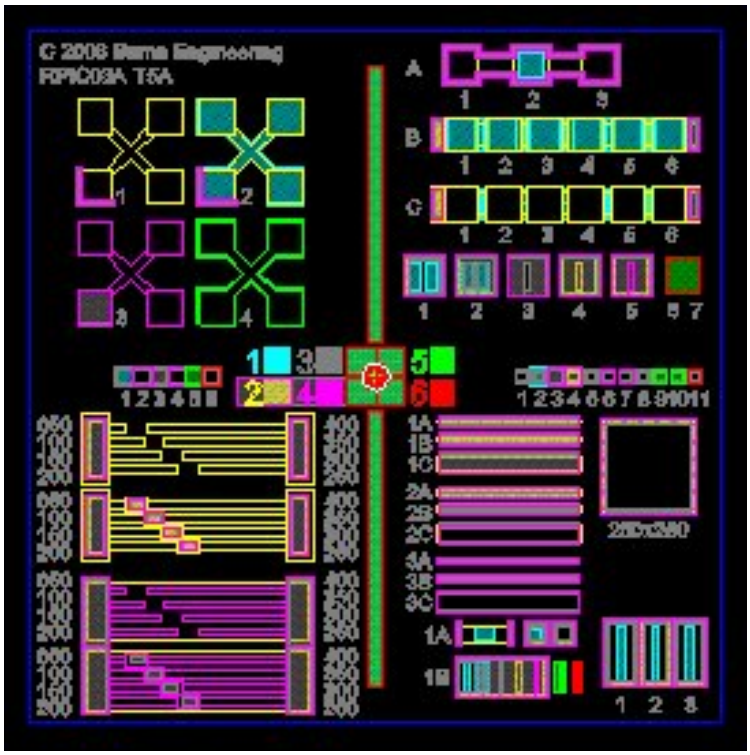

Figure 2. Layout of the test chip shows electrical, mechanical and process characterization structures.

Test die in the mask set contain various process and device characterization structures along with some specialized devices. For example, one of the test chips includes tensile strain diagnostic structures. Another test chip contains tensile and compressive strain diagnostic structures for each of the mechanical silicon layers and a series of square sealed cavities, which can be used to verify sacrificial etching and reactive sealing of the resonators. Other test chips include devices such as an array of singly supported and doubly supported sealed-cavity resonators of various lengths and styles. An example of a test chip die is shown in Fig. 2, including test structures for process monitoring, characterization, verification and debugging. These include sheet-resistivity test structures, out-diffusion test structures, scanning-profilometer test structures, Nanospec test areas, undercut structures, sealing-verification structures, a copy of the primary-die test structures, cross-sectional analysis test structures, compressive-strain diagnostic structures for key layers, etch-completion squares, and alignment marks.

The first developmental runs of the custom-designed sensor die were completed using a combination of patented[2], patent-pending, and proprietary processes. Process development and sensor fabrication was completed at the Stanford Nanofabrication Facility (SNF). Unit process steps were developed and improved where needed. Sensor fabrication used custom substrates available from a local vendor. Less expensive single-sided and double-sided polished silicon wafers were used for process development. Updated process flows and drafts of the associated travelers were prepared. With the specialized material already in hand, nearly all of the process steps were then completed at SNF.

Several run travelers were prepared in preparation for sensor fabrication. Variations between the travelers included various process nuances. Several short-loop process development cycles were undertaken to establish process parameters. Two pilot runs were started on a staggered schedule, and three fabrication (development) runs were completed during the course of the program. The pilot runs were primarily developmental to exercise all of the

process sequences and to determine which steps needed the most attention. While the first fabrication run proceeded relatively well, two additional process runs were undertaken while processing at SNF. The three fabrication runs were nearly identical to each other, with small variations in process parameters. Overall, five independent development runs were completed at the Stanford Nanofabrication Facility.

F. Package Design and Development

During the contract period, five models of the package were developed. Sample parts were obtained for each of the initial four designs and evaluated. SolidWorks CAD tools for solid modeling were used to design and construct the low-profile custom packages. All five package designs were fabricated at a local vendor using a 3-D printing approach with extruded ABS plastic and water-soluble supports. Although the resolution capability of the 3-D printing approach is not able to pick up the fine detail existing in the package CAD files, the prototypes provided 1:1 models for quick handling and evaluation.

One design for the low-pressure plastic package had a base, a lid and a nut, and accepted 2.2 mm plastic optical fiber from the side including a portion of the unjacketed fiber core. The lid presses into place, and has a hole for gage or differential pressure measurements. A second design used a barbed fitting with an e-ring, a pin clip, or a split washer for securing the package to the parachute fabric. A third design used a split package body with a left side and a right side. The halves of the base were pressed together and glued. A fourth design for the low-pressure plastic package replaced the split rectangular package with a cylindrical base section and tip section.

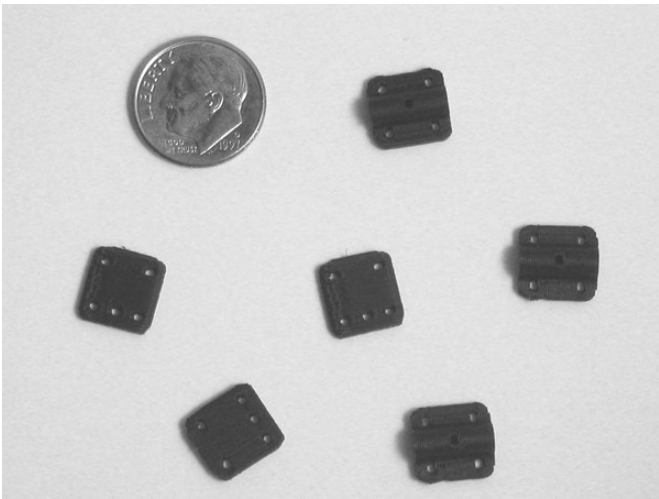

Figure 3. Three pairs of low-pressure packages and retainers fabricated using extruded 3-D printing, shown with a dime for size reference.

An additional design was needed to eliminate the need for a two-piece package body, to increase the package size around the sewing holes, to increase the depth of the fiber insert hole, and to prevent snagging and bunching of the Nylon fabric when attached. A fifth design was then developed, and samples were procured using the 3-D printing approach for quick evaluation (see Fig. 3). The package design, comprising the package body and the package retainer, was then sent to a stereolithography prototyping facility to make additional parts. The parts were manufactured with a high-resolution stereolithography process using a moderately clear water-resistant material. Multiple pairs of the package body and associated retainer were obtained. The resolution capability of the SLA approach is able to pick up the fine detail existing in the package CAD files, and provided samples that were suitable for handling, evaluation and subsequent demonstrations with the sensors. Initial evaluations show that while the package itself is light and has little impact on the movement of the fabric, the 2.2-mm-diameter fiber jacket imposes some objectionable rigidity on fabric movement that can be resolved with small-diameter fiber. As noted Section IV below, a reduced-diameter fiber was located and procured to minimize this issue.

