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Non-Contact Opto-Fluidics-based Liquid Level Sensor for Harsh Environments

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ABSTRACT

This paper presents a non-intrusive, non-contact liquid level sensor. The proposed sensor is a free-space-based optical sensor that uses opto-fluidic technology-based agile optics to direct light from a laser source to the Liquid Under Test (LUT). The presented design makes the proposed sensor ideal for use in environments where levels have to be determined for caustic or toxic liquids having a small window interface on the containers carrying them. The proposed design uses very low optical power levels (< 100 μW) making it useful for measuring levels of combustible liquids (e.g., jet fuels) which have a danger of being ignited at higher power levels. The proposed sensor can find potential applications in transportation, chemical and aerospace industries.

Keywords: Liquid Level Sensors, Optical Sensors, Harsh Environments

1. INTRODUCTION

Sensors are required in various applications to determine the levels of different liquids. The key requirements for such sensors include robustness, reliability, industrial applicability and cost. Specifically, the design of a liquid level sensor depends on the aimed application. Several industrial applications involve caustic, toxic, volatile and cryogenic liquids. Under these harsh conditions, it is practically impossible to deploy a contact-based liquid sensor as this may either lead to unwanted chemical reactions and chemical degradation of the sensor or a physical damage to the sensor probe under high temperatures and pressures. Additionally in extremely harsh environments, it is generally not possible to read the liquid level using a scale on the container. In order to access and measure the level of such liquids, it is imperative to have a small external liquid viewing window and to use a non-contact measurement technique. Wired sensors using techniques requiring physical contact with the liquids have been proposed in prior art. These include contact-based optical [1-15], electrical [16-17] and ultrasonic [18] sensors. Such intrusive designs require an open interface to have access to the liquid. Laser radar-based liquid level sensors [19-20] are more viable for non-intrusive applications but these systems are susceptible to Electro-Magnetic Interference (EMI) due to the use of RF signals and RF electronics. Optical triangulation [21] is a computer vision based technique requiring the use of a special geometric arrangement between the Liquid Meniscus, the viewing position sensitive CCD and the optical source. For minimal error operation, the triangulation technique requires a wide viewing angle. Hence it would require a large viewing window for best performance which is not always a case in extreme environments. A non-contact distance sensing technique using spatial signal processing was proposed in ref. 22 [22]. This paper extends the distance sensing method in Ref.22 to propose a non-contact liquid level remote sensor. The proposed method of liquid level sensing requires low optical power levels (<100mW) which is ideal for use in volatile combustible environments [23].

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2. PROPOSED LIQUID LEVEL SENSOR DESIGN

