Design and Implementation of Capacitive Drip Rate Monitoring Sensor for Intravenous (IV) Administration

Sheikh Faisal Ahmad[1][a], Byoung Ju Yun[2][b], Jun Ho Hwang[1][c] and Hyun Deok Kim[1,2][d]
[1]*Institute of Advanced Convergence Technology, Kyungpook National University, 80 Daehakro Bukgu, Daegu, South Korea*
[2]*School of Electronic and Electrical Engineering, Kyungpook National University, 80 Daehakro Bukgu, Daegu, South Korea*

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Abstract: This paper presents a novel capacitive sensor designed for real-time monitoring of the infusion drip rate during intravenous (IV) therapy administration. The proposed sensor, operating on the principle of proximity capacitance sensing, establishes a longitudinal electric field within the IV drip chamber, thereby enhancing the efficiency and reliability of drip rate monitoring under both nominal and adverse operating conditions. Departing from conventional capacitive sensor configurations, the proposed capacitive sensor comprises two coaxial but asymmetrical hollow cylindrical metallic electrodes of distinct top and bottom diameters, separated by a narrow gap and positioned on the IV drip chamber. A comprehensive electrostatic analysis was conducted using finite element method-based numerical simulations for the design and analysis of the proposed proximity capacitive sensor. For a standard 20 drops/ml (GTT/ml) drip factor, simulations indicated 1.4 times increase in the average sensitivity of liquid drop detection using the proposed capacitive sensor compared to the conventional one. The simulation results conclusively demonstrated the superior and more reliable performance of the proposed proximity capacitive sensor across all operating conditions. Additionally, sensitivity measurements confirmed 1.3 times increase in the average sensitivity using the asymmetrical proximity capacitive sensor validating the results obtained from the numerical simulations.

1 INTRODUCTION

The drip rate (drops/min) constitutes a critical parameter in intravenous (IV) therapy. The efficacy of IV treatment hinges on the precise regulation of drip rate, which must align with the patient's age, underlying condition, infusion duration, and fluid type. Historically, adjusting the drip rate to achieve desired infusion conditions has been a manual, observational process involving counting the number of liquid drops that appear in the IV drip chamber from the drip bag within a specified time frame. However, advancements in sensor technology and electronic components have facilitated the development of IV monitoring systems capable of not only measuring but also automatically adjusting drip rates (even remotely) based on patient-specific factors. These systems typically comprise two primary parts; a sensor that detects the occurrence of drops in the IV drip chamber and an electronic circuit that converts the detected sensor's signal into meaningful information for display on a monitoring console. The decision-making circuitry responsible for drip rate adjustment is also an integral part of the electronic circuit. The sensor is a critical component of these monitoring devices, as its accurate drop detection capabilities directly influence the drip rate adjustment and infusion control. Any sensor malfunction can lead to erroneous information, potentially posing a significant risk to patient safety.

A variety of sensing mechanisms have been employed for drop detection in IV drip chambers. Optical sensing, in particular, is widely utilized in IV drip rate and infusion monitoring devices (Barros et

[a] https://orcid.org/0000-0001-7165-7024
[b] https://orcid.org/0000-0002-9898-2262
[c] https://orcid.org/0000-0002-6406-4770
[d] https://orcid.org/0000-0002-3195-5438

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al., 1998; Yang et al. 1998; Qiliang et al., 2013). Electromagnetic sensors, such as those based on ultrasonic waves (Cosentino et al., 1978; Krithika et al., 2014; Udayan et al., 2016) and microwave time-domain reflectometry (TDR) (Cataldo et al., 2011), have also been implemented. However, these sensors share a common drawback: susceptibility to external environmental influences (Bustamante et al., 2007). Capacitance detection-based conventional sensors, which are least affected by the surrounding environmental conditions, offer a viable alternative (Kirkby et al., 1989; Kim et al., 2017; Leeudomwong et al., 2021; Zhang et al., 2011). Several IV drip rate and infusion monitoring devices incorporate capacitance sensing principles (Kirkby et al., 1989; Brown et al., 2003; Ogawa et al., 2010; Wei et al., 2011). These devices typically employ planer or curved electrode topologies (for capacitance sensing) that are either directly integrated into the IV drip chamber or positioned within other components of the IV therapy administration set.