The fifth design for the low-pressure plastic package has a unitary package body and a separate custom retainer to accommodate a 1.0 mm diameter tubular pressure port while avoiding snagging of fabric positioned between the package body and the retainer during attachment and use. The package has a larger size to increase the material around the stitching holes and to increase the depth of the fiber hole for improved fiber strain relief. Pressure ports comprising a one-millimeter hole on the top and another one on the bottom (offset from each other by 3.0 mm) allow for either gage or differential pressure measurements. The package accepts a 2.2 mm plastic optical fiber from one end and will also accept a smaller-diameter fiber with a 0.5 mm core and a 1.0 mm jacket. Figure 4a through 4d show the prototype package with a sensor die and fiber optic connection, the metal tubular pressure port, the package body and package retainer with the tubular pressure port, and a close-up view of the package body with the tubular pressure port.

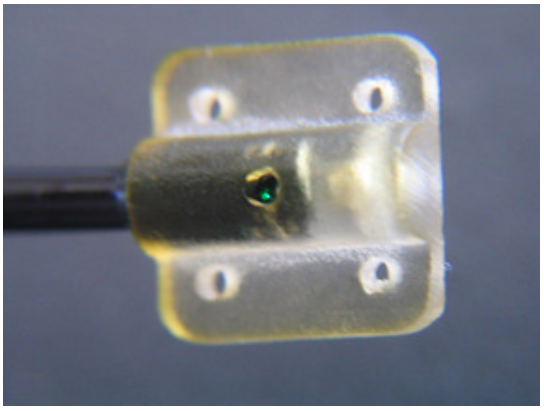

Figure 4a. Prototype package with sensor die and fiber optic connection, showing a spot of green light from an externally connected LED.

Figure 4b. Stainless steel tube pressure port with one end tapered and the other end flush.

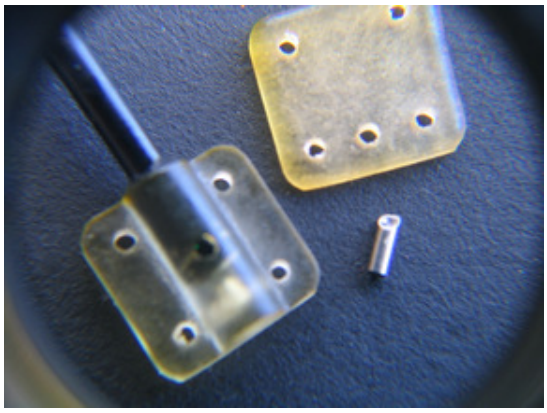

Figure 4c. Prototype pressure- sensor package body with sensor die and optical fiber, tubular pressure port and package retainer.

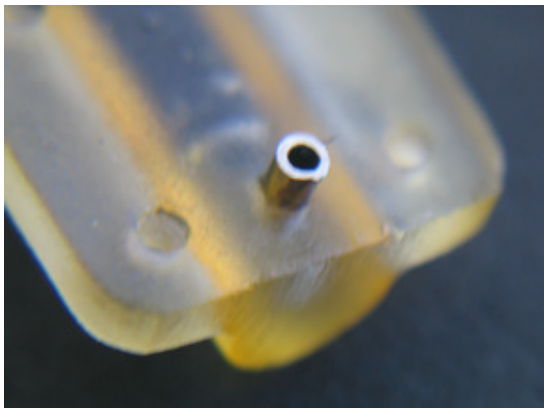

Figure 4d. Close-up of prototype package body with sensor die, optical fiber, and tubular pressure port (package retainer not shown).

The compact, package with the custom retainer accommodates the sensor die, differential pressure ports, and optical fiber. The package body and retainer are sewn together to secure the package to the fabric. The package with the sensor die, retainer and pressure ports is lightweight (~0.35 gms excluding the fiber). The small diameter of the tubular pressure port allows the sensor package to be carefully mounted on and dismounted off of a parachute canopy without harming the parachute or leaving torn fibers. To extract sensor data, a length of optical fiber is connected between each sensor and a canopy- or payload-mounted controller. Because of the small size and weight of the pressure sensor die and the pressure-sensor package, multiple sensors can be mounted strategically onto a single parachute gore for the monitoring of canopy pressure at different locations. In summary:

- A fifth version of the low-pressure sensor package includes a unitary axial body and accommodates a tubular pressure port.
- A separate aerodynamically designed retainer slips over the tubular pressure port and prevents the fabric from snagging on the tube. The retainer also allows stitching of the body to the retainer without snagging or bunching of the Nylon fabric.
- The package body is 10.0 mm x 10.0 mm and is 4 mm high, including a 1.5 mm high flange. The retainer is 10.0 mm x 10.0 mm and is 1.5 mm high. The retainer, when inserted over the pressure port and sewn to the package body with the fabric in between, is flush with the end of the metal tube.
- The weight of the package body is 0.204 gms, the retainer is 0.136 gms, the tube is 0.008 grams, and the total weight is approximately 0.348 gms.
- The 1.0 mm diameter tubular pressure port allows penetration of the parachute fabric without ripping or tearing of any fibers using modest effort. Removal of the tubular pressure port results in minimal, if any, damage to the parachute fabric.

III. Interface Electronics, GUI Development and Sensor Networking

The interface electronics drive and sense the resonant frequencies of the resonators on the sensor die, then convert those frequencies into a formatted pressure sensor output that can be stored locally and read out later, or converted to other forms such as a voltage or current for reading by an external data acquisition board. A wireless network can be used to extract pressure and temperature information from individual sensors or from an array of sensors.

G. Interface Electronics and Data Storage

After converting the resonator frequencies to a pressure and a temperature in the desired units, the data is stored in a logger measurement file. Entries in the measurement file include an identification number associated with each data point, the date and time associated with each data point (to the nearest second), fractional seconds to provide millisecond or microsecond resolution, the pressure reading, the temperature at the sensor, at least one copy of the local logger name, and at least one copy of the electronic serial number associated with the particular sensor. A summary of the measurement data is listed in Table 2.

Table 2. Contents of Logger Measurement Files

Parameter	Comments
ID	Unique identification number associated with each data point
Date and Time	Date and time associated with each data point
Fractional Seconds	Sub-second time associated with each data point; can be added to the date and time field to provide millisecond or microsecond resolution
Pressure (Pa)	Pressure reading (in Pascals) measured by the logger
Temperature (C)	Temperature reading (in C) measured by the logger
Local Logger Name	Re-creation of local logger name defined by the setup file; can be omitted from each data record except the first record or when the local logger name has changed during the measurement sequence
ESN	Re-creation of the electronic serial number in the EDS file and in the setup file; can be omitted from each data record except the first record or when the local logger name has changed during the measurement sequence

To set up the sensor for data acquisition, setup information is provided to the sensor. As found in Table 3, the setup information includes a unique identification number associated with each setup in the sequence, a local logger name, a starting date and time, time between readings, the total number of data points, units for the primary sensor (pressure), units for the secondary sensor (temperature), an electronic serial number associated with the logger, and additional user options.

