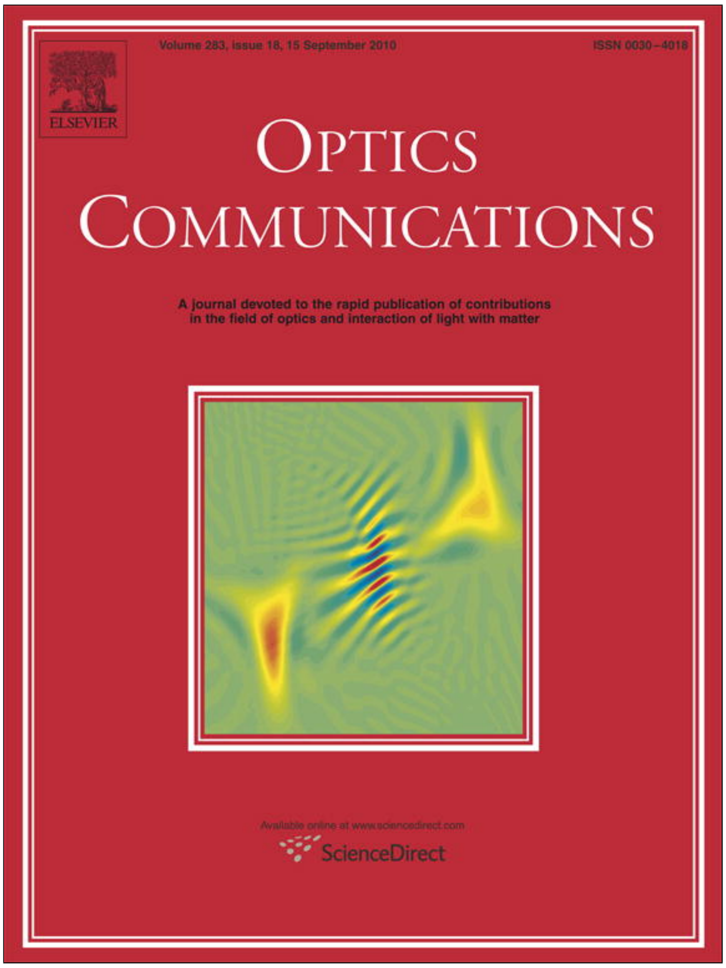
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Agile lensing-based non-contact liquid level optical sensor for extreme environments

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ABSTRACT

To the best of the author's knowledge, demonstrated is the first opto-fluidic technology- based sensor for detection of liquid levels. An opto-fluidic Electronically Controlled Variable Focus Lens (ECVFL) is used to change the spatial intensity profile of the low power optical beam falling on the liquid surface. By observing, tuning and measuring the liquid surface reflected intensity profile to reach its smallest size, the liquid level is determined through a beam spot size versus ECVFL focal length calibration table. Using a 50 μW 632.8 nm laser wavelength liquid illuminating beam, a proof-of-concept sensor is tested using engine oil, vegetable oil, and detergent fluid with measured liquid levels over a 75 cm range. This non-contact Radio Frequency (RF) modulation-free sensor is particularly suited for hazardous fluids in window-accessed sealed containers including liquid carrying vessels in Electromagnetic Interference (EMI) rich environments.

1. Introduction

Liquid level sensors are used extensively in various industrial applications where the liquid depths have to be monitored with robustness, reliability, and repeatability. Many industrial processes and aerospace platforms involve toxic and combustible fluids, including fluids under extreme temperatures (e.g., cryogenic conditions), pressures and radioactivity. In addition, fuel cells for scalable renewable energy storage also require the monitoring of caustic liquid levels. Typically, such liquids are stored in mechanically robust large volume tanks with small optical windows for basic liquid visual viewing. Given these hazardous liquid tank conditions, it is generally not possible to insert any type of sensor into the tank cavity as the sensor module can suffer degradation with liquid contact, apart from acting as a potential trigger for liquid chemical or electrical instability. As the container is sealed, a wired sensor, whether optical [1–15] or electrical [16,17] or ultrasonic [18] is highly intrusive and suffers from the additional problem of having no access point for wire insertion into the tank. A non-contact optical sensor such as a laser radar sensor [19,20] is a preferred sensor for the hazardous liquid environment, although this type of sensor requires phase-sensitive RF electronics that can be expensive and EMI sensitive. The use of ultrasound radar is another attractive non-invasive technique to measure liquid levels, but these sensors require special ultrasonic wave coupling hardware that can be vibration noise sensitive [21,22]. Another useful non-invasive sensor uses the classic concept of optical triangulation [23] with computer vision image processing algorithms to determine a liquid level. This method of triangulation works best when the lighted beam paths can have large angular access such as via open freespace scenarios. In the hazardous large depth liquid tank scenario, one typically has a restricted small viewing window that can also be physically thick. These optical window restrictions can cause triangulation-based sensor performance limitations given off-axis beams are engaged for liquid depth measurement. Another type of non-contact optical sensor using freespace optical beams launched and received from Plastic Optical Fibers (POFs) has been proposed [24], although this method uses large 1 mm diameter multi-mode fibers that produce limited collimation in addition to having inherent receive beam capture and alignment issues.