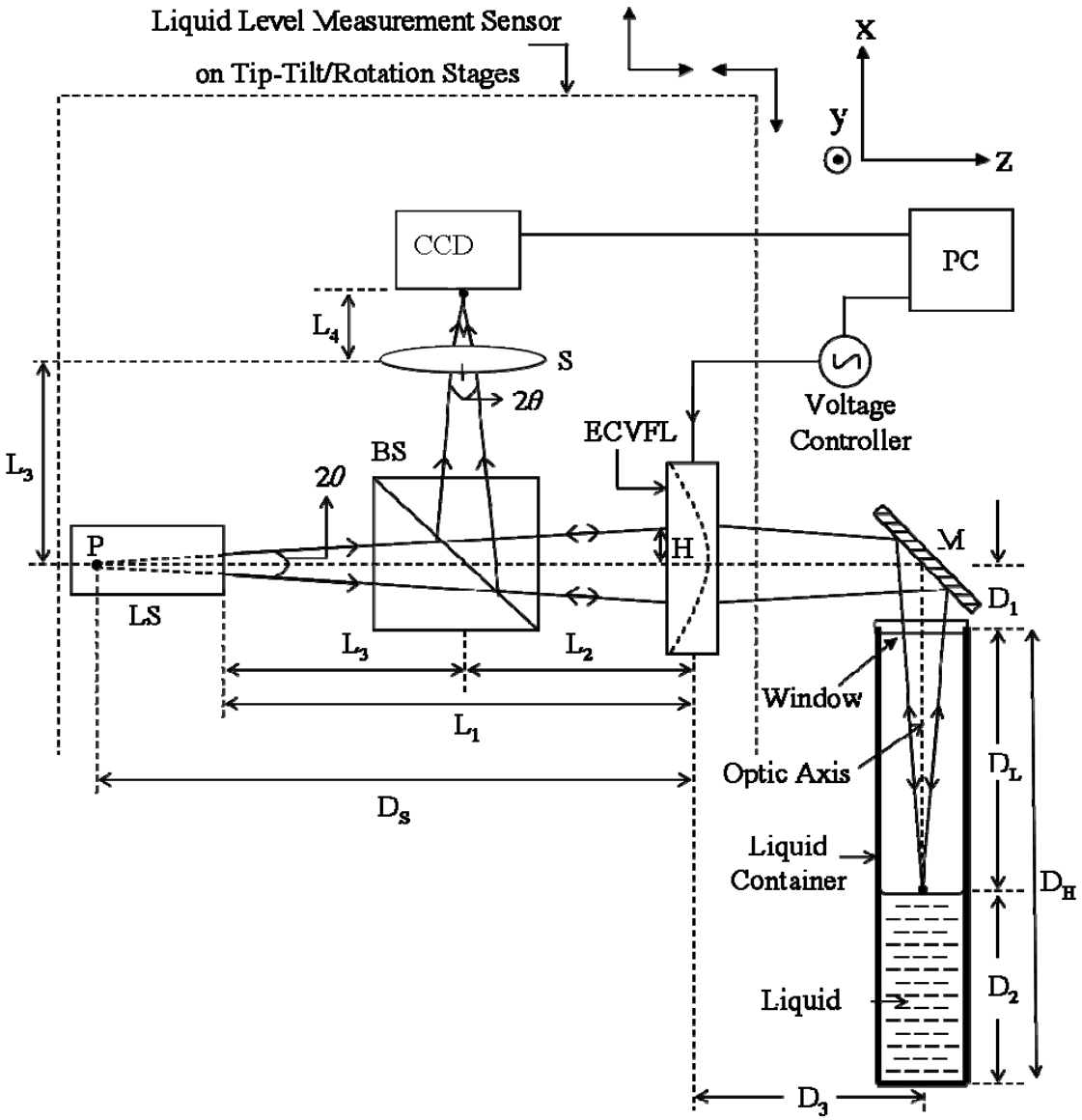


Fig.1 The proposed liquid level sensor using agile lensing.

Fig.1 shows the design of the proposed liquid level using agile lensing implemented through the ECVFL. A naturally diverging laser beam from a Laser Source (LS) is made to pass through a Beam Splitter (BS) and the ECVFL. The ECVFL is used in the convex mode of operation such that the ECVFL is powerful enough to converge the previously diverging beam. This converging beam is passed through an optional Mirror M which helps direct the beam inside the liquid container enabling the beam to strike the surface of the Liquid Under Test (LUT) at normal incidence. This beam is partially reflected from the liquid surface depending on the refractive index of the liquid. The reflected beam traces the path of the incoming beam through the ECVFL. The presence of the BS ensures that part of reflected beam is made to change direction and fall on a CCD camera. This beam falling over the CCD camera is used for analysis.

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As mentioned earlier, the beam after passing through the ECVFL is made to converge over the surface of the LUT such that the optical beam makes a minimum beam spot over the liquid surface. Hence a unique ECVFL focal length value F satisfies this condition for every liquid depth D_L.