A conventional capacitive sensor used to detect the change in capacitance in cylindrical pipes of finite diameter (for microflow detection applications) typically consists of two curved metal electrodes mounted outside the cylindrical pipe with a narrow separation (Aslam et al., 2014). Variation of capacitance in the absence and presence of the liquid drop between the electrodes is in the order of femtofarad (fF). A precise and sensitive capacitance measurement system is thus mandatory for detecting such a small change in capacitance. While the capacitance bridges and capacitance measurement ICs are available for such measurements, the shape and orientation a capacitive sensor's electrodes significantly influence the measured capacitance. The capacitive sensor (conventional capacitive sensor) typically used to detect the occurrence of drops in the IV drip chamber is composed of curved electrodes (Brown et al., 2003; Kirkby et al., 1989; Leeudomwong et al., 2021). Although this kind of capacitive sensor is least affected by the surrounding environmental conditions as compared to the other sensors for IV drip monitoring however, experimental evidence suggests that some physical factors like drip rate, drop passing position in the sensor or fluid level within the IV drip chamber can affect the performance of conventional IV drip capacitive sensor.

This paper introduces a novel capacitive sensor design for IV drip rate monitoring that overcomes the limitations of conventional capacitive sensors, which are susceptible to external physical disturbances. While traditional capacitive sensors use two flat or curved electrodes for drop detection in IV drip chambers, the proposed capacitive sensor, on the other hand, uses two hollow, cylinder-shaped electrodes that are stacked on top of each other. Furthermore, due to the tapered cylindrical surface of the IV drip chamber, the electrodes in the proposed sensor are asymmetrical, with distinct top and bottom diameters. This electrode arrangement creates a proximity capacitor with a longitudinal electric field distribution along the IV drip chamber's axis. The proposed capacitive sensor (or proximity capacitive sensor) detects the altered capacitance due to the perturbation of liquid drops in the electric field. Furthermore, the proposed asymmetric electrode configuration for the proposed proximity capacitive sensor demonstrates enhanced sensitivity compared to the symmetrical electrodes in detecting the liquid drops within the IV drip chamber (Kim et al., 2017).

2 CAPACITIVE SENSOR FOR IV DRIP MONITORING

2.1 Basics of Capacitance Sensor

A basic capacitor comprises two parallel conductive plates, or electrodes (anode and cathode), separated by a dielectric material as illustrated in Figure 1.

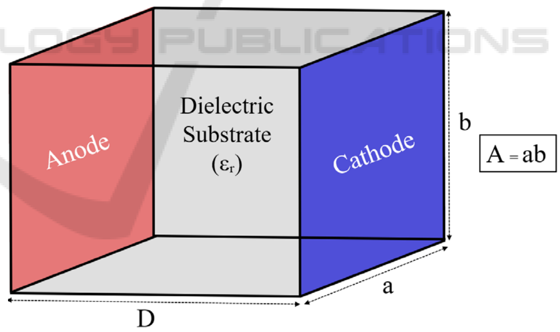


Figure 1: Simple parallel plate capacitor.

