Universal Liquid Level Sensor Employing Fresnel Coefficient Based Discrete Fiber Optic Measurement Technique

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ABSTRACT

A compact and light weight liquid-level-measuring system based on fiber-optics sensor technology is presented as alternative to systems based on float gauges and other conventional level sensors for liquids that pose fire, corrosion and explosion hazards. These Fresnel reflection based fiber-optic sensors are inherently safer because they do not include electrical connections inside fuel/chemical tanks, and they exploit changes in internal reflection of guided electromagnetic modes as a result of contact between the outer surface of optical fiber and a liquid. Discrete changes in light transmission/reflection are used to indicate that liquid has come into contact with a suitably designed fiber optic probe at the output end of the fiber. This endeavor presents a quasi-continuous fiber optic level detection system that measures liquid level to within known increments of depth, by placing the probes of a number of such sensors at known depths in a tank where each probe effectively serves as a level switch. Due to the fiber optic nature of the design, the system can operate from cryogenic applications to boiling fluids. Experimental results for liquid nitrogen and water are presented.

Keywords: Liquid level sensor, fiber optic sensor, optical sensor, cryogenic level sensor, fiber optic level sensor

1. INTRODUCTION

Electronic means of liquid level measurements are reliable and inexpensive; however, certain liquid storage environments, such as fuel tanks, liquid hydrogen and oxygen storage facilities and hypergolic fuel storage reservoirs are vulnerable to spark generated explosions and can cause serious threat to safety of personnel and property. Alternative designs, such as float gauges, typically do not allow for precise, reliable and accurate measurement of fluid levels[1]. Fiber optic sensors[2-5] such as strain gauges[6-8] etc., have been used in broad range of industrial applications. They are inherently safe, can be used in hazardous environments and can be adapted to challenging environments such as zero G applications[9-11]. Furthermore, they offer significantly higher sensitivities when compared to mechanical devices such as float gauges. Generally fiber optic liquid level sensors utilize optical strategies such as Bragg gratings[12-23], interferometers[24-31], and evanescent based sensors[32-35]; however, these devices demand precision during manufacturing process and tend to require either expensive optical components or costly electronic readout or both. Alternative designs attempting to address these issues have been reported[36, 37] during the last few years. These include reliable and inexpensive liquid level sensors[38, 39] that offer all the inherent advantages of optical fiber sensors despite their simple and inexpensive design. This endeavor presents a low cost and uncomplicated fluid level detection scheme based on Fresnel reflections.

The wave guiding properties of fibers tend to deviate from the normal at dielectric interface, and its reflection and transmission properties depend on the surrounding medium that contacts it. Fresnel's equations explain transmission and reflection properties of light incident at the interface of two dielectric media. If a cleaved fiber is immersed in fluid, it encounters a reflection coefficient that is smaller than that of air. The opposite is true for transmitted intensities. This is caused by difference in the refractive indices of fluid and air. Therefore, fluid level in a tank can be determined by measuring the amount of light transmitted or reflected by the fiber, in presence or absence of target fluid. The reflection based approach is extremely desirable due to its intrinsic nature and the advantages that the fiber optic sensor technology offers over the conventional sensing schemes.

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The resultant approach eliminates almost every possibility of fire and explosion in hazardous areas that may be caused by sensor malfunctions. This enhancement in safety owes to the fact that only light and passive optical fiber cables come in contact with the target fluid. As a result, it can be safely used for challenging applications such as rocket propellant inside space vehicle fuel tanks. The tank is not subjected to metallic parts or electrical signals. Lightweight and small size of this system is inherent to fiber optics while better accuracy for this scheme is derived from the fact that the sensor directly detects the presence or absence of the fluid. It does not utilize indirect approaches like level floats, pressure within the fuel tank, and absorption or attenuation of radio frequencies inside the liquid vessel etc. Indirect approaches tend to falter due to many variables including voids, which can be formed because of boiling of liquefied gasses. Another very important feature of this liquid level sensor is the ability of the system to operate without any field calibration owing to a simple signal processing approach that leads to a reliable threshold and quasi-continuous output. Therefore, this design can be used to accurately measure levels of liquid to any desired resolution. Furthermore, the system is potentially very low cost due to minimum number of components and practically no special parts. The small size, weight, geometrical versatility, and physical as well as chemical compatibility of the system to any specific set of requirements are additional benefits that will reduce the overall deployment/flyaway cost of the final system.