This best focus observation is governed by the imaging condition between the virtual object point P and the surface plane of the LUT given by:

$$D_T = D_S F / (D_S - F). \tag{1}$$

D_T is the total distance from the ECVFL plane to the surface plane of the liquid, i.e., $D_T = D_1 + D_L + D_3$, while D_S is the distance of point P from the ECVFL given by:

$$D_S \approx H/\theta \tag{2}$$

The height of the liquid tank D_H as well as the distances D_1 and D_3 are known. Using these numbers D_T can be determined from Eqn.1 which leads to a value for D_L. Next the liquid level $D_2 = D_H - D_L$ is determined as changing liquid levels imply a changing D_L. The CCD camera is placed such that the minimum waist forms simultaneously at the CCD film and the liquid surface. This is achieved by placing the CCD at a distance L_4 from a spherical lens S placed between BS and the CCD. L_4 is given as:

$$L_4 = \frac{F_V F_S}{(F_V + F_S)}. \tag{3}$$

L_4 can also be seen as the effective focal length of the S placed next to a virtual lens which converges marginal rays to an angle of θ. F_S is the focal length of the spherical lens and F_V is the focal length of a virtual lens. The derivative of D_T with respect to the F is calculated from Eq.1 and it is given by:

$$\frac{dD_T}{dF} = \frac{D_S^2}{(D_S - F)^2}. \tag{4}$$

Therefore the liquid level measurement step ΔD_T is given by:

$$\Delta D_T(V) \approx \frac{dD_T}{dF}\Delta F(V) = \frac{D_S^2}{(D_S - F)^2}\Delta F(V). \tag{5}$$

The percentage measurement resolution R_δ is given by:

$$R_\delta = \frac{\Delta D_T}{D_T} = \frac{(D_S - F)D_S + D_S F}{(D_S - F)D_S F} \times \Delta F = \left(\frac{1}{F} + \frac{1}{D_S - F}\right)\Delta F. \tag{6}$$

It can be deduced from the expression in Eq.6 that the percentage resolution varies with the liquid level due to a variation of the focal length step ΔF for a given F that satisfies Eq.1. This is due to the non-linear behavior of the ECVFL focal length with applied voltage V.

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3. EXPERIMENTAL DEMONSTRATION

The Fig.1 design was implemented using a Varioptic Arctic 320 liquid lens, a 632.8nm 10mW He-Ne LS with θ = 1.24 mrad. The experimental setup is shown in Fig.2. The ECVFL F_{Max} = 21.2 cm at 43V and F_{Min} = 13.07 cm at 46V. The ECVFL transmittance is 92% for λ_L = 632.8nm. The liquid container has a height $D_H = D_2 + D_L$ = 1m and a diameter of 5cm. The spherical lens S used had F_S = 10cm and mirror M was a gold coated plane mirror. In the experimental setup $D_1 + D_3 = 25\ cm$ and an ECVFL minimum focal length step of ΔV = 200 mV and a response time of less than 100ms. For the experiment H = 0.3275mm, L_1 = 11 cm with $L_1 = L_2 + L_3$ and L_2 = 6 cm and L_3 = 5 cm. L_4 is calculated using Eq.3 and comes out to be 6.07cm for the given experimental setup. Using Eq.5, the measurement resolution is calculated to be $\leq 0.9\ cm$ with a resolution percentage of <1.2 %. The incident optical power of the liquid surface was measured to be 50μW.