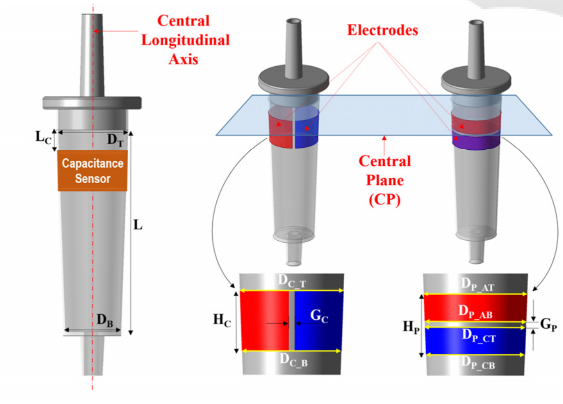
The capacitance C of this simple parallel plate capacitor is defined by Equation (1).

$$C = \varepsilon_o \varepsilon_r (A / D) \quad (1)$$

In equation (1), ε_o represents the permittivity of free space, ε_r is the relative permittivity (dielectric constant) of the dielectric material, A is the area of each electrode, and D is the distance or separation between the electrodes as shown in Figure 1. Given fixed A and D, changes in capacitance are directly related to changes in ε_r of the dielectric medium between the electrodes. Consequently, the variation in capacitance of the capacitance sensor is a function of the variation of dielectric constant ε_r. In addition to relative permittivity, the capacitance of a parallel plate capacitor also depends upon the intensity and the distribution of the electric field E. For the parallel plate electrode configuration shown in Figure 1, the electric field intensity E near the open edges of the electrodes exhibits a slight deviation from its value at the center owing to the phenomenon of the fringing electric field. For a dielectric material relatively smaller in dimension compared to the electrodes, the capacitance of the sensor becomes a function of the dielectric material's spatial position.

2.2 IV Drip Chamber

The IV drip chamber is typically made of transparent and flexible polyvinyl chloride (PVC) material and is available in cylindrical and tapered cylindrical shapes. Their dimensions vary according to the intended infusion application. Despite these differences, IV drip chambers are primarily characterized by their drip rate, which typically have the drip factor ranges from 10 to 60 drops/ml (or GTT/ml). The highest drip rate corresponds to the smallest drop diameters (Flack et al., 1975). A standard tapered hollow cylindrical IV drip chamber, featuring distinct top and bottom diameters, is depicted in Figure 2(a). L, D_T, D_B, and L_C represent the length, top external diameter, bottom external diameter, and clearance of the capacitive sensor location from the top of the IV drip chamber, respectively.



(a) **IV Drip Chamber** (b) **Conventional** (c) **Proposed**

Figure 2: Standard IV drip chamber and capacitive sensors with asymmetrical electrodes.

2.3 Conventional Capacitive Sensor

A conventional capacitive sensor, often utilized in the IV drip chamber typically comprises two curved rectangular electrodes (Kirkby et al., 1989; Leeudomwong et al., 2021). To ensure a perfect fit with the tapered cylindrical walls of the IV drip chamber, however, two curved trapezoidal electrodes with slightly varying top and bottom diameters (D_{C_T}, and D_{C_B} respectively) can be employed in the conventional capacitive sensor as illustrated in Figure 2(b). H_C denotes the height while G_C represents the narrow gap between two asymmetrical (curved) electrodes of the conventional capacitive sensor.

Typically, when the medication is not being administered via IV drip therapy, the IV drip chamber is partially filled with liquid medicine. In this situation, drops do not appear between the electrodes, leaving only a PVC layer and an air gap. The capacitance measured under these conditions is referred to as C_{AIR_C}. When the medicine administration is started, liquid drops start to appear in the empty region between the electrodes from the top of IV drip chamber. The dielectric constant (ε_r) of these drops is significantly greater than unity, causing a sudden change in capacitance. The peak capacitance value measured by the sensor as the drop passes through it can be referred to as C_{LIQ_C}. For a standard 20 drops/mL IV drip chamber, these capacitances are typically in the picofarads (pF) range. The sensitivity of the capacitive sensor, defined as the capacitance difference ΔC_con between the presence and absence of a liquid drop, is typically in the femtofarads (fF) range (Kirkby et al., 1989).