Recently, a new type of non-intrusive distance sensor has been proposed that alleviates the limitations of both laser radar and triangulation design distance sensors [25]. In particular, the Ref. [25] sensor can be optimized for use as an extreme environment liquid level sensor without the need for broadband RF electronics and large beam displacement off-axis viewing. The purpose of this paper is to demonstrate for the first time how the sensor design in Ref. [25] can be used to measure liquid levels. Specifically, the demonstrated liquid level sensor uses a direct smart spatial signal processing technique via an on-axis (or near axis) laser beam targeted to hit the liquid surface within the limited viewing access storage tank. The sensor is designed for use with very low (e.g., <100 μW) laser powers within large liquid volumes, thus keeping the optically absorbed energy levels much below typical ignition energy values for combustible liquids. The rest of the paper describes the sensor design and its experimental results.

2. Proposed liquid level sensor design using agile lens

Fig. 1(a) shows the proposed liquid level sensor using an ECVFL. A low power Laser Source (LS) forms a directed optical beam that passes through a Beam Splitter (BS), an ECVFL, and an optional mirror M to

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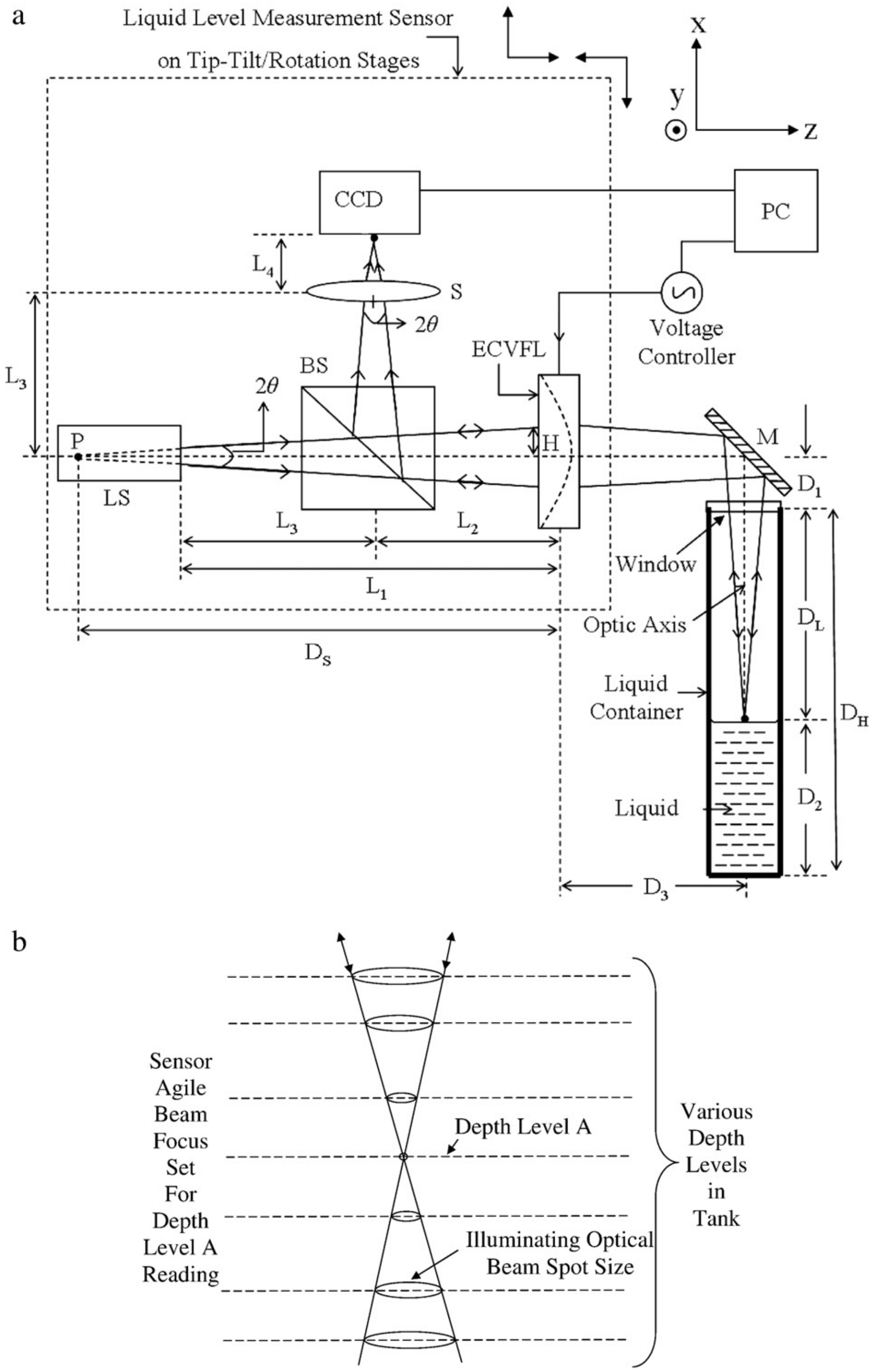