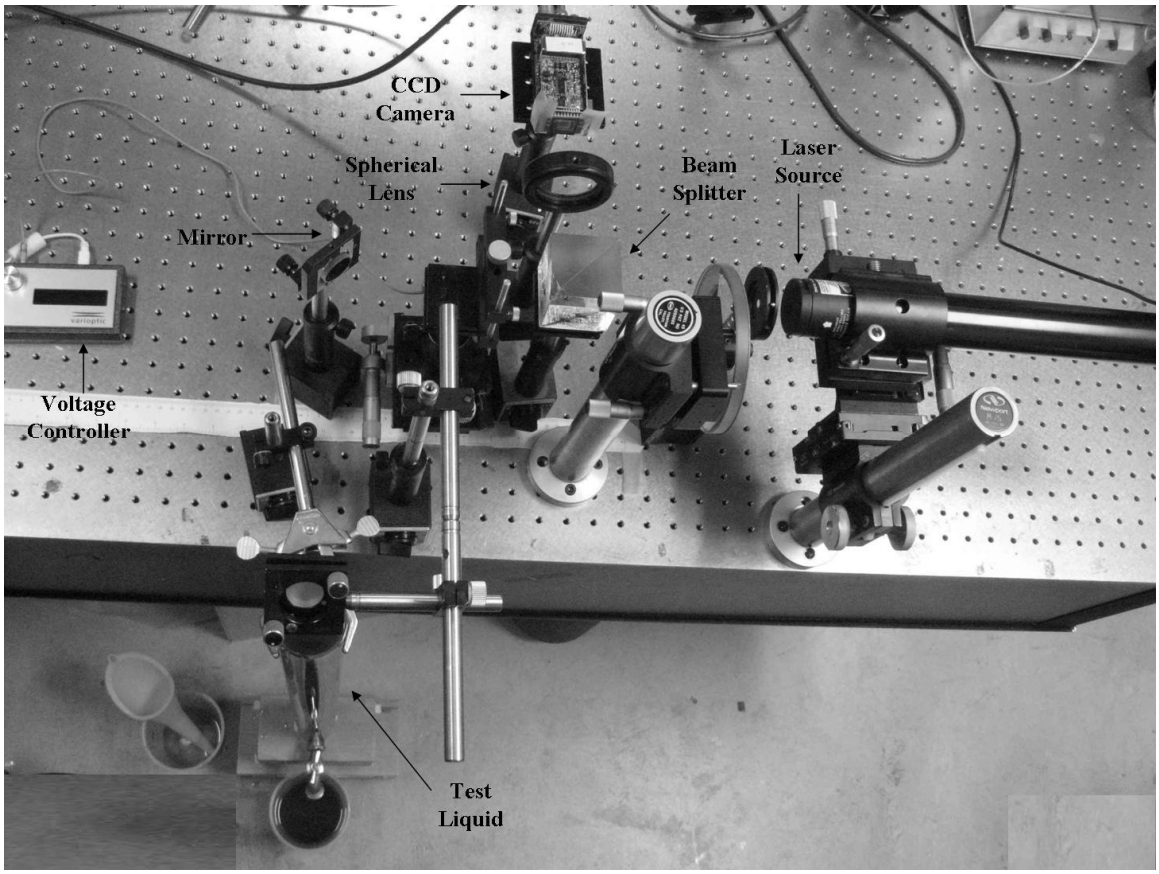
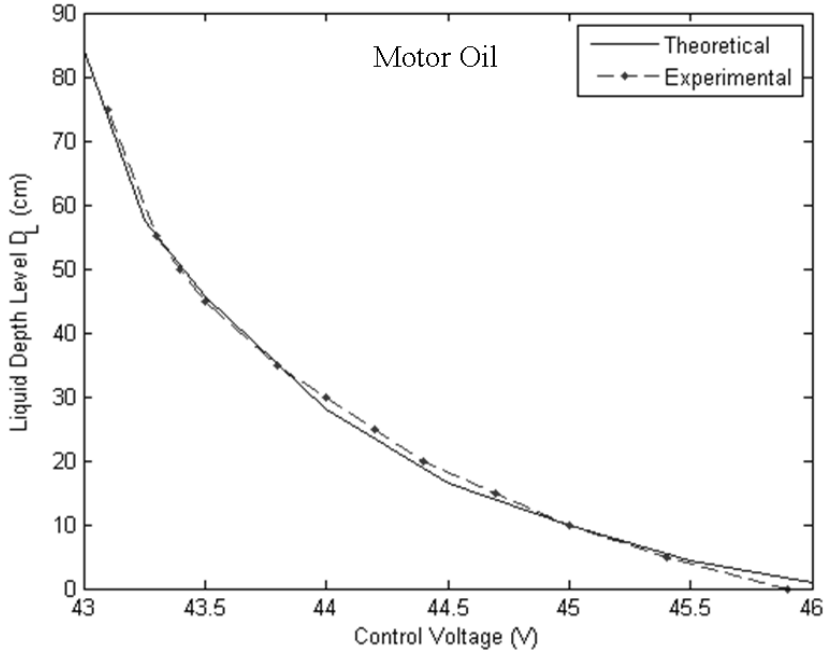