At any interface between two optical media of differing refractive indices, any incident light will be divided into reflected and transmitted components. Fresnel's laws of reflection[40, 41,] precisely describe the amplitude and phase relationship between the reflected and incident light at the boundary between two dielectric media. For optical energies, in a medium of refractive index n_0, incident normally on an interface to a dielectric medium of refractive index n_1, the relative amplitude of reflected light, r, can be given by equation 1. Figure 1 shows the percentage of reflected light as a function of the refractive index of the target fluid, where n_1, the refractive index of glass fiber is 1.5 and n_0 is either the refractive index of air, 1.0, or that of the target fluid and may vary between 1.0 and 1.5.

$$r = \left(\frac{n_1 - n_0}{n_1 + n_o} \right)^2 \tag{1}$$

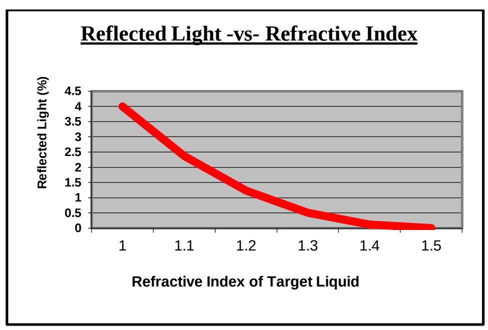

Figure 1: Percentage of reflected light as a function of the refractive index of the target fluid.

An experimental breadboard laboratory fiber-optic liquid level detection system was built and tested for initial proof of principle demonstration. This experiment involved a standard 2x2 multimode optical fiber coupler. The output ends of the coupler were cleaved to serve as sensing fibers. A beaker containing water at room temperature was used to measure the response of the sensing system for two levels of water column. The system block diagram is composed of a suitable optical transmitter (TX) and a matching optical receiver (RX) connected to a 3-dB coupler with the output ends of the coupler serving as optical switches, S1 and S2. This block diagram is shown in figure 2.

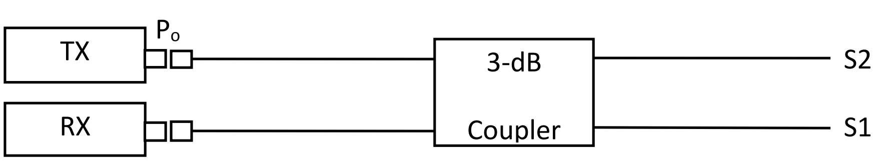

Figure 2: Block diagram of discrete liquid level sensor system.

2. EXPERIMENTAL SETUP & RESULTS

The experimental set up for the Fresnel reflection based quasi-continuous fiber optic liquid level detector system is illustrated in figure 3, where an LED source is used to launch light into one of the two input arms of a 2x2 fiber coupler. A PIN diode is connected at the end of second input arm for detection of the sensing signal. This liquid level sensor employs reflection mode, instead of transmission mode; hence, reflections from output ends of the coupler is measured and processed to detect fluid levels. This system configuration forces light launched from the optical source to split into two while traveling towards the two output ends of the 2x2 coupler. It should be noted that a 2xN coupler could also be used. When light reaches the other end of the fiber, most of it is transmitted into the interface medium; however, a small fraction of the total optical power is reflected back towards the detector and in accordance with Fresnel's laws, the intensity of the reflection received at the detector is a function of the difference between the refractive indices of the optical fiber and the interface medium. The amount of reflection can be calculated by equations 1. Experimental results show that two distinct reflection levels are seen by the detector, depending on the presence and absence of fluid at the ends of the two fibers. This distinction in the reflection coefficients owes to the differences in the refractive indices at the 'fiber-environment' interface due to presence or absence of target fluid at the interface. Figure 4 shows the response of this quasi-continuous or stair-case digital liquid level sensor system to two different levels of water.