Table 3. Logger Setup Information: File Contents

Parameter	Comments
ID	Unique identification number associated with each setup in the sequence (one or more measurement sequences with, for example, different measurement intervals can be set up at one time)
Local Logger Name	User-definable name associated with the logger; can include information relevant to the particular measurement sequence
Start Date/Time	User-specified start date and time; referenceable to PC time base
Time Between Readings	User-specified time between readings of microseconds to hours or days, consistent with the minimum measurement interval specified in the EDS file
Total Data Points	Total data points to be taken during each measurement sequence; total data points for all measurement sequences must be less than the available memory allows
Primary Sensor (Units)	List-extracted options available as the primary sensor output (i.e. Pressure (Pa))
Secondary Sensor (Units)	List-extracted options available as the secondary sensor output (i.e. Temperature (C))
ESN	Electronic serial number associated with the logger and assigned by the manufacturer
Additional Data Set Request and Other Options	Contains user options such as requesting additional data sets to be taken after the current measurement sequence is executed

Several choices exist for the controller, although on-chip A/D and D/A converter requirements and local FLASH memory capability narrows the choices considerably. While an ADuC7020 analog controller from Analog Devices remains a viable controller candidate, an emphasis on a USB 2.0 interface between the sensor and the PC resulted in the selection of another controller, the LPC2148 from NXP (formerly Phillips). The NXP LPC2148 controller operates at up to 60 MHz, has 40 kbytes of on-chip RAM and 512 kbytes of on-chip FLASH memory.

Before developing specific code routines to extract sensor data, the design and organization of the graphical-user interface (GUI) was laid out to ensure proper and future functionality of the software/hardware interface and controller specifications. Code routines to excite and measure resonant frequencies of the resonators and to extract the differential pressure are currently being developed. Figure 5 shows the IAR evaluation board with the NXP controller.

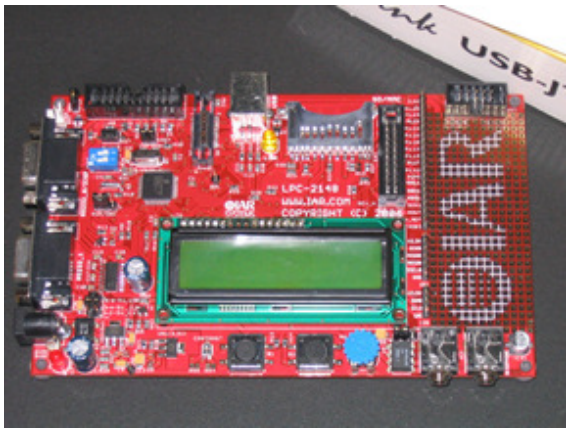

Figure 5. IAR KickStart development software, USB-JTAG debugger and LPC2148 microcontroller evaluation board with 512 kBytes of on-chip Flash memory, 14 channels of A/D conversion and 1 channel of D/A conversion.

In summary:

- Controller interface development remains under internal development.
- Two evaluation boards with controllers (ADuC7020 from Analog Devices and LPC2148 from NXP) are being used in the development.
- Embedded systems development tools from IAR and Keil are being used to develop the software interface.

H. GUI Development

In-house development tools have been used to develop a graphical user interface for reading and controlling the sensor and to allow verification of sensor performance. GUI development has proceeded with the preliminary specification of desired functions for sensor setup and data extraction including the initial details of file-submission and data-extraction protocols.

The development of the GUI for the parachute instrumentation application with subsequent data acquisition has resulted in the completion of a version that allows the user to 1) set up the logger, 2) extract data from the logger, 3) view data previously saved from the logger, and 4) exit the program. Interface with the sensor occurs via three files: a setup file, a measurements file, and an electronic data sheet (EDS) file, each in ASCII (.txt) format. Each of the three files are readable, viewable, modifiable and saved with the GUI. The GUI was developed on a database development system that allows for initial interaction with the sensor and provides a pathway for initialization and extraction of larger sensor arrays using wired or wireless protocols. The software incorporates the desired functions for sensor setup and data extraction. With the firming up of GUI functionality and operational procedures, details of the file-submission and extraction protocols were solidified. Currently, the contents of the logger measurements file extractable from each sensor are listed above in Table 2, and the contents of the logger setup information file, customizable for each sensor, are listed in Table 3.

The application software is invoked by double-clicking on or opening the logger application on a PC. The MegaSense™ Logger Introduction window pops up and waits until the user accepts the posted terms of use. The Logger Main Menu window opens, presenting the user with four options: 1) Set Up Logger; 2) Stop and Read Logger; 3) Show Logger Data; and 4) Exit, as seen in Fig. 6.

In the logger setup dialog window, the user may accept or modify the logger name or units for the primary and the secondary sensor and modify, add, delete or inspect the settings. Currently, the primary sensor units and secondary sensor units are restricted to pressure (Pa) and temperature (C), respectively. The available choices for the sensor units are found in the corresponding electronic data sheet (EDS).

The Logger-Trigger, Time and Data-Rate Setup window allows the user to continue to modify, add, delete or inspect setup sequences. The user may enter the desired field for possible modifications to the start date and time, the measurement interval, the total number of readings and a checkbox that indicates an additional data set is being requested after the first has been completed.

The Logger-Trigger, Time and Data-Rate Review window allows the user to check and verify setup information. The navigation aid at the bottom allows the user to rapidly view the setup scenarios. An estimate of the time duration for each test sequence in the overall setup is provided.

When the "Stop and Read Logger" button or label is clicked on the main menu, the Logger Data-Extraction window appears. The Logger Data-Extraction Warning window allows the user to cancel out of the operation or to proceed with stopping the logger.

The Logger Data-Extraction Filename Specification window allows the user to enter a filename for the logger data, or to use the default name provided. The user may save the logger data under the selected filename and proceed to the Logger Measurements window.

The Logger Measurements window allows the user to view the measured data. Several data summaries are presented, such as the total number of data points or the maximum and minimum values for the primary and secondary sensors. The user may use the navigation tool at the bottom of the window to view various data records.

The Logger Chart window allows the user to view the measured data in chart form. The chart plots the data on one or two axes, with the data ID serving as the x-axis.

The Logger Electronic Data-Sheet window allows the user to view the EDS information and update the information if desired. The vertical scroll bar allows other information to be viewed.

When the "Show Logger Data" button or label is clicked on the main menu, the Logger Data-File Selection window appears.

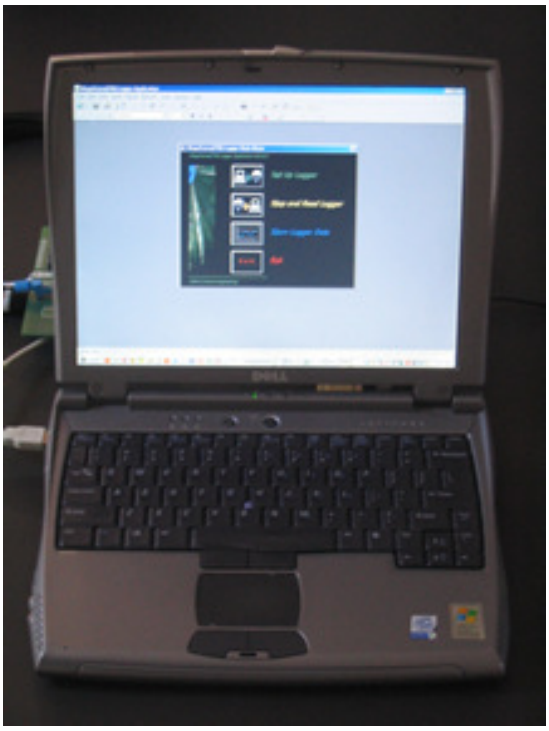

Figure 6. The main menu for the sensor graphical user interface (GUI) provides four commands to 1) set up the logger, 2) stop the logger and extract the data, 3) view saved data, and 4) exit the application. An Analog Devices microcontroller board with an ADuC7020 processor is visible behind the laptop computer.