Fig. 1. (a) Proposed liquid level sensor using spatial signal processing. (b) Sensor laser beam agile focus operation set for liquid depth level A reading corresponding to smallest liquid illumination beam focus spot. Dashed lines represent different liquid depth levels.

actively illuminate a small zone on the liquid surface. The liquid is enclosed in a window sealed tank suitable for large volume storage of hazardous liquids. The light reflected off the liquid surface retraces the transmit beam path and is deflected by the BS to pass through a lens S to fall on an optical detector chip such as a Charge Coupled Device (CCD). The sensor transceiver module is mounted on tip/tilt and rotation stages for optimizing optical alignment with the liquid in the tank. For optimal on-axis reflection, the Liquid Under Test (LUT) should form an optically smooth partially reflective surface at the laser wavelength λ_L. In the event that the LUT is unable to form an adequate optically smooth surface for on-axis reflection, off-axis viewing of the LUT scattered light surface is engaged using an optical camera also placed in the modified transceiver module. The refractive index of the liquid n_L and the refractive index n_G of the non-liquid region (e.g., filled with air, nitrogen or simply vacuum) provides a measure of the liquid-gas interface reflectivity via the normal incidence Fresnel optical power reflectivity coefficient $R_F=[(n_L-n_G)/(n_L+n_G)]^2$. The values of R_F, liquid optical absorption coefficient at λ_L, and the maximum and minimum liquid volume levels in the tank determines what maximum laser power can be safely used for measurement given some light absorption is expected in the liquid.

The liquid level sensing via the transceiver module is implemented by changing the ECVFL applied control signal. This action in-turn changes the focal length F of the ECVFL that is swept across different values that result in various spot sizes on the plane of the LUT surface. As shown in Fig. 1(b), the best focus condition is achieved when the optical beam falling on the liquid forms a minimum spot or a minimum beam waist at the plane of the liquid surface, in this case liquid depth level A. 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:

$$D_T = D_S F / (D_S - F). \quad (1)$$

As shown in Fig. 1(a), 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. The point P position is determined using the known laser beam divergence half angle θ and the known beam radius H at the ECVFL as using geometry:

$$D_S \approx {}^H/_\theta. \quad (2)$$

As D_H the tank height and D_1 and D_3 are fixed, D_T can be determined from Eq. (1) leading to a value for D_L. Next one finds the liquid level $D_2 = D_H - D_L$ as changing liquid levels implies a changing D_L. Note that each distinct liquid level D_2 in a given tank would require the ECVFL to be adjusted to a different focal length F in order to form the minimum spot on the liquid surface as viewed by the on-axis CCD or the off-axis camera. Thus by simply noting the ECVFL drive signal value (or the equivalent F) that provided the smallest spot on the liquid level and using a stored calibration table of liquid level versus ECVFL F value, one determines the liquid level in the tank.

In order to reduce the transceiver module size in Fig. 1(a), a spherical lens S having a focal length F_S is placed between the BS and the CCD. This ensures that the minimum spots still form simultaneously at the CCD and the liquid surface but with a smaller L_4 distance. Without S, the CCD must be placed at a longer distance D_S from the ECVFL plane to ensure that minimum spots get imaged at both the CCD and the liquid surface planes. The distance L_4 needed for the transceiver design is computed in the following way. S is placed at a distance of $L_2 + L_3$ from the ECVFL plane. Therefore the converging rays falling on S can be thought to have converged due to a focal length F_V virtual lens present before S. The distance L_4 is the effective focal length of a two lens (i.e., S and the virtual lens) system with zero inter-lens distance. Hence, using the standard formula for two cascaded lenses one gets:

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

Given that the ECVFL is controlled by voltage V control, the resolution of liquid level measurement depends on the smallest voltage step that is achievable with a particular voltage controller. The derivative of D_T with respect to the F is calculated from Eq. (1) and it is given by:

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

Therefore the liquid level measurement step is given by:

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

The focal length step ΔF depends on the regime of operation of the applied voltage and therefore it is a function of V. The dynamic range of liquid level measurement depends on the range of the focal lengths that the ECVFL can be tuned to as well as the degree of collimation of the laser. Note that better laser beam collimation would result in an increased dynamic range of the proposed sensor.