2.4 Proximity Capacitive Sensor

Unlike the electrode topology deployed in the conventional capacitive sensor, the proposed proximity capacitive sensor comprises two coaxial hollow cylindrical metallic (copper) electrodes separated by a gap as illustrated in Figure 2(c). Given the tapered cylindrical shape of the IV drip chamber, the asymmetrical (conical) upper and lower electrodes have varying diameters of their top and bottom sections. The top and bottom diameters of the upper and lower electrodes are denoted as D_{P_AT}, D_{P_AB}, D_{P_CT}, and D_{P_CB} respectively. The height of each electrode is H_P, while the gap between them is G_P. Although the capacitance values C_{AIR_P} and C_{LIQ_P} of the proposed capacitive sensor are also in the picofarad (pF) range, they are significantly larger than those obtained with the conventional capacitive sensor. However, the capacitance difference ΔC_pro

remains in the femtofarad (fF) range. The capacitance sensing mechanism employed in the proposed capacitive sensor is regarded as proximity capacitance sensing which is a widely used capacitance sensing technique in various applications (Chen et al., 2004; Kim et al., 2017).

2.4.1 Proximity Capacitive Sensor Working Principle

In standard practice, IV drip chambers are recommended to be suspended vertically to facilitate gravity-driven fluid infusion. A capacitive sensor can detect the maximum capacitance only when the liquid droplets appear in the central plane (CP) shown in Figure 2 of the IV drip chamber. However, various physical factors can tilt the vertically suspended IV drip chamber, rather than the intended straight vertical suspension. This change in orientation results in the liquid drops passing the central plane (CP) closer to the chamber walls, rather than the central longitudinal axis shown in Figure 2. Due to the curved geometry of the electrodes, the electric field inside the capacitive sensor is non-uniform within the CP plane. Therefore, the electric field distribution within the IV drip chamber, as established by the electrodes constitutes a critical factor influencing the performance of capacitive sensors. Given the proposed structural configuration of the proximity capacitive sensor, the electric field distribution within the IV drip chamber is orthogonal to the CP Plane. This orientation contrasts with the parallel (to the CP Plane) distribution of the electric field observed in conventional capacitive sensors. This unique radially varying electric field distribution pattern in the CP plane which is symmetrical in all directions within the IV drip chamber, ensures reliable sensitivity of the proximity capacitive sensor.

3 DESIGN AND ANALYSIS

3.1 3D Modelling & Simulation Setup

The 3D models of the asymmetrical conventional and proposed IV drip capacitive sensors were created in ANSYS. A standard 20 drops/ml IV drip chamber made of PVC material with L = 50mm, D_T = 17.5mm, D_B = 14mm, T = 1mm was used in simulations. For more realistic analysis the IV drip chambers half-filled (25mm) with water was used in simulations. The diameter of a spherical liquid drop is a variable parameter that depends upon the drip speed or infusion rate (Flack et al., 1975; La Cour et al., 1965). The radius of the spherical liquid drop was fixed to 2.3 mm in all simulations which coincides with the standard 20 drops/ml drip factor specification.

The sensitivity characteristics of the conventional and proposed proximity capacitive sensors were investigated numerically using finite element method (FEM)-based electrostatic simulations in ANSYSY MAXWELL. Capacitance of both sensors were measured in the absence and presence of liquid drops within the electrodes under various conditions. Water, with its relatively high relative dielectric constant (ε_r = 81), was used as the liquid medium in all simulations.

The electrode height (vertical length along the cylindrical surface of the IV drip chamber) was the primary parameter which was required for the sensitivity characteristics study. While longer electrodes can potentially increase capacitance, they do not enhance sensitivity (Leeudomwong et al., 2021). Furthermore, a sudden capacitance change is required for IV drip chamber applications upon the appearance of a drop between the electrodes.