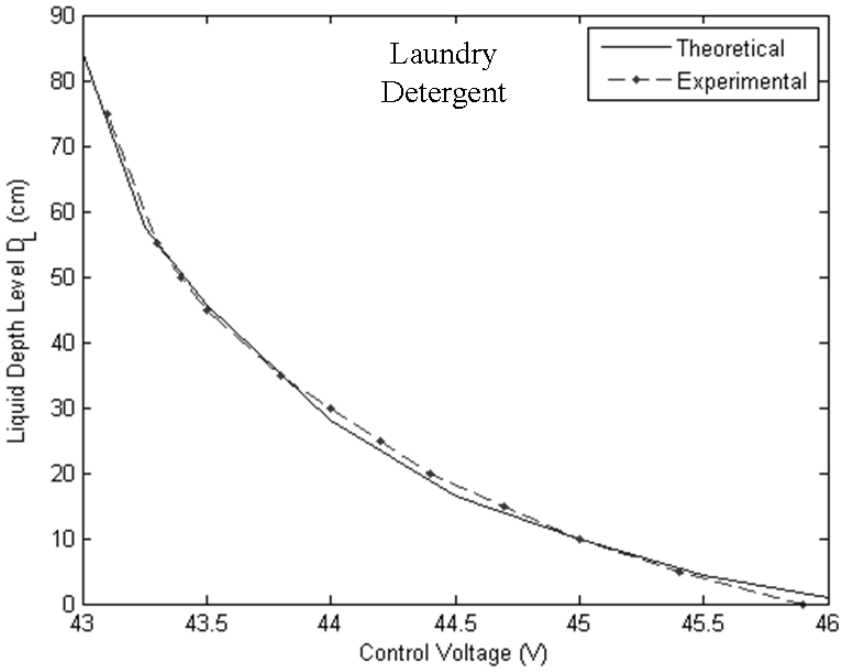
Fig.2 Experimental setup of the proposed liquid level sensor.

The experiment was performed with two liquids, namely, motor oil and laundry detergent. The liquid optical power reflectivities are measured to be 1.26% and 1.55% for motor oil and laundry detergent, respectively. The CCD camera is operated in an unsaturated mode to measure beam profiles. This is done to make the system tolerant to laser power fluctuations.

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(a)



(b)

Fig.3 Theoretical and experimental curves for required ECVFL applied voltage to measure any given liquid level depth D_L for (a) Motor oil and (b) Laundry detergent.

Fig.3 compares the theoretical and experimental results for a given liquid level and the required voltage V to achieve minimum beam spots on the liquid surface and the CCD. As seen from the plots, the sensor

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measurement results are in good agreement for both test liquids. V is varied from 43.1V to 45.9V to measure liquid depth between 0 cm and 75 cm. It is also seen from Eq.1 that the measurement range of the proposed sensor improves when θ is reduced, i.e., the beam collimation is improved.

4. CONCLUSION

The paper demonstrates for the first time an agile lensing-based sensor for liquid level measurements. The demonstrated sensor is non-intrusive using small optical power levels, thus making it appropriate for use in harsh environments that involve toxic, caustic or volatile liquids. Furthermore, the sensor is useful when liquids are at high temperatures and pressures and where intrusion-based sensors would not be able to withstand those extreme temperatures and pressures. Future work relates to the measurement of liquid levels for vibration-susceptible liquids with low viscosities.

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