Progress Towards the Development and Qualification of an All Optical Temperature and Pressure Compensated Fiber Optic Oxygen Sensor for Monitoring Ullage Environment in Aircraft Fuel Tanks

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ABSTRACT

Redondo Optics Inc. (ROI) in collaboration with Aviation Safety Facilitators (ASF) is in the process of developing an all-optical pressure and temperature compensated fiber sensor oxygen for use in the in-situ closed-loop-control monitoring of the inert atmosphere environment inside fuel tanks of military and commercial aircraft. The all-optical atmosphere environment control sensor is a passive optical sensor device with no electrical connections leading to the sensors install within the fuel tanks of an aircraft. To control the fuel tank environment, an array of multiple sensors is deployed at multiple locations within the fuel tanks of the aircraft, and a remote multi-channel optoelectronic system is used to monitor the status of all the sensors in real time, and to provide feedback environment information to the OBIGS system. The deployed sensors install in the tanks is connected to the optoelectronic system via a fiber optic conduit. The all optical sensor consists of an integrated multi-parameter fiber optic sensor probe that integrates a fluorescence based optical oxygen optrode with built-in temperature and pressure optical sensors within the same probe for compensation of temperature and pressure variants induced in the fluorescence response of the oxygen optrode. A multichannel frequency-domain fiber optic sensor read-out (FOxSense™) system is used to interrogate the optical signal of all three sensors in real-time and to display the fuel tank oxygen environment suitable for aircraft status and alarm applications. Preliminary testing of the all optical fiber optic oxygen sensor have demonstrated the ability to monitor the oxygen environment inside a simulated fuel tank in the range of 0% O2 to 21% O2 concentrations, temperatures from (-) 40°C to (+) 60°C, and altitudes from 0-ft to 40,000-ft.

Key Words:
Embedded fiber sensors, fuel sensors, atmospheric sensors, structural health monitoring, nondestructive inspection, aerospace, military, and miniature.

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INTRODUCTION

Redondo Optics Inc. (ROI) is developing a family of all–optical distributed, multi-point, fiber optic oxygen sensor system for the remote monitoring of the oxygen environment inside the fuel tanks of aircraft or for ultra-fast cryogenic oxygen fuel leak detection for monitoring the cryogenic fuel tank integrity in high altitude space rocket propulsion technology such as the NASA Aries 1-X rocket. The all-optical distributed fiber optic oxygen sensor (FOxSense™) network system is based on the use of point like fluorescence lifetime based oxygen, temperature, and pressure sensors packaged within a minimally invasive (0.25-inch diameter x 12-inch length) stainless steel packaged. The sensors are produced by coating an environmentally benign fluorescence material at the tip of an optical fiber followed by incorporating the coated sensor fiber in a robust, corrosion free, integrated fiber sensor packaged as shown in Figure 1.