I. Sensor Networking

To extract real-time or logged data from one or more parachute-mounted sensors wirelessly, radio transceivers, antennas and network communication chips are combined with the controller chip into a communication node. Figure 7 shows a block diagram of a wireless sensor for instrumenting parachutes, with a single-chip RF transceiver, an analog microcontroller, an optoelectronic emitter and detector, and a battery. The optically coupled pressure sensor is connected to the controller/communication node via a single length of plastic optical fiber. A wireless network of highly accurate, lightweight sensor nodes can be configured with a single or multiple sensors fiber-connected to each communication node. A preliminary package concept for the wireless sensor communication node contains a resonant pressure sensor, an optoelectronic interface, a controller, a single-chip radio transceiver, a battery, a crystal oscillator, an antenna, and associated capacitors and resistors. The total package weight, including a 3V lithium battery, is estimated at about 17.8 grams. The package has an outer diameter of about 48 mm (1.9 inches), and extends outwardly 8 mm on one side of the Nylon fabric and 3 mm on the other. The size and weight of the node supports the architecture of one or more fiber-connected pressure sensors extending from the node, such that each pressure sensor remains small and lightweight, thereby not affecting the flow or structural dynamics of the parachute. Appreciable reductions in size and weight are possible with judicious design, careful selection of components, and a custom-designed integrated circuit. Work is currently underway to demonstrate network connectivity using an ad hoc network with IEEE 802.15.4 ZigBee™ physical and medium access control (MAC) layers operating in the 2.4 GH band.

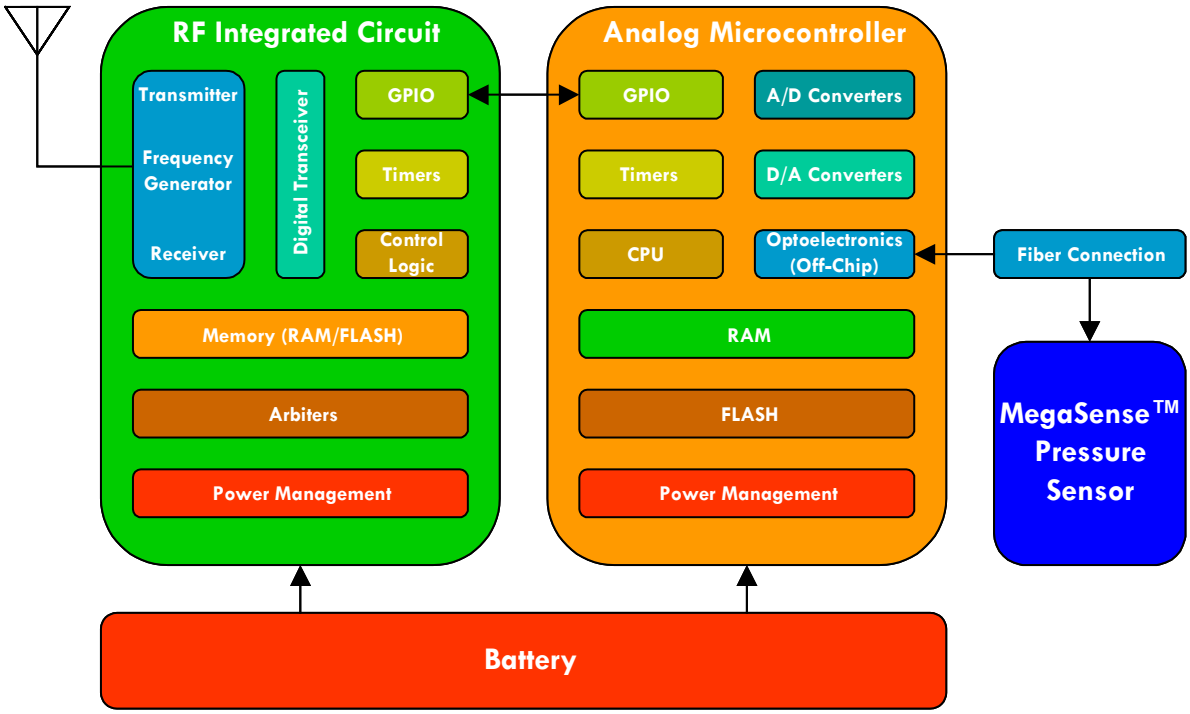

Figure 7. Block diagram of a wireless sensor for instrumenting parachutes. Using an IEEE 802.15.4 (ZigBee) protocol, dozens or more sensors coupled to the fabric provide differential pressure and related measurements for real-time and accumulated measurements.

IV. Assembly and Test

In-house assembly equipment and processes were used to assess, assemble and test the completed sensors. In-line testing of the sensor die occurred during sensor fabrication. Post-fabrication evaluation and testing of the die including optical profilometry measurements were completed. Detailed focused ion beam (FIB) and scanning electron microscope (SEM) testing of the sensor die were done at Stanford's Nanocharactization Laboratory (SNL). Sample die from each wafer run completed during the program were viewed in the FIB at SNL. Multiple die from each wafer run were attached to an aluminum mount with conductive graphite. A cross-sectional view of a resonant beam and shell showed smaller than expected gaps between the resonator and the substrate and shell. A gap on the sides of the beam was not visible, largely due to re-deposition during the ion-assisted milling and partly due to the selected process sequence. Resonant testing of the die has yet to be performed. Provisions for field testing the sensor include attaching it to a test parachute and applying small differential pressure across the fabric by air dropping, air lifting (vertical lift) or air dragging the parachute. Pressure testing resources are accessible; from simple puff-and-measure verification to calibration against some of the best transfer standards.

J. Preliminary Parachute Testing

Structurally intact die from the pilot run were inserted into one of the stereolithographically produced prototype packages along with the optical fiber to demonstrate that the packages can accommodate the sensor die and that light from the fiber can be entrained onto the die within the package body. The package and die was attached to a swath of 1.1 oz/yd ripstop Nylon using sewing thread, verifying that the

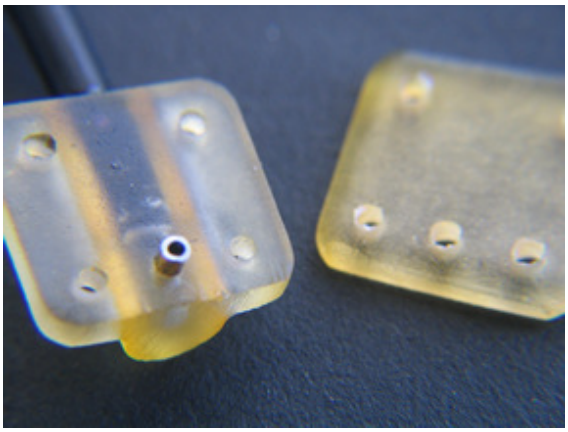

Figure 8. Prototype pressure-sensor package body with sensor die and optical fiber, tubular pressure port and package retainer. The base and retainer are 10 mm on each side.

design does not damage the fabric when properly installed or removed, and that snagging or tearing of the fabric does not occur during parachute deployment. Another sensor package with a sensor die and 2.2-mm OD optical fiber was assembled and sewn to the 1.1 oz/yd ripstop Nylon. Although the sensor package was sufficiently light, the flexibility and weight of the POF were not satisfactory, and an alternative was pursued.