Considering this, we first optimized the height of asymmetrical electrodes of the conventional capacitive sensor using electrostatic simulations. The interspacing G_C was maintained at 1mm between the electrodes on both sides. The sensitivity ΔC_con of the conventional capacitive sensors is illustrated in Figure 3. The optimal electrode height (H_C) of the conventional capacitive sensor was determined to be 10mm, as further increases did not significantly improve the sensitivity.

The height of the proposed asymmetrical proximity capacitive sensor electrodes was then optimized with a fixed interspacing (G_P = 1mm). As shown in Figure 3, the optimal height (H_P) of the proximity capacitive sensor (with each electrode equal to half of H_C) was determined as 11mm as any further increase in the electrode height did not significantly improve the sensitivity.

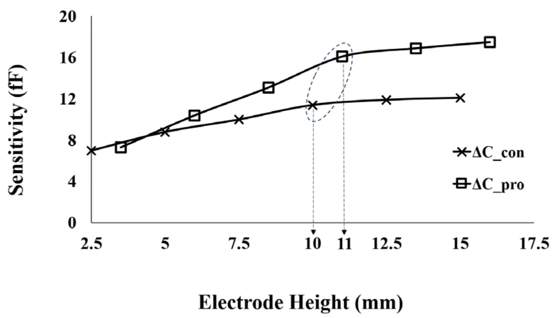


Figure 3: Electrodes height optimization.

3.2 Electric Field Distribution

The electric field distribution of the asymmetrical conventional (with H_C =10mm) and proximity (with H_P = 11mm) capacitive sensors along the central plane CP, and an orthogonal plane passing through the central longitudinal axis of the IV drip chamber is illustrated in Figure 4.

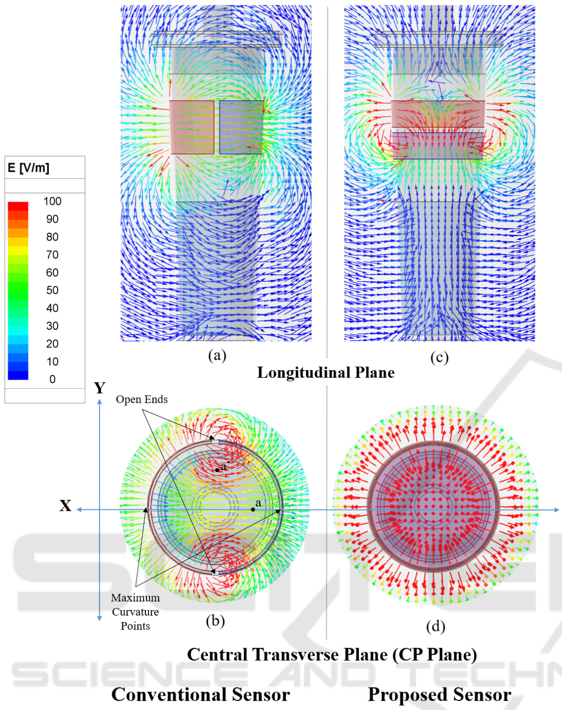


Figure 4: Electric field distribution in the longitudinal and CP plane of the asymmetrical capacitive sensors.