Using Eq. (1) and Eq. (2), one can write:

$$D_T = \frac{H \times F}{(H - F\theta)}. \quad (6)$$

The sensor dynamic range R is then given by:

$$R = D_{TMax} - D_{TMin} = H\left(\frac{F_{Max}}{(H - F_{Max}\theta)} - \frac{F_{Min}}{(H - F_{Min}\theta)}\right). \quad (7)$$

The minimum F_{Min} and maximum F_{Max} values for the tunable F depend on the type and make of the ECVFL. The radius of the optical beam H at the ECVFL plane should be less than the radius of clear aperture of the ECVFL. The degree of collimation can be adjusted according to the required sensor application and different liquid container depths.

The percentage measurement resolution R_δ is given by:

$$R_\delta = \frac{\Delta D_T}{D_T} = \frac{(D_S - F)D_S + D_S F}{(D_S - F)^2} \times \Delta F \times \frac{D_S - F}{D_S F}, \quad (8)$$

$$\Rightarrow \frac{\Delta D_T}{D_T} = \frac{(D_S - F)D_S + D_S F}{(D_S - F)D_S F} \times \Delta F = \left(\frac{1}{F} + \frac{1}{D_S - F}\right)\Delta F. \quad (9)$$

As can be seen from Eq. (9), the percentage resolution varies with the liquid level. The Eq. (9) expression depends on the focal length needed to form a minimum beam spot at the liquid surface and this value of F varies with changing liquid levels. Fundamentally, the sensor resolution is limited by the physical effect of the illuminating Gaussian laser beam diffraction for a given F(V), specifically the beam axial (along beam propagation direction) resolution determined by the λ/4 Rayleigh criteria given by $\sim\pm 2\lambda\,(F\#)^2$, where F# (F-number) of the ECVFL is equal to F(V)/D and D is the diameter of the ECVFL [26].

3. Experimental demonstration

Fig. 2 shows the experimental setup to demonstrate the working principles of the proposed Fig. 1(a) liquid level sensor. Used is a highly attenuated beam from a 10 mW He–Ne LS with $\lambda_L = 632.8$ nm and $\theta = 1.24$ mrad. In addition, deployed is a Varioptic (France) Arctic 320 ECVFL [27] with $F_{Max} = 21.2$ cm at $V = 43$ V and $F_{Min} = 13.07$ cm at $V = 46$ V. The ECVFL has a transmittance of 92% at λ_L. The liquid container has a length $D_2 + D_L = 1$ m and diameter 5 cm. A gold mirror M and a glass spherical lens S having a focal length of 10 cm are deployed. For the ECVFL, the applied voltage step is $\Delta V = 200$ mV and the response time is less than 100 ms. $H = 0.3275$ mm and the distance from the ECVFL to the liquid container top, i.e., $D_1 + D_3 = 25$ cm. $L_1 = 11$ cm with $L_1 = L_2 + L_3$ and $L_2 = 6$ cm and $L_3 = 5$ cm. For the given experimental conditions, D_S is calculated from Eq. (2) to be 26.43 cm. Therefore F_V is computed as $F_V = D_S - L_1 = 15.43$ cm and L_4 comes out to be 6.07 cm. Using Eq. (5), the measurement resolution is calculated to be ≤0.9 cm with a resolution percentage of <1.2%. In the present case with $\lambda = 632.8$ nm, F_{Max} (43 V) = 21.2 cm and D = 3.4 mm, the fundamental λ/4 Rayleigh criteria based sensor resolution is ±4.92 mm. The optical power incident on the liquids is ~50 μW.