The main body of the package houses the sensor die and has a topside pressure port accessing one side of the sensor die and a bottom side pressure port accessing the other side of the sensor die. A tubular pressure port with a 1-mm outside diameter protrudes from the bottom of the package body. The bottom of the package body mates to a package retainer with the canopy fabric in between the two parts. The protruding tubular pressure port on the bottom of the package body (Fig. 8) penetrates the fabric, and the package retainer is placed snugly over the pressure port. The package body and retainer are sewn together to secure the package to the fabric. While the tubular pressure port has a small inside diameter that can restrict the flow of the pressure medium, the short length of the tube and the small volume between the tube and the bottom of the sensor die results in a high frequency response that enables rapid pressure changes to be measured during parachute inflation and high-frequency fluid-structure interactions. The small diameter of the tubular pressure port allows the sensor package to be carefully mounted on and dismounted off of a parachute canopy without harming the parachute or leaving torn fibers (see Fig. 9a and 9b).

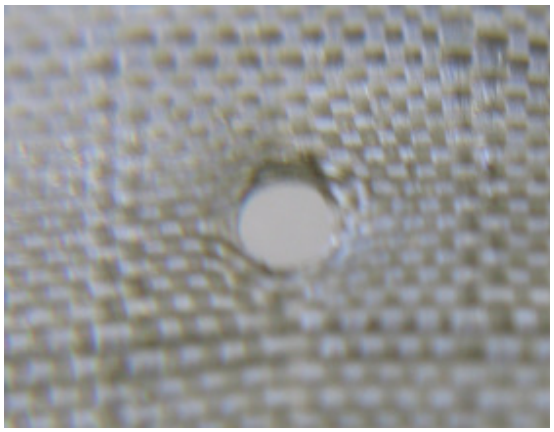

Figure 9a. Nylon parachute fabric after penetration and removal of a 1-mm diameter (OD) tubular pressure port shows a residual hole though no broken threads.

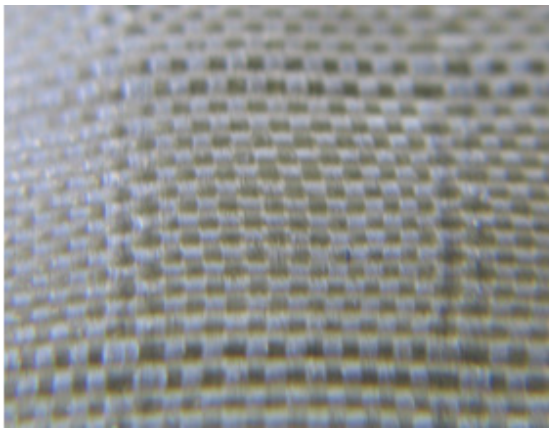

Figure 9b. Nylon fabric of Fig. 9a after manually kneading the fabric to re-orient the fibers shows complete fabric restoration.

One of the sensor packages was assembled with a sensor die and attached to the 36" test parachute. The sensor with ten feet of optical fiber and an LED light source at the opposite end was preliminarily tested using a manually operated centrifugal parachute test apparatus. The pressure-sensor package body with a sensor die and an optical fiber, tubular pressure port and package retainer that are mounted on the test parachute can be seen in Fig. 10. The connecting fiber has an outer diameter of 2.2 mm.

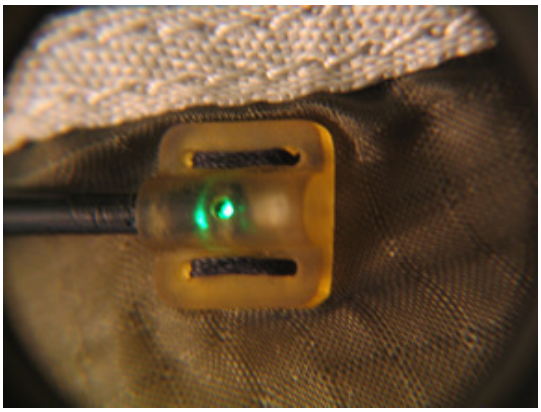

Figure 10. Close-up view of the prototype pressure sensor attached near the seam between two parachute gores, with an LED light source coupled to the sensor package via 10 feet of 2.2-mm diameter plastic optical fiber.

K. Optical Fiber Enhancements

A smaller diameter, lower weight plastic optical fiber was located and procured to mitigate some of the concerns about the relatively stiff 2.2-mm OD fiber. The new fiber offers several advantages over the original fiber, including ~1/4 the weight, less than ½ the diameter, and about 1/2 the bending radius. Pertinent specifications are shown in Table 4. The relative stiffness of the two fibers and of the test-parachute suspension lines are listed in Table 5. The normalized stiffness ratio does not include the relative weight of each sample. The effective stiffness ratio includes the weight differences per unit length relative to the 1.0 mm OD fiber. The bending stiffness of the smaller-diameter fiber is

less than 10% of the larger-diameter fiber, though the relative stiffness of the 1.0-mm POF is still about five times that of the suspension line used for the test parachute, assuming a density per unit length of 1 gm/m. Figures 11a and 11b illustrate the tighter bending radius of the smaller-diameter fiber, reduced from approximately one inch to about ½-inch. Four assembled sensors with 6" fiber pigtails are shown in Fig. 12. The SLA packages were retrofitted with the 1.0-mm OD fiber and mounted on a 36" test parachute. The retrofitted sensor packages were attached in a cross configuration, with three sensors along the length of one gore seam and the other two centered along an adjacent gore seam on each side of the first (see Fig. 13).

Table 4. Comparison of Old and New Plastic Optical Fiber

Parameter	Old Value	New Value	Units	Description
Jacket OD	2.2	1.0	mm	Outer diameter of jacket
Fiber Core OD	1.0	0.5	mm	Outer diameter of core
Temperature Range	-55 to +85	-55 to +70	C	Operating range
Jacket Material	Chlorinated Polyethylene	Polyethylene	N/A	Outer jacket material
Jacket Color	Black	Black with White Stripe	N/A	Outer jacket color
Weight	4.0	1.0	gm/m	Weight of fiber
Insertion Loss	0.14	0.22	db/m	Insertion loss
Bending Radius	25	15	mm	Bending radius

Table 5. Relative Stiffness of POF and Suspension Lines

Material	Outside Diameter	Normalized Stiffness Ratio	Effective Stiffness Ratio
Plastic Optical Fiber (2.2-mm OD)	2.2 mm	2.83	11.3
Plastic Optical Fiber (1.0-mm OD)	1.0 mm	1	1
Suspension Line (3/64" Nylon)	1.2 mm	0.19	0.19*

* Assumes the weight per unit length of the parachute suspension line is the same as the 1.0-mm OD fiber.

Figure 11a. The initial plastic optical fiber has an outside diameter of 2.2 mm and a minimum 25-mm radius of curvature. The green light transmitted through >100 ft of fiber is visible to the unaided eye at the exposed end.