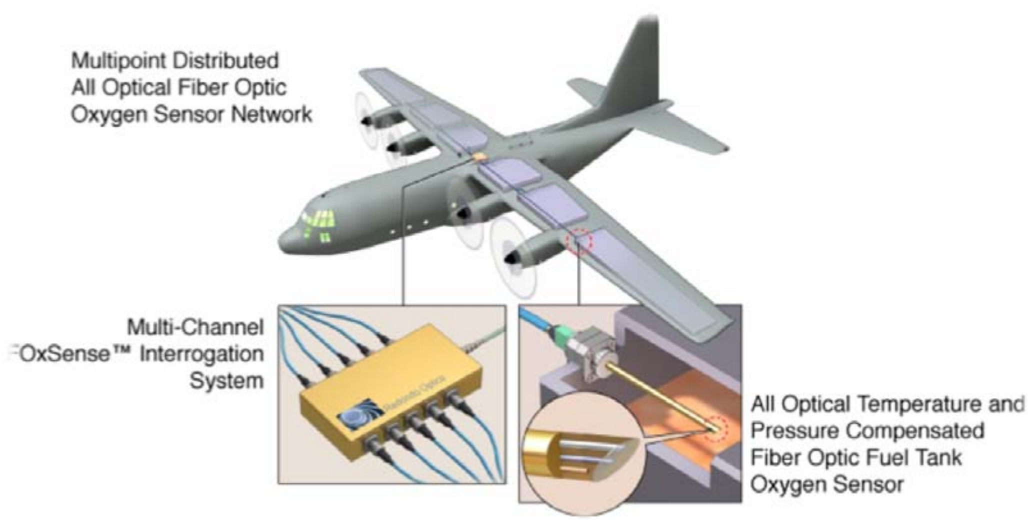

Figure 1. Distributed Multi-Point All Optical Fiber Optic Oxygen Sensor (FOxSense™) Network System for Aircraft and Spacecraft Safety.

An array of the all optical fiber sensors can be distributed at multiple locations along the length of an optical fiber bus deployed to monitor the oxygen gas environment inside the fuel tanks of aircraft or for oxygen gas leaks in the cryogenic fuel tanks of rockets and payload ground facilities. The distributed optical sensors are monitor using a miniature, light weigh, and low power consumption sensor interrogation FOxSense™ hub unit. The operational principle of the FOxSense™ sensor interrogation unit is based on ROI’s proprietary frequency-domain “phase-lock” fluorescence lifetime detection technology that enables the ultra-fast, wide dynamic temporal range, interrogation on the fluorescence lifetime state of the distributed sensors with micro-second response times. The FOxSense™ hub unit connects to a remote system control station using standard data transfer communication protocols via USB, Ethernet, Blue-Tooth, or wireless communication. A remote ground station sensor control unit monitors the status of all the distributed sensors and triggers an alarm in the event that an excessive oxygen concentration level is detected in the fuel tank of the aircraft, or that a potentially catastrophic oxygen leak is detected prior to the spacecraft launch. The all-optical FOxSense™ technology offers a low cost, reliable, solution to monitor in real-time the oxygen environment in potentially explosive fuel and cryogenic tanks with built-in optical temperature and pressure compensation, enabling effective flight control and planned ground processing (trouble shooting) through the predictive capabilities of real-time monitoring of system health and streamlined problem isolation, and will improve ground and flight safety through early detection and prediction of component failures, and by improving visibility into safety critical systems.

On-board fuel tank gas inerting system

The motivation behind this work is based on the U.S. Federal Aviation Administration (FAA) finding of the cause for the catastrophic failure of the Paris-bound TWA Flight 800, On July 17, 1996, a Boeing 747-131, that broke up in flight shortly after departure from New York Kennedy (JFK) Airport, and exploded in the air killing all of the 230 people onboard. FAA Investigators determined that the explosion of flammable vapors in the center wing fuel tank probably caused the breakup. Based on this finding a may others similar aircraft occurrences through the years has driven the FAA to establish a regulation aimed at preventing and eliminating the risk of catastrophic fuel leak explosions. Under this regulation the FAA mandates all commercial and military aircraft to be equipped with an on-board fuel tank gas inerting system (OBIGS). The OBIGS system replaces oxygen in a fuel tank with an inert gas, such as nitrogen, to reduce the risk of flammability.

Although some of the newer Boeing and Airbus aircraft are equipped with various types of on-board inert atmosphere systems, these systems currently operate blindly with safety redundancy since there is currently not a means of actually monitoring the oxygen concentration environment inside the fuel tanks of the aircraft. State of the art monitoring technologies currently under investigation by the aviation industry rely on the extraction of sample concentrations of the fuel environment via extraction pumps that deliver the gas sample to a remote, electrical-based, sensor monitoring station. The concept of extracting samples gaseous environment samples from the fuel tanks is far from ideal, since multiple issues can arise during the sample extraction, transport, an analysis of the fuel tank environment. For this reason, Redondo Optics has been involve in the development of a potentially viable solution using all optical oxygen environment fiber sensors.

ALL-OPTICAL FIBER OPTIC OXYGEN SENSOR (FOXSENSE™) SYSTEM

The distributed, multipoint, all optical, temperature and pressure compensated, fiber optic oxygen sensor (FOxSense™) network system uses an array of point-like oxygen sensors distributed at multiple locations of the fuel tanks of an aircraft or a high altitude propulsion rocket. ROI has currently developed a family of miniature, power and weight, efficient FOxSense™ systems capable of interrogating either a single sensor or an array of sensors as shown in Figure 2.