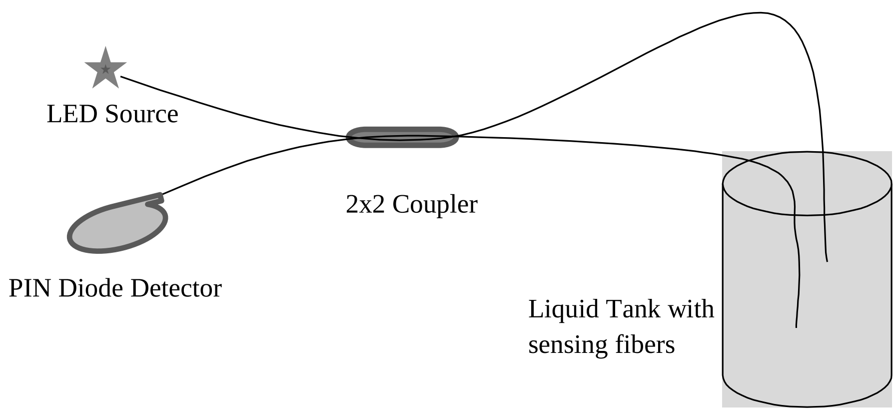

Figure 3: Schematic diagram of Discrete Liquid Propellant Level Sensor System

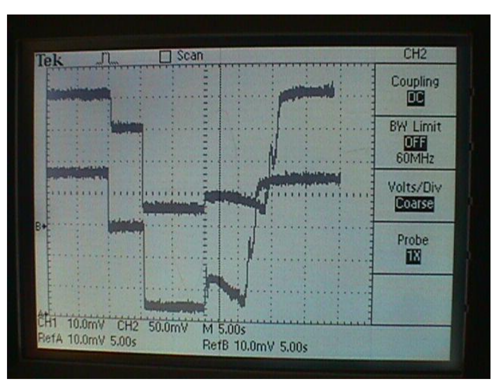

Figure 4: Two typical output response traces of the discrete liquid level sensor system to water.

Figure 4 shows two oscilloscope traces corresponding to two identical test runs. These experimental results were saved as Reference A and Reference B on the Oscilloscope. The 'A' and 'B' followed by the small arrow to the extreme left of the oscilloscope screen indicate the ground level for each individual trace. The top trace, Reference B, is at its maximum value during the first two divisions of the time scale, i.e. for approximately ten seconds. The output is at its maximum as both the ends of the 2x2 coupler are in air and the reflection is also at its maximum. After approximately ten seconds, one of the output arms of the coupler is submerged in water with a resultant dip in output level due to reduction in reflection. After a delay of additional 5 seconds, the other end of the coupler is also submerged in water. Immediately, the sensor output dips to a value very close to the ground level and stays that way for the next two divisions. At that point, both the arms of the sensor are withdrawn from water and nearly 11 seconds after withdrawal from water the sensor output approaches its initial value.

The bottom trace depicting Reference A shows a rerun of the experiment described by Reference B. It can be seen that both these traces are almost replicas of each other. The experiment was repeated multiple times over a period spanning over three months and similar results were obtained.

A breadboard version of the fiber-optic liquid propellant level detection system as shown in figure 3 was also employed to detect levels of liquid nitrogen. Liquid nitrogen was filled in a Dewar and the quasi-continuous/stair-case digital liquid level sensor was inserted and withdrawn manually, to measure the response of the sensing system to different levels of liquid nitrogen. The two output ends of the 2x2 coupler effectively behaved as two optical switches, where each switch was able to detect the presence or absence of the target fluid. Figure 5 shows the simple design of the fiber optic sensor, which consists of only standard optical fibers. Almost any number of fibers can fit into small openings and almost every geometry. Hence, any desired resolution for the fluid level is possible. The sensor in figure 5 is shown against a dark background to enhance visibility. This sensor is rugged and has survived multiple insertion and withdrawal cycles in multiple fluids including liquid nitrogen.