Figure 11b. The upgraded plastic optical fiber has an outside diameter of 1.0 mm and a 15-mm radius of curvature. The green light transmitted through >100 ft of fiber is visible upon close inspection.

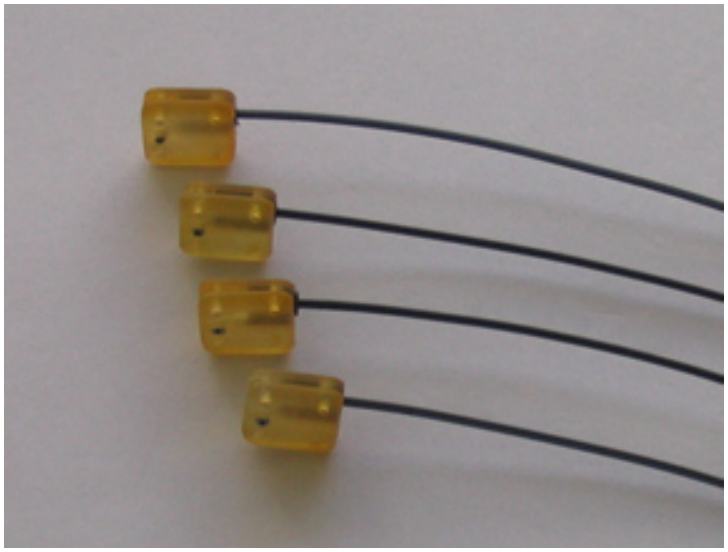

Figure 12. Assembled 100 Pa differential pressure sensors with 1.0-mm OD fiber pigtails.

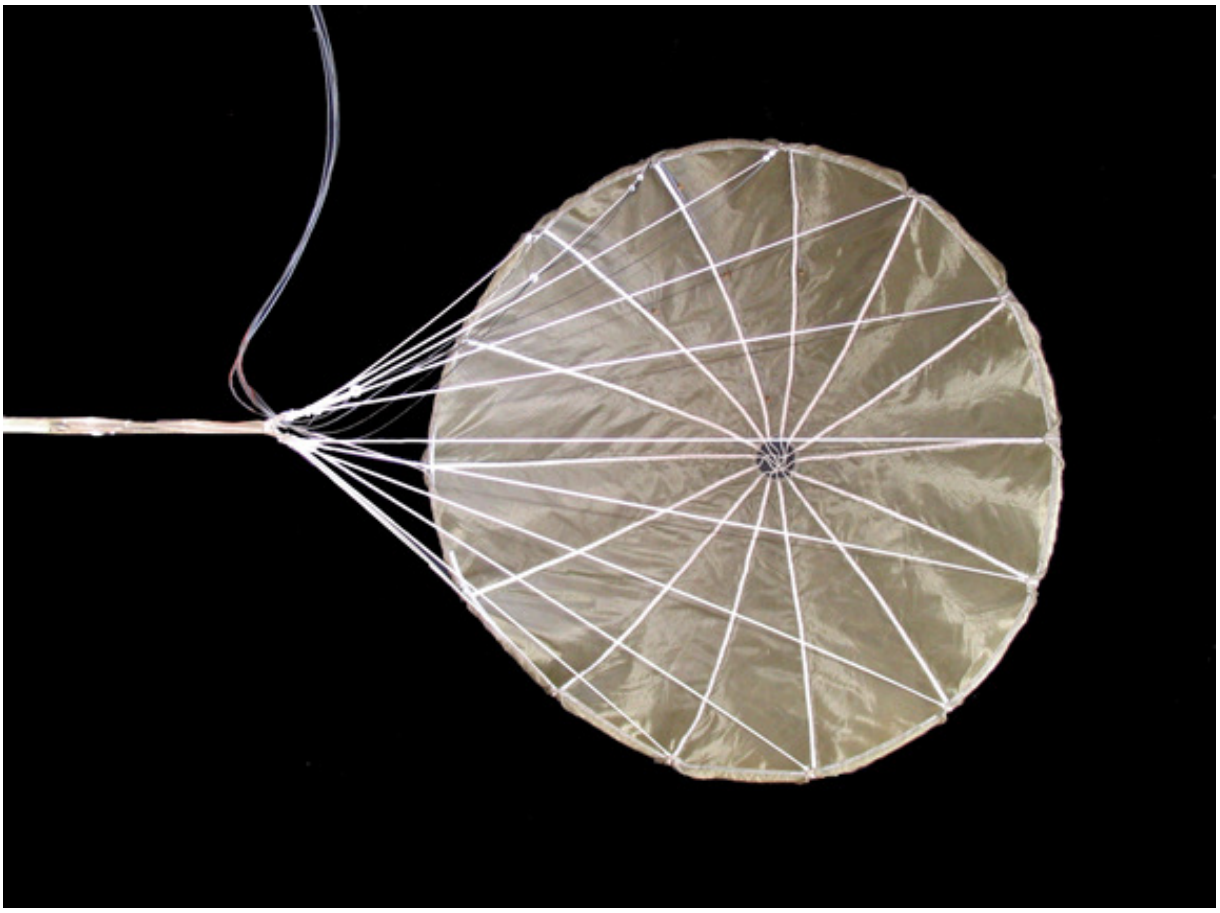

Figure 13. Five assembled pressure sensors mounted on a 36" diameter test parachute. The five strands of connecting fiber have a jacket outside diameter of 1.0 mm and a length of ~10 feet. Three of the sensors are located along the upper canopy gore seam just to the left of the vertical seam, and the remaining two form a cross with one to the left and one to the right of the first seam. The five fibers are visible in the upper left corner of the photograph.

L. Parachute Implementation Considerations

Use of the fiber-coupled parachute sensors on a parachute highlights researchers' concerns about overall weight, sensor attachment, fiber attachment, parachute folding and stuffing, and dynamic affects during parachute deployment and operation. Many of these concerns have been addressed.

Attachment of the prototype packages to a loose piece of 1.1-oz ripstop Nylon and waving the fabric in the air showed that package weights under a gram have little if any affect on the movement of the fabric. At 0.4 gm per sensor, over 75 sensor packages would equal the weight of a 3 ft x 3 ft piece of fabric. The weight, stiffness and radius of curvature constraints of the optical fiber have a bigger impact on usability, although these concerns are mitigated by use of the smaller 1.0-mm OD fiber. The total length of the small-diameter fiber, with a weight of 1 gm/m, could extend over 100 feet to equal the weight of 1 sq. yd. of the fabric, and still be only a small portion of the total weight of the suspension lines. Each length of fiber is of similar weight to a similar length of suspension line.

The stiffness of the fiber, over five times that of the suspension lines, causes some distortion of the parachute fabric though the distortion becomes negligible when the parachute is inflated. The minimum recommended bending radius of the fiber prevents folding the parachute directly over the optical fiber. However, initial tests show that bending limitations of the fiber are less than one might think. Even a crisp parachute crease can be traversed by the fiber if the fiber approaches the crease at a modest non-zero angle, as can be demonstrated by placing the fiber against an edge of a credit card and in contact with each side to emulate the path of the fiber through the crease. Parachute gores are slightly more forgiving than a credit card, since the fabric itself can slide and reorient to accommodate the fiber as the parachute is folded and stuffed. Further reductions in the crease angle can be obtained by housing the fiber loosely within a strip of seam material, 3/8" or wider, attached at each side to the parachute fabric, to allow the fiber to find its own way around the crease. Special consideration may need to be given to stuffing procedures for sensor-implemented parachutes, particularly if the distance between pleats or the length of a fold is less than twice the bending radius of the fiber (30 mm).