Figure 2. Single-Point and Multi-Point All Optical Fiber Optic Oxygen Sensor (FOxSense™) System.

The principle of operation of the all-optical FOxSense™ sensors is based on a fluorescence quenching mechanism, in which depending on the packaging mechanism of the sensor, a fluorescence coating can be made sensitive to the oxygen, temperature, or pressure environment. To monitor the changes in the fluorescence properties of the sensor, ROI uses a proprietary frequency-domain "phase-locked" detection mechanism. Frequency-domain detection of the technique of choice for monitoring fluorescence based sensors since the technique measures the fluorescence lifetime state of the sensor as a function of the near environment of the fluorescent moiety. An advantage of the fluorescence lifetime measurement is that it is independent of the fluorescence light intensity levels, hence, it is insensitive to light intensity fluctuations induced by the light source drifting, indicator photodegradation, and fiber bending. In addition, ROI uses a custom "phase-locked" electronics detection mechanism that results in an ultra-fast, microseconds response, and accurate measurement of the lifetime state of the sensor.

Once a sensor package is produced it is pre-calibrated over the operational environment of the sensor. For aircraft fuel tank monitoring applications, the sensor is calibrated to operate in the range from 0% to 30% oxygen, -50°C to + 60°C temperature, and from 0-psi to 15-psi pressure. A typical multi-dimensional oxygen and temperature calibration run for a sensor is shown in Figure 3.

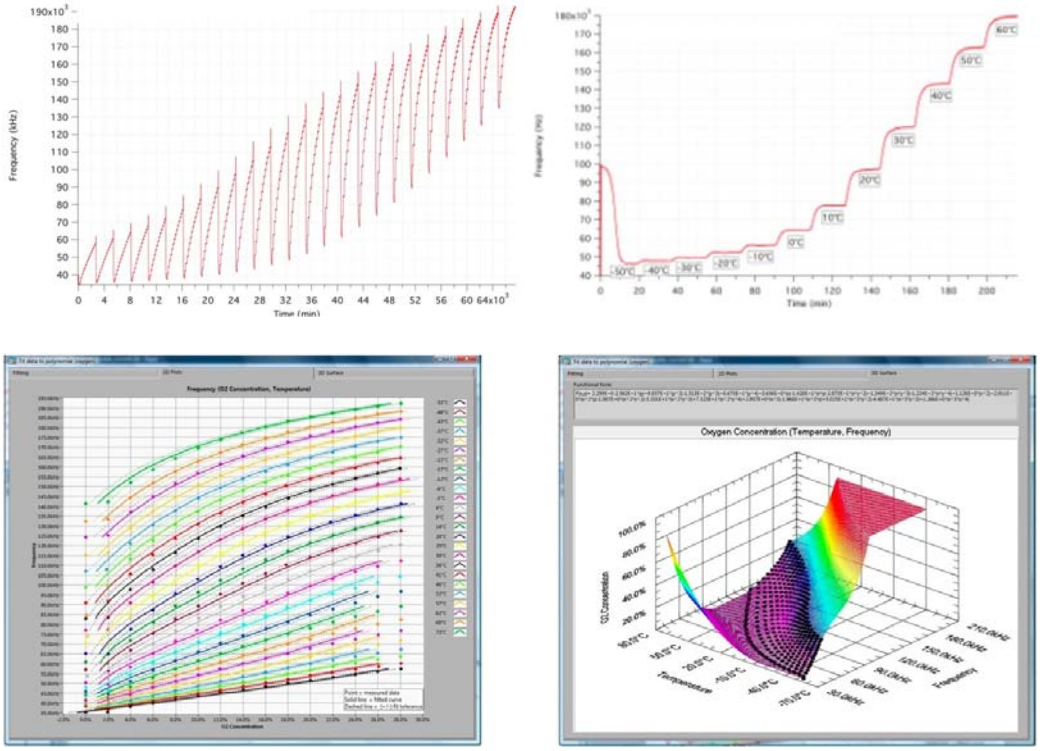

Figure 3. Typical Multi-Dimensional Calibration Protocol for All Optical Fiber Optic Oxygen Sensor.