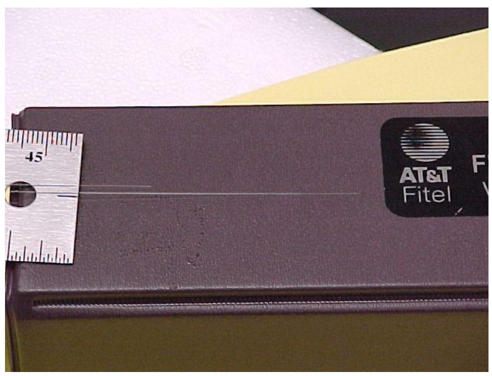

Figure 5: Simple sensor assembly for the stair-case digital liquid propellant level detection system.

As discussed earlier, two discrete output intensity levels are seen at the detector, depending on the presence and absence of liquid nitrogen at the end of the fiber. Figure 6 shows responses of the sensor to different levels of cryogenic liquid nitrogen.

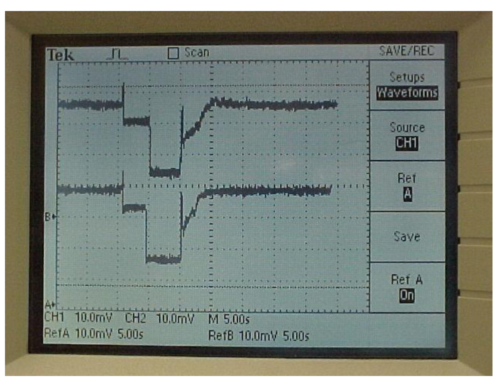

Figure 6: Distinct sensor response is seen for different levels of liquid nitrogen.

The two oscilloscope traces presented in figure 6 correspond to two different experimental runs. These experimental results were again saved as Reference A and Reference B on the Oscilloscope. The system response is also identical to that for water. However, there are two significant differences. First, the change in output signal is smaller and it does not approach the ground level, due to a smaller difference in refractive index. It should also be noted that though the change in the output signal is smaller compared to that for water, there is still a significant change in the sensor output and a suitable threshold level can easily be chosen. The second difference involves shorter delay in sensor recovery. The total recovery time for liquefied nitrogen is about 5 seconds as opposed to approximately 11 seconds that the sensor took in order to approach its initial value for water. It should be noted that this 5 seconds is the total time taken by the system to return to its initial value. Properly set thresholds will reduce this delay to approximately 1-2 seconds and indigenous sensor housing designs have the potential to reduce it further. This hysteresis cold be reduced to less than a second by orienting the fibers in a fashion that assists the residue of the fluid to quickly channel away from the fiber end-face.

The sequence of events can easily be predicted by looking at the oscilloscope traces. The top trace, Reference B, is at its maximum value during the first 11seconds. At that point one of the two ends of the sensor was submerged in liquid nitrogen. This results in distinct reduction in the output. After waiting for approximately 4 seconds, the other end of the sensor was also submerged in the cryogenic fluid, which results in another significant drop in the sensor output. The output stays unchanged for nearly 5 seconds, as there was no activity. At that point both the arms of the sensor were withdrawn from fluid, and approximately 4-5 second after withdrawal, the sensor output approached its initial value. The bottom trace shown by Reference A is identical to Reference B. It can be seen that both these traces are almost replicas of each other. This experiment with liquid nitrogen was repeated multiple times over a period spanning over three hours with similar results. The system is discrete in nature with stair case digital or quasi-continuous output.