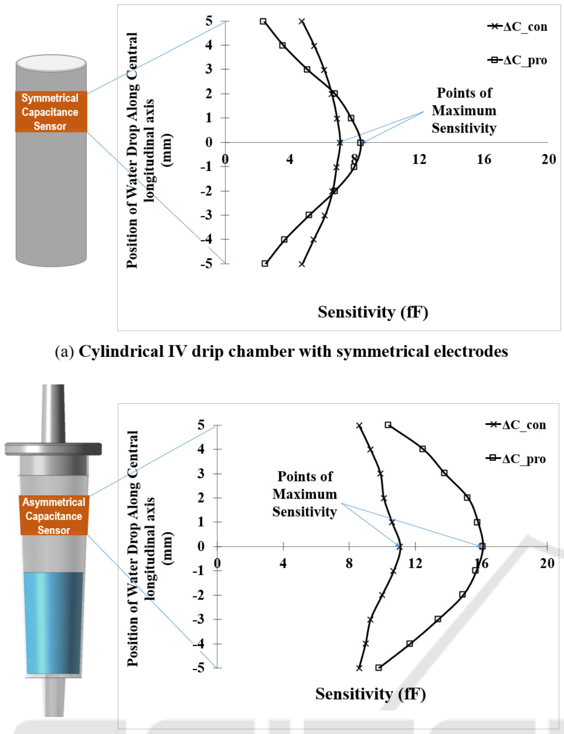
The electrodes of a conventional capacitive sensor establish an electric field in the direction transverse to the axis of the IV drip chamber. This electric field distribution in a longitudinal plane which is orthogonal to the CP plane and passing through the X-axis is shown in Figure 4(a). Owing to the variable distance between corresponding points on the anode and cathode, the electric field strength exhibits variations in the radial directions within the CP plane. As depicted in Figure 4(b), the electric field intensity is most pronounced near the open ends of the electrodes along the Y-axis, whereas it is least intense near the points of maximum curvature situated along the X-axis. Consequently, the capacitance resulting from perturbations of the liquid drop along the X and Y axes at equidistant points (a and a') from the center within the CP plane exhibit different magnitudes. This disparity in sensitivity across different directions compromises the reliability of the IV drip capacitive sensor with conventional electrodes topology.

In contrast, the electrodes of the proposed proximity capacitive sensor establish an electric field along the axis of the IV Drip chamber. This electric field distribution in a longitudinal plane which is orthogonal to the CP plane and passes through the X-axis is shown in Figure 4(c). Due to the axial symmetry of the electrodes, the variation in the electric field in all radial directions within the CP plane of the proximity capacitive sensor is symmetrical. There exist contours of constant electric field strengths encircling the axis of the IV drip chamber as illustrated in Figure 4(d). This electric field distribution within the proximity capacitive sensor enhances the reliability of capacitance measurements, mitigating the impact of perturbations caused by liquid droplets at different locations within the CP plane.

3.3 Results & Discussion

Initially, we compared the sensitivity of the proposed asymmetrical capacitive sensors to that of symmetrical capacitive sensors, previously investigated by the authors (Kim et al., 2017). We evaluated the capacitance detection capabilities of both conventional and proposed proximity sensors along the axis of a vertically suspended cylindrical and tapered cylindrical IV drip chamber. To assess the sensitivity (or capacitance difference ΔC_con and ΔC_pro) of each sensor, electrostatic simulations were conducted by systematically varying the position of the water drop along the central longitudinal axis of the IV drip chamber, as illustrated in Figure 5.

Due to their closer proximity to the IV drip chamber, the proposed asymmetrical proximity capacitive sensor demonstrated 2.8 times increase in the average sensitivity compared to the previously proposed symmetrical proximity capacitive sensor, as illustrated in Figure 5. Moreover, the proposed design exhibits 1.4 times increase in the average sensitivity when compared to the asymmetrical conventional capacitive sensors. The results depicted in Figure 5 reveal that conventional capacitive sensors, both symmetrical and asymmetrical, exhibit a lower standard deviation of sensitivity relative to their peak values compared to the proposed proximity sensor. However, this characteristic may pose a limitation in distinguishing between multiple drops that could simultaneously appear within the sensor during high infusion rates. Conversely, the proposed proximity sensor's higher standard deviation relative to its peak sensitivity is advantageous for precise drop counting during intravenous (IV) infusion administration.



(a) **Cylindrical IV drip chamber with symmetrical electrodes**

(b) **Tapered cylindrical IV drip chamber with asymmetrical electrodes**

Figure 5: Sensitivity concerning water drop position along the IV drip axis in the sensor for two different shapes of IV drip chambers and sensor topologies.

A critical scenario for comparing the performance of the two capacitive sensors is the