Liquid levels for three different liquids, namely motor oil, vegetable oil and laundry detergent are measured using the experimental sensor. The liquid optical power reflectivities are measured to be 2.32%, 1.26% and 1.55% for vegetable oil, motor oil

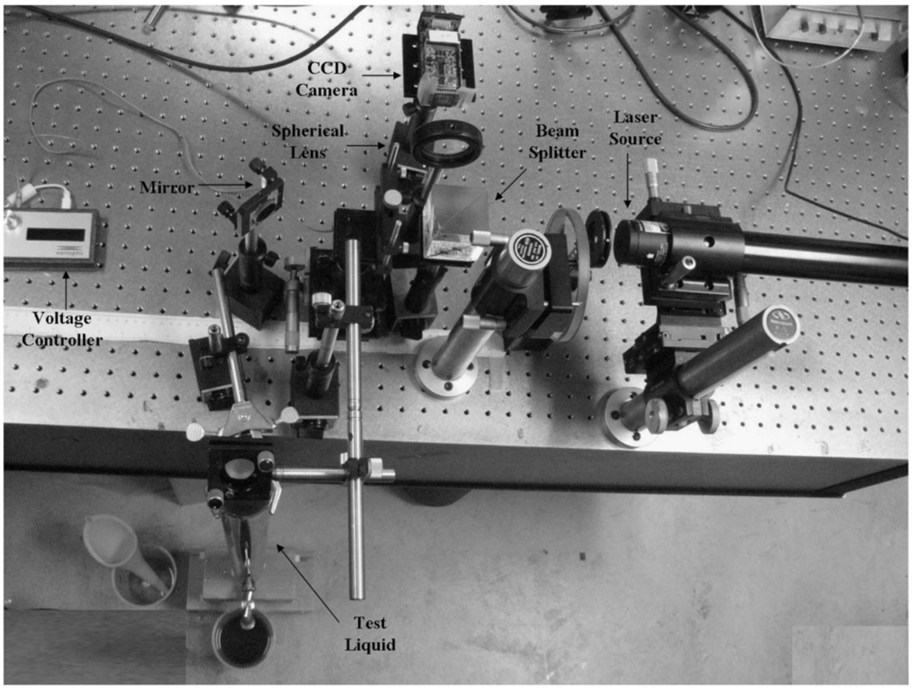

Fig. 2. Experimental setup of the proposed liquid level sensor. Note that the liquid tank did not use a window given the friendly nature of liquids deployed in the experiment.

and laundry detergent, respectively. Do note that one must operate the CCD in an unsaturated mode to obtain true beam spot size readings. Hence, by using the CCD in its unsaturated mode, any optical power fluctuations within the observed spot size do not affect the spot boundary, thus providing robustness to the liquid level sensor measurement. Note that depending on the designed liquid sensor range and apertures of the optics deployed (i.e., mirror, ECVFL, BS, S, and CCD), one must align the targeting beam accordingly with the surface of the liquid to have full receive beam capture on the CCD. Normal incidence of the beam on the liquid surface is ideally desirable as it retains circular symmetry of the of the ideal circular irradiance distribution of the ideal laser source. Nevertheless, if the laser irradiance is not perfectly symmetrical (e.g., somewhat elliptical such as common with many lasers including laser diodes and the laser used in the experiment), determining the ECVFL voltage when the received beam relative spot size is minimal is more critical to sensor operations versus the actual spot size measurement. Thus, appropriate image processing steps must be performed to compare similar shape beam spots to determine which one has the smallest beam size measure. Depending on the shape of the deployed laser beam, a variety of measurement parameters can be designed and implemented via computer processing such as $1/e^2$ power points for typical Gaussian laser beams or the 10% power point of the major (i.e., long) axis of an elliptic beam [28,29].

Plots in Fig. 3a–b compare the theoretical and the experimental applied voltage levels V corresponding to minimum beam spots at the liquid surfaces for different theoretical and deployed liquid levels. As seen from the plots, the theoretical and experimental data are indeed in good agreement for all three test liquids. The measured D_L liquid level depth ranges from 0 cm to 75 cm when V is varied from 43.1 V to 45.9 V. In Fig. 3, the measured control voltage is an average of three voltage data points taken for a given liquid level depth D_L. Note that because the deployed Varioptic ECVFL focal length response is non-linear with voltage (see Fig. 4) [27,30] and Eq. (5) also contains an F^2 dependence in its denominator, one should expect a non-linear response for the sensor as is also experimentally confirmed with the results in Fig. 3. The proposed sensor can be operated over a larger dynamic range by increasing the collimation 'θ' of the laser beam. The present sensor design using the raw diverging laser beam and Eq. (7) design equation can provide a liquid depth level dynamic range R of 109.44 cm. This full dynamic range can be completely utilized when the ECVFL is in close proximity to the window of the liquid tank. In the existing laboratory setup, the liquid lens is placed 25 cm away from the liquid tank entrance and therefore ~ 84 cm of dynamic range is available for liquid depth sensing for the experimental sensor. Note that the theoretical versus experimental data curve fits are better for the motor oil and detergent liquids versus the vegetable oil. This is because the motor oil and detergent liquids have a higher viscosity than vegetable oil and laboratory environment vibrations have a stronger effect on the lower viscosity liquid surface optical quality. Note that one can use a faster frame rate camera to capture higher spatial stability beam spot images that are more tolerant to liquid vibrations and surface fluctuations. More importantly, one can deploy adaptive optics on the receive beam via a deformable mirror device and a Hartmann-Shack wavefront sensor in collaboration with the higher speed camera to reduce spatial deformations on the detected beam to produce a vibration robust liquid level sensor. Also note that in certain flow situations, the liquid surface may not be uniform such as when the liquid flow is being subjected to vibrations. Again, the solution to alleviate this liquid surface variation problem is to use adaptive optics-based optical wavefront correction on the receive beam before beam capture on the CCD to complete robust image processing for beam size measurement.