In cases where high pressures are applied during packing, the fiber or the packages could possibly be crushed although plenty of fabric near the sensors and the fiber would spread out and diminish the forces. Embedded communication ports in the parachute canopy may have more problems withstanding such forces than the individual sensors or the fiber. The weight and size of each communication port is also of concern, though separation of the sensor probes from the communication ports with a length of fiber minimizes the impact on reliable pressure measurements without distortion of the parachute or perturbations of the flow field.

During parachute deployment, stretching of the fiber and ripping of the fiber out of the package body has been raised as a concern. These concerns can be mitigated with proper strain relief in the sensor body and by the inclusion of a small length of looped or snaked fiber sewn into a small pouch near each sensor using fabric and some seam material. Drop testing or chute deployment tests were not done during the program to validate these concerns or to verify the proposed solutions.

V. Development Status

During the nine-month program, the first versions of the sensor, package, controller interface and GUI, including a demonstration of a state-of-the-art sensor mounted on a parachute, were developed. Completed tasks included system definition, the design for the sensor, several (five) design and fabrication iterations for the package, processing of five pilot and development runs of the sensor die, development of the controller interface for analyzing the frequency output from the sensors, and an initial version of the graphical user interface for preparing and presenting the data. The custom package with a sensor die, tubular pressure port and a retainer was connected via small, lightweight plastic optical fibers mounted on a 36" test parachute for testing and evaluation. Table 6 gives a summary of component weights.

Table 6. Component Weights

Parameter	Weight	Units	Description
Package Body	0.20	gms	Base is 10.0 mm x 10.0 mm with a radial height of 4.0 mm
Package Retainer	0.14	gms	10.0 mm x 10.0 mm x 1.5 mm
Tubular Pressure Port	0.01	gms	1.0 mm diameter metal tube
Sensor Die	0.001	gms	Optically coupled resonant sensor
Fiber (2.2-mm Diameter)	4.0	gms/m	Plastic optical fiber
Fiber (1.0-mm Diameter)	1.0	gms/m	Plastic optical fiber

Work on the controller interface continues and the GUI is being upgraded under internal funding. All preliminary testing on the sensors is positive, yet the full operation of the sensors requires verification. Advanced work on setting up the sensors in an ad hoc 802.15.4 (ZigBee™) network is currently underway.

While the current two-part package with a square retainer appears to yield favorable results, an alternative package has been designed with a narrower, cylindrical package body and retainer that have external grooves rather than holes to accommodate thread for attaching the package to the parachute fabric. Figure 14 shows a solid model of the two-piece package. This package concept features a smaller cylindrical package body, a snap-fit rectangular retainer, omission of the sewing holes, grooves around the periphery of the package body and retainer for securing the package with sewing thread, an integral plastic port that replaces the metal pressure port, a side port at the center of the retainer, a second pressure port at the end of the axial package body opposite the fiber, and 1.0-mm outside diameter fiber. The design reduces the overall size and weight to less than 0.1 gram (excluding the fiber) and makes the package easier to install on the Nylon ripstop fabric.

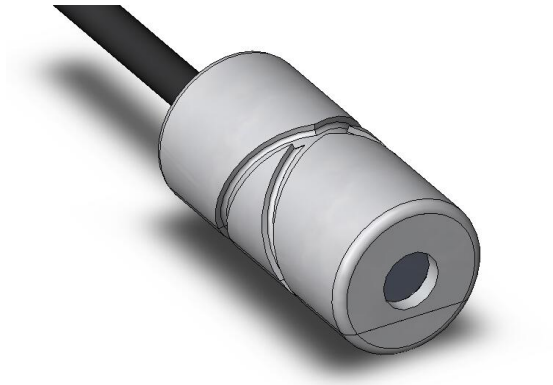

Figure 14. Compact two-piece cylindrical package concept features a plastic side port, an axial pressure port, a snap-fit retainer and grooves around the package body and retainer for securing with thread. The package is 8 mm long and 4 mm in diameter, weighs less than 0.1 gm, and accommodates 1-mm OD plastic optical fiber.

VI. Summary of Results

Significant findings of the completed program include:

• Lightweight packages weighing less than about 0.4 grams are applicable to parachute instrumentation because the low weight has minimal impact on fabric flexibility and movement.

• Sensor packages less than approximately 10 mm x 10 mm x 4 mm in size have minimal impact on parachute operation.

• A package body with sewing holes and a package retainer that mates with the pressure port and package body allow sewing or stitching the sensors to the parachute fabric and provide a reasonably good method of sensor attachment without snagging or catching on the fabric.

• Lightweight plastic optical fiber with a 1.0-mm outside diameter of the jacket can be used to interconnect sensors mounted on a parachute gore, although larger-diameter (2.2-mm OD) fibers have increased stiffness and greater weight that impact the natural displacements of the 1.1-oz/sq.yd Nylon fabric.

• Fiber-connected sensors have applicability to parachute modeling and testing.

• Resonant sensor die can be fabricated to provide the sensitivity required for low-pressure (+/- 100 Pa) measurements while withstanding high differential and absolute pressures well in excess of 100,000 Pa (~1 atm).

• Custom packages with a 1-mm OD tubular pressure port or less can penetrate the fiber mesh in the 1.1-oz/sq.yd Nylon fabric and be removed without damaging the parachute.

• It is feasible to operate the sensors via small-diameter fiber extending between the sensor and the controller.

• A suitable architecture for parachute instrumentation is a configuration with one or more sensors coupled via short or long lengths of optical fiber to an electronics and wireless communications hub mounted, for example, near the vent hole of the parachute.

• Data rate requirements during parachute deployment and inflation are appreciably higher than background rates, suggesting that data should be logged locally during the high-rate periods and downloaded at a later time.

• Occasionally high data rates and limited data storage capability in the sensor or hub suggest that the sensors be programmable with variable data rates and triggered remotely or via an internal time base.

• A custom graphical user interface (GUI) allows a user to set up the sensors with programmable data rates, provide local logger names, and obtain a record of each data point taken with a time and date stamp.

• The GUI can provide the user with electronic data sheet (EDS) information regarding the sensor, including maximum data rates, pressure range limitations, multi-sensor capability (e.g. temperature), and calibration data.

Successful completion and demonstration of the sensors provides instrumentation capability for parachute design, simulation and verification. Pressure-sensor instrumentation that helps verify and validate computation analytical methods to develop new parachute designs and manufacturing techniques will reduce research time and cost significantly. In addition, this instrumentation may reduce the manufacturing and testing requirements of parachutes for airborne force projection and aerial delivery methods that are critical for many military and humanitarian missions.