In a follow-up experiment, the total height of fluid tank was divided into eight equally spaced intervals, and the presence or absence of fluid at pre-designated levels was successfully detected and measured using this quasi-continuous fiber optic liquid level sensing scheme. The block diagram of the eight level fluid measurement system and its experimental implementation is shown in figure 7, where SP1 through SP4 are simple threshold based signal processing units. The individual fibers can be attached at any desired location inside the fluid tank to achieve the desired sensing resolution. Furthermore, this sensor is inherently safe in explosive, corrosive, and hazardous locations due to its all optical nature which ensures that no electrical current is introduced inside the fluid tank. Choice of a broad range of silica and plastic fibers allows the use of this sensor for a vast range of practical applications. It should also be noted that in addition to level detection, this sensor can also be used to determine and characterize the fluid itself by employing appropriate signal processing algorithms and a lookup table that correlates the intensity of the reflected signal to the refractive index of the fluid and then matches the refractive index to a specific fluid. Tunable sources could also be used to provide better discrimination between fluids with similar properties.

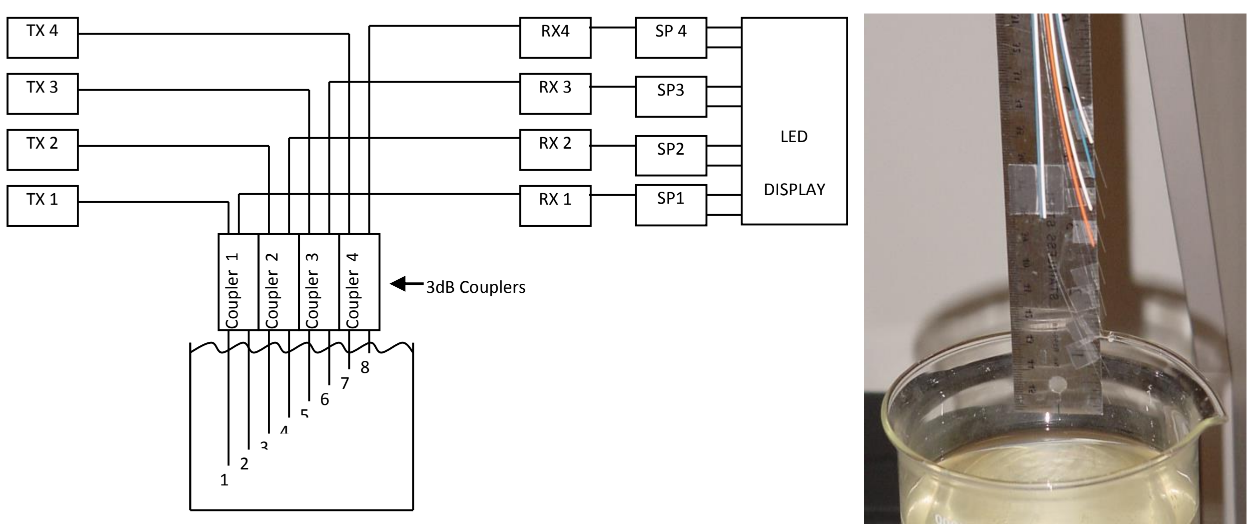

Figure 7: Simple system construction indicates feasibility of any desired resolution for fluid levels.

This design lends itself to remote real-time operation as every component of this design including the transmitter (TX), receiver (RX), signal processor (SP), display LEDs and the couplers can be housed at any desired remote location. Only the standard communications grade optical fiber cable goes to the fluid tank and comes in contact with the measurand. This leads to a versatile sensing scheme that is negligible in size, inexpensive, lightweight, highly reliable, and is almost universal in nature and can be used in almost any application with a geometry that is adaptable. It has a straightforward design with limited electronics utilizing simple optical transmitter and receiver circuits coupled with negligible signal processing and requires minimal power to operate. Total current consumption for the eight level sensor is approximately 60mA. This current can be easily reduced to about 15mA if the transmitter circuits are operated in series. Pulse width modulation of the circuit can further reduce the power requirements by orders of magnitude. The base line design uses four 2x2 multimode couplers. The system efficiency could improve further with 2x4 and 2x8 couplers and other multiplexing techniques. The transmitter circuit shown in figure 8, consists of a simple transistor (2N2222) circuit driving an infrared LED (OPF-692).