Figs. 5, 6 and 7 present sequences of pictures clearly showing a large spot size swing recorded on the CCD changing from maximum to minimum to maximum. The picture sequences presented here are for motor oil in Fig. 5, laundry detergent in Fig. 6, and vegetable oil in Fig. 7 recorded at different depth levels for each liquid. In Fig. 5 for motor oil with a depth level D_L of 30 cm, 51 V, 48 V, 45.5 V, 43.3 V and 38 V are applied to produce beam spot diameters of 4.06 mm, 3.29 mm, 1.78 mm, 1.06 mm and 4.06 mm, respectively. In Fig. 6 for laundry detergent with a depth level D_L of 45 cm, the applied voltage is tuned to 50 V, 47 V, 43.5 V, 40 V, and 38.5 V to produce beam diameter sizes of 5.1 mm, 3.41 mm, 1.66 mm, 3.52 mm and 5.3 mm, respectively. Fig. 7 shows the reflected beam spot variation for vegetable oil with a depth level of 0 cm and V is tuned to 50 V, 46 V

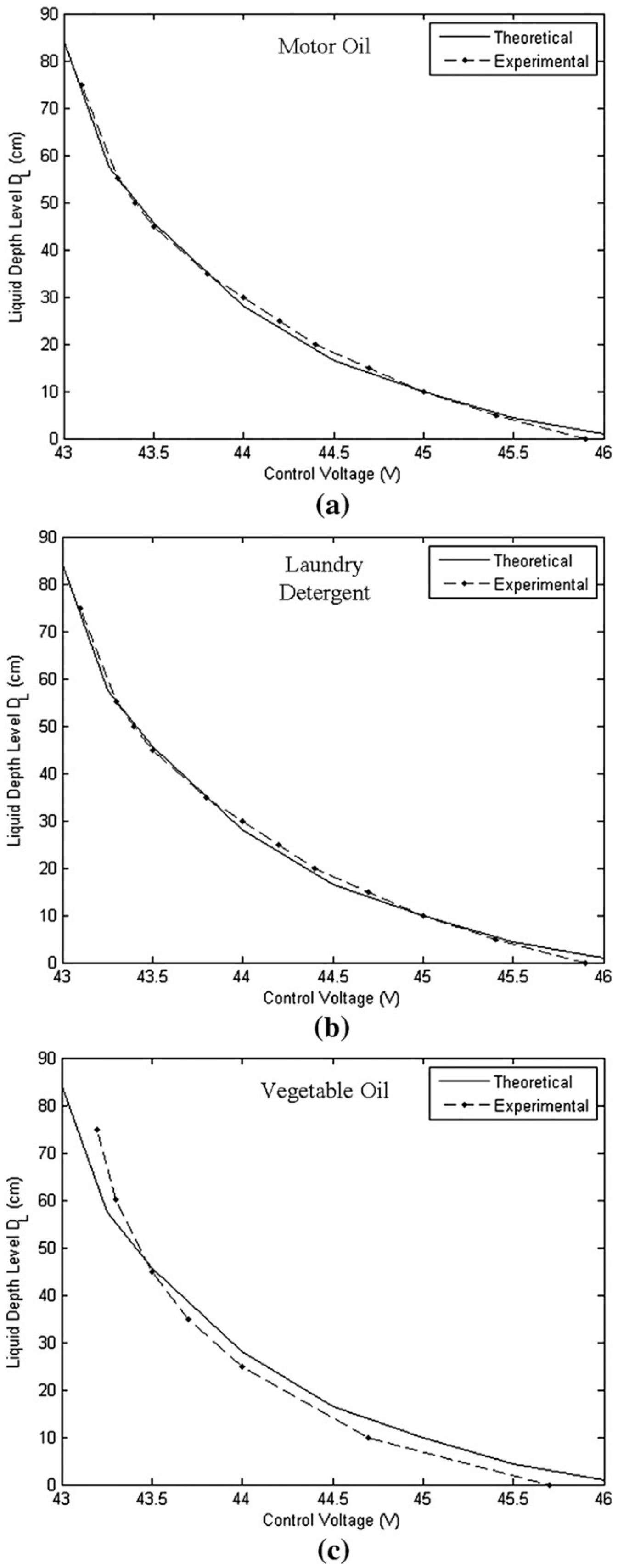

Fig. 3. Sensor theoretical and experimental plots for the liquid depth level versus the required ECVFL control voltage for formation of minimum beam spot on the liquid surface for (a) motor oil, (b) laundry detergent and (c) vegetable oil.