M. Case for Optically Coupled Resonant Sensors for Parachute Pressure Measurements

Optically coupled resonant pressure sensor probes offer the small size and weight required for instrumentation of parachutes to measure the generally small, aerodynamic pressures that occur across the parachute canopy with minimal affect on the flow field, even at high velocities. Pressure measurements made directly on the canopy avoid frequency loss and false signals associated with the use of flexible tube pickoffs. The resonant frequencies of the resonators are readily distinguishable from other types of noise and interference, and can be used to verify resonator operation even if the sensors are stuffed tightly in a deployment bag. The sensitivity of the resonators allows minute pressure measurements and a high-pressure range in either absolute or differential (gage) configurations. The resonant pressure sensors are more sensitive at lower pressure ranges than are conventional piezoresistive devices. Unlike typical capacitive sensors, each side of the deformable diaphragm can be exposed to the pressure medium, allowing direct measurement of differential pressure across the diaphragm.

A single plastic optical fiber connects the sensor probe to a communications hub where data can be formatted, sent or saved for later retrieval. The sensors have no metal in them, reducing the radar cross section and avoiding negative attributes of potentially large, static discharges. The communications hub includes a controller, batteries, and radio networking circuitry for interpreting sensor signals and for communicating externally during or after an airdrop. Data rates are spurious, being high only during parachute deployment and descent. Local data logging allows the collection of the data until delivery is requested. Low latency of wireless protocols makes the delay minimal, and offers the ability for active parachute control during descent with effectively closed-loop control using an open-loop system.

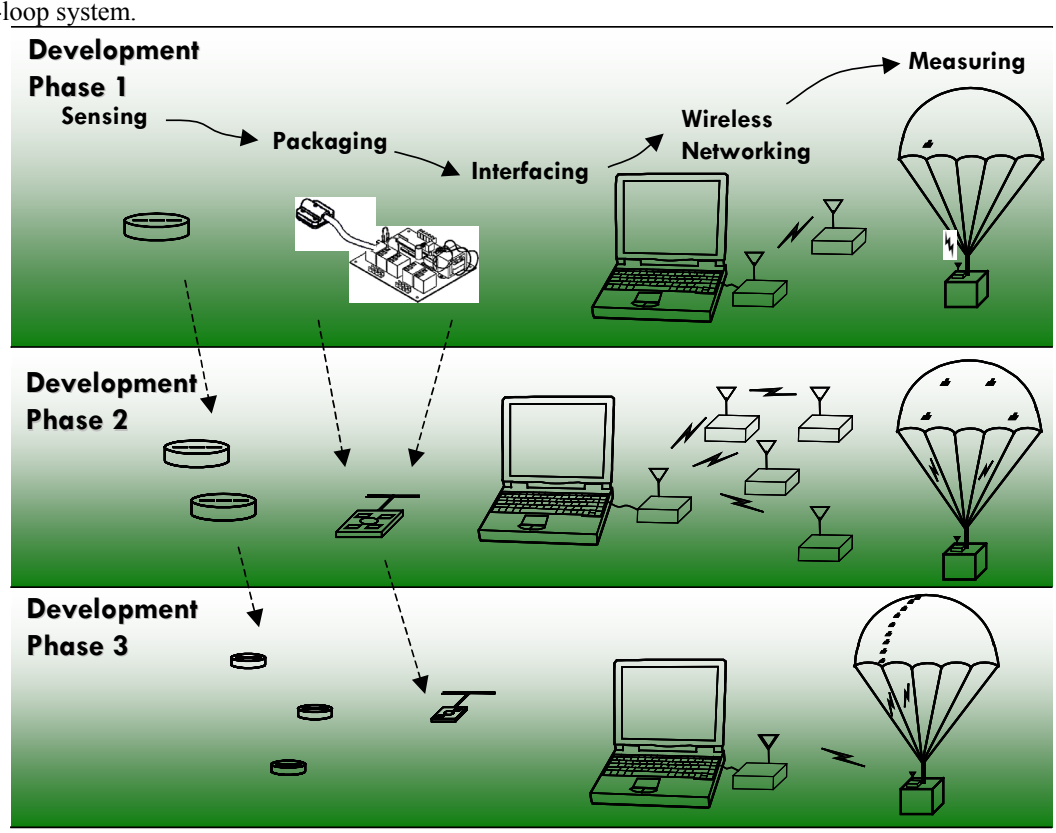

Figure 15. Further phases of sensor development for advanced personnel and cargo airdrop systems show reductions in size and weight for the sensor die, packaging and interface circuitry, with increased network size.

N. Further Development

Further developments beyond the demonstrations outlined in this paper are needed to deploy and commercialize the compact, optically coupled pressure sensors. The first program phase, as illustrated in Fig. 15, demonstrates the sensor die, package, interface electronics, single-sensor wireless network and a single sensor on a parachute. The next phase 1) improves the sensor die, package and interface electronics, 2) enlarges the wireless network and 3) reduces the size and weight of the package, controller and RF circuitry. The final phase prior to commercialization demonstrates a fully implemented sensor/communication hub on the canopy or on the payload with a larger number of sensors.

VII. Conclusion

The results of the program include the design, development and fabrication of small, high-accuracy pressure sensors in custom packages capable of measuring and monitoring the minute pressure differentials that occur across the fabric of a deployed parachute. The sensors are optically coupled via lightweight plastic optical fibers to a remote interface board for interrogating, processing, and formatting the pressure readings. The custom packages were designed with a particularly small size and weight to minimize impact on the deployment of the parachute and influence on the flow stream. The package body and retainer, with a footprint of 10 mm x 10 mm, are 4.0 mm high (axial cylinder height) and 1.5 mm high, respectively. The package body, tubular pressure port, sensor die and retainer weigh under 0.4 gm. The plastic optical fiber initially specified for the optical interconnections has an outside diameter of 2.2 mm and a weight of 4.0 gm/m, and has been superceded by a smaller diameter, more flexible and lighter fiber with an outside diameter of 1.0 mm and a weight of about 1.0 gm/m. First estimates are that the network hub – whose development and size and weight optimization were outside the scope of this program – would have a diameter of about two inches, a height of less than one-half inch, and a weight of about 2/3 of an ounce. This size and weight could be reduced two to four fold or more as advanced single-chip analog controllers with wireless links become available commercially.

As part of parachute instrumentation, optically coupled sensors generate differential pressure measurements that can be used to evaluate the aerodynamic performance of a parachute. Optically coupled pressure sensors address military, aerospace, industrial and commercial markets that need robust and accurate pressure sensors for a wide range of pressure and temperature in difficult environmental conditions, including pressure measurements below 100 Pa (0.015 psi) to pressures above 500 MPa. While the operating temperatures of current sensors are between -55C and +70C, further sensor and package development may extend the operating temperature of the sensors even further, from below –65C to above 300C. Other advantages of this fiber-optic technology are its electromagnetic interference (EMI) immunity and increased safety in harsh, volatile, or explosive environments.

Another application area needing highly accurate and stable pressure sensors is measurement systems providing primary check and transfer standards for certified weights and laboratory-gauge calibration pressures. Numerous industries and laboratories look for pressure measurement standards and calibration capabilities that are critical to their equipment productivity, as well as the quality and safety of their products and processing.

Other applications and potential markets for the described optically coupled technology include industrial and commercial applications as diverse as wind turbine monitoring, food processing, tsunami detection, diamond-making, energy exploration, aerospace, avionics, process automation, industrial calibration, and biomedical instrumentation.

Acknowledgments

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