LOW ALTITUDE FIGHT SIMULATION TEST PROTOCOL

A typical test flight protocol involves varying the oxygen, temperature, and pressure environment inside a simulated fuel tank of an aircraft. At ROI, currently there is no pressure control chamber so simulating a pressure environment at various altitudes runs a vast majority of the test. Pressure compensation is achieved by varying proportionally the partial pressure of oxygen to simulate the effect of altitude pressure on the tank at that particular altitude. A simulated low altitude test, approximately 12,000 feet above sea level, protocol is shown in Figure 4. In a simulated typical test, the test starts by simulating an aircraft parked at a run-away during fueling. During the fueling stage the inert atmosphere system triggers and the oxygen environment inside the fuel tank drops from 21% oxygen to 0% oxygen. The three alarm states of the system occur at 5% O_2, (safe), 10% O_2 (warning), and 15% O_2 (danger). During the test the temperature is varied from ambient temperature (20°C) to hot (60°C) simulating the aircraft parked in the run-away for some period of time. Then the aircraft takes off and the temperature rapidly decreases to 0°C and the to -10°C to achieve the simulated 12,000-feet altitude. At each of these temperatures the oxygen concentration is varied to achieve the three alarm levels. Finally, the test concludes with a rapid decent to ambient temperature.

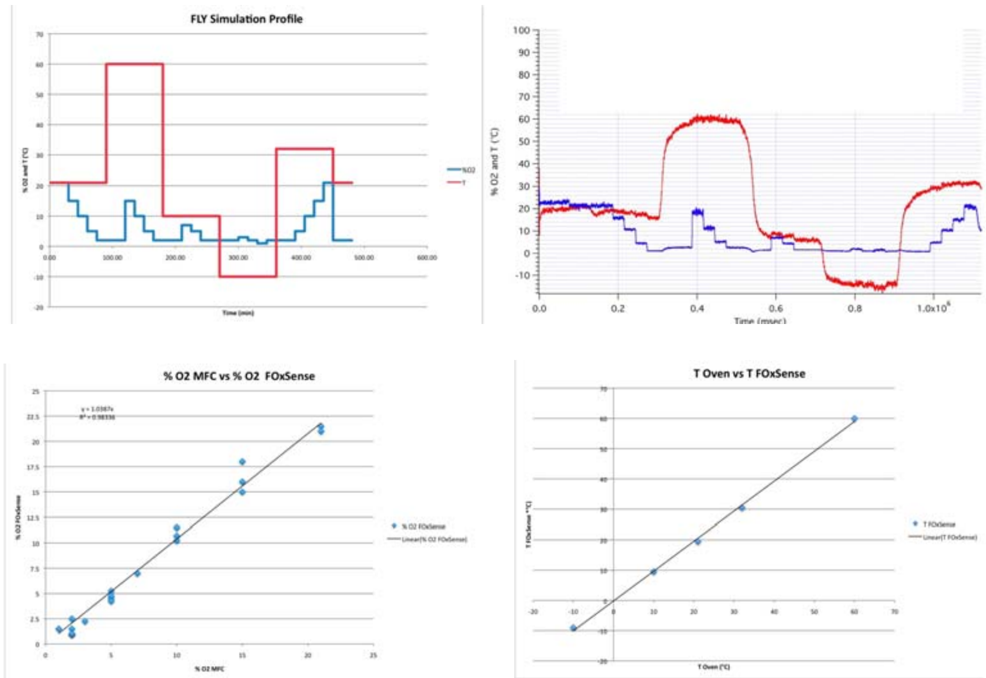

Figure 4. Low Altitude Simulated Test Flight Using All Optical FOxSense™ System.

SUMMARY

The all optical, temperature and pressure, compensated FOxSense™ system offers a potential cost effective, alternative solution, for the real time monitoring of the oxygen fuel environment inside the fuel tanks of an aircraft or for the cryogenic fuel leak detection of a spacecraft.

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