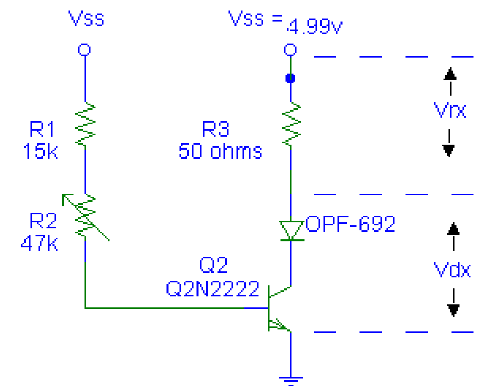

Figure 8: Simple transmitter circuitry provides threshold adjustment for the detection system.

The optical receiver circuit utilizes an inexpensive OPF-792 type PIN photo diode. In addition, the detector circuitry uses two Op-Amps. One behaves as a non-inverting buffer while the second one acts as an inverting amplifier. The output of the second amplifier is fed to a signal processing circuit that basically works as a comparator. The output signal from the receiver circuit is compared to a predetermined threshold. The threshold level is adjustable; hence, the decision-making circuitry can be tuned to any desired fluid. Figure 9 gives the schematic diagram of the detection circuit, which is a combination of the receiver and signal processing circuitries.

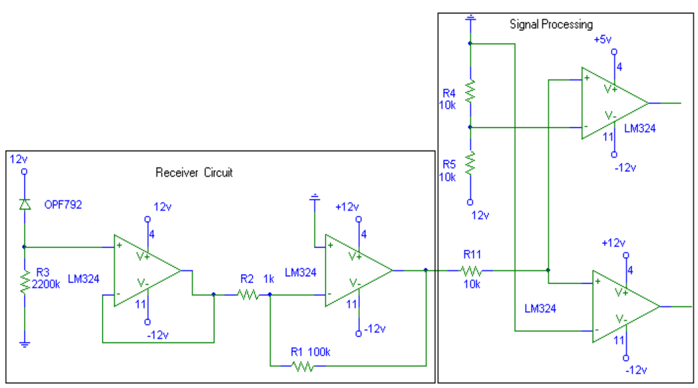

Figure 9: Schematic diagram of the signal detection and processing circuit.

Generally, successful operation of any intensity modulated optical system requires intensity compensation for undesired environmental effects such as micro-bends or the drift in the transceiver output. Due to its digital nature, this design does not require any intensity compensation schemes. In an extreme scenario, a portion of the output can be fed back to a detector to cater for any deviations in the system. In this case, additional intelligence could be built into the system, and an algorithm can be developed that will use the feedback to determine the type and quality of the measurand. Wavelength dependent methods could also be used to discriminate between different fluids.

3. CONCLUSION

A novel, quasi-continuous fiber optic liquid level sensor exploiting Fresnel reflections is presented. This design has been employed to determine the levels of a broad range of fluids and successfully tested for a host of liquids including liquid nitrogen, vegetable oils, and water. The proposed fiber-optic level sensor exploits changes in reflection of light when it comes in contact with a target liquid to measure the fluid levels. The measuring system is inherently safe, compact, lightweight, simple, and low cost in nature.

In short, this endeavor has produced a universal optical fiber liquid level sensor composed of point sensing optical switch architecture, which can be used to detect presence or absence of a broad range of liquids under almost any environment. This design significantly reduces the sensor diameter and eliminates stresses induced on the fiber due to physical conditions such as tight bending radii. As a result, this leads to a mechanically rugged, low cost, and simple system that can endure thermal stresses caused by cyclic cryogenic applications. The digital nature of this system greatly enhances the reliability of the overall design. It is composed of readily available off-the-shelf components and can be deployed quickly in an inexpensive fashion.

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