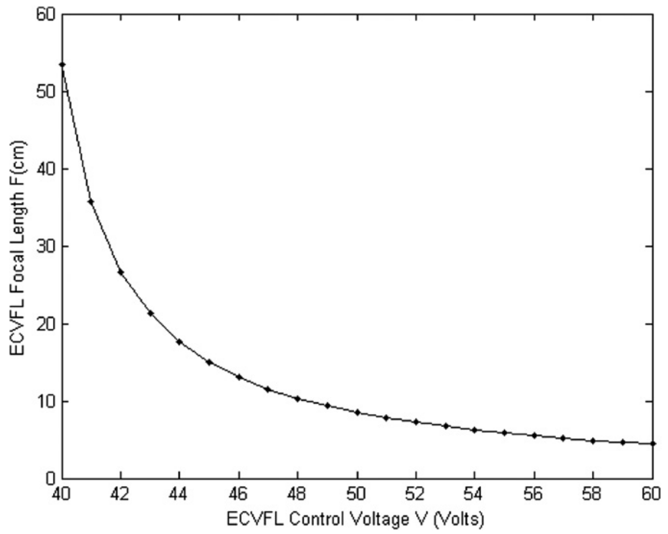

Fig. 4. Non-linear experimental response of the Varioptic ECVFL shown for lens focal length F versus lens drive Voltage V.

and 40 V producing spot sizes of 5.10 mm, 1.85 mm and 5.36 mm, respectively. By testing the proposed sensor for three different liquids with different refractive indices, viscosities and textures, it has been shown that the sensor works for a variety of liquids having different optical and chemical properties. Of course, one must use the appropriate laser wavelength and optical power to get sufficient optical reflectivity off the variety of liquids the sensor is designed such that the CCD operates above its noise floor but below its saturation point.

Reflections from the container window are reduced using Anti-Reflection (AR) coatings on the window faces. Distortions via the window are minimal as a high collimating beam is expected to pass through a high optical face flatness window. Furthermore, any unexpected distortions from the window aperture can be corrected using the adaptive optics in the sensor system. Note that the proposed sensor resolution is a percentage of the liquid level within the calibrated distance range of the sensor [25]. For example, the designed sensor resolution exhibits a less than 1.7% percentage resolution for a 200 mV ECVFL voltage change. This means the sensor has a 1.7 cm reading resolution when the liquid level is at a distance of 100 cm from the ECVFL position and in a similar vein, a 0.51 cm resolution for an ECVFL to liquid level distance of 30 cm. Hence, for some liquid level measurement applications, the demonstrated sensor design may be considered adequate. Note that an improvement in sensor resolution can be achieved with a higher collimation laser beam and smaller voltage change ECVFL drive electronics.

4. Conclusion

Demonstrated is a novel liquid level sensor based on a photonic spatial signal processing technique using an ECVFL. The proposed sensor is non-intrusive and uses low optical power with no RF electronics, thus making it suitable for closed liquid tank conditions used when the liquid under measurement is toxic, caustic or combustible including liquids at extreme temperatures and pressures. The basic proof-of-concept sensor design has been experimentally tested using a variety of laboratory friendly liquids over a range of 75 cm depth variations. Future work relates to optimization of the sensor design for closed tank hazardous liquid level tests and adaptive optics-based sensor designs for environments with vibrations.

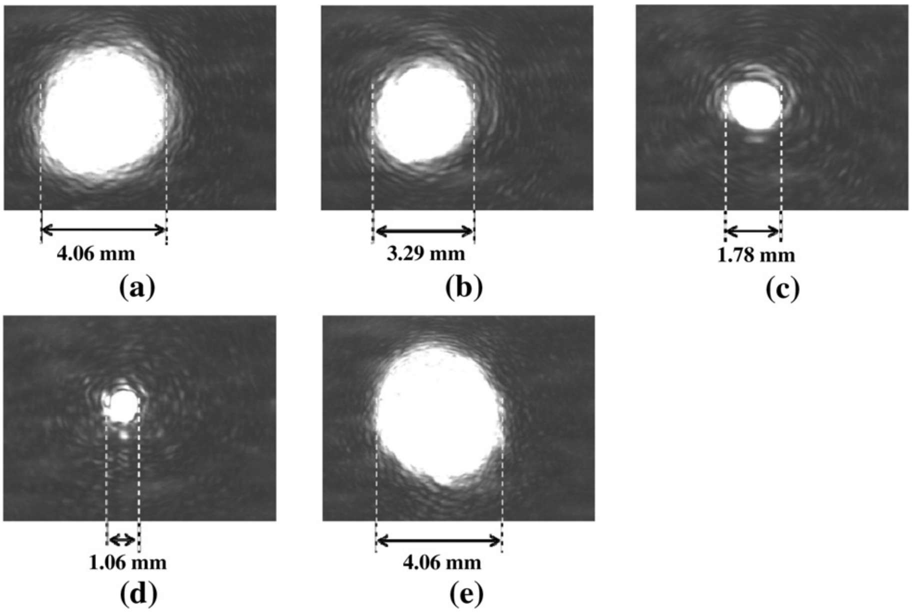

Fig. 5. Minimum beam spot (and measured size) for the motor oil liquid when viewed on the CCD during sensor measurement operations for a liquid depth level D_L of 30 cm with ECVFL control voltages of (a) 51 V, (b) 48 V, (c) 45.5 V, (d) 43.3 V and (e) 38 V.

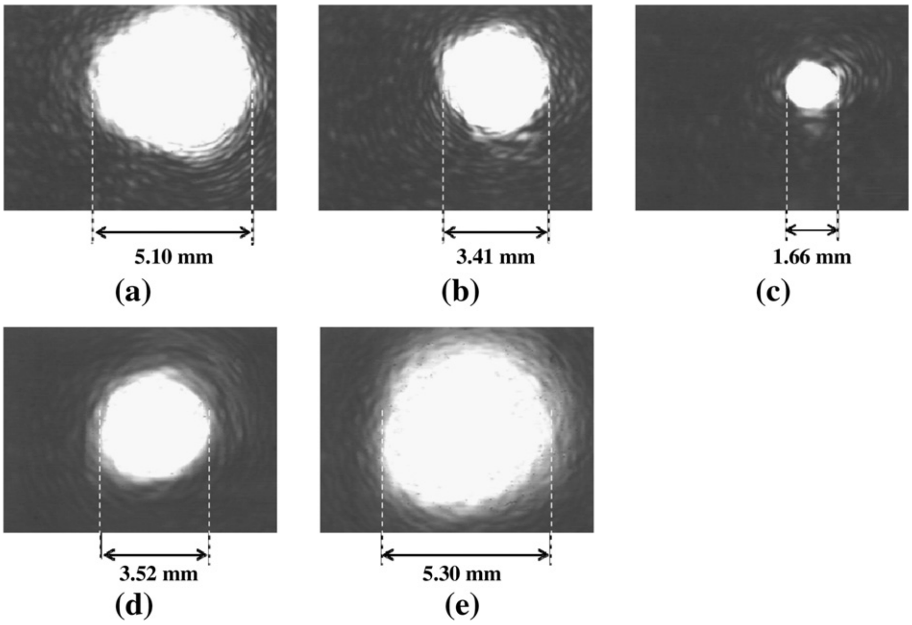

Fig. 6. Minimum beam spot (and measured size) for the laundry detergent liquid viewed on the CCD during sensor measurement operations for a liquid depth level D_L of 45 cm with ECVFL control voltages of (a) 50 V, (b) 47 V, (c) 43.5 V, (d) 40 V and (e) 38.5 V.

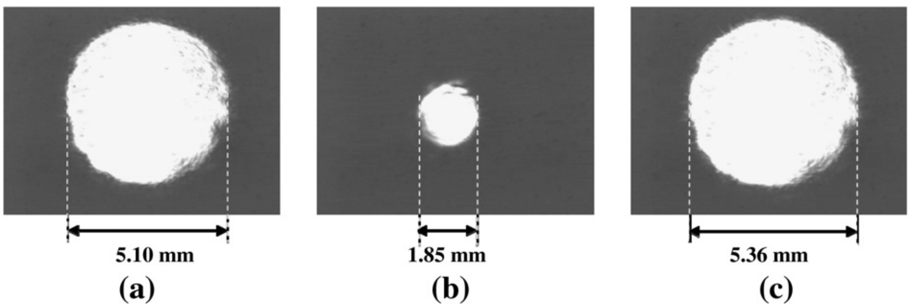

Fig. 7. Minimum beam spot (and measured size) for the vegetable oil liquid viewed on the CCD during sensor measurement operations for a liquid depth level D_L of 0 cm with ECVFL control voltages of (a) 50 V, (b) 46 V and (c) 40 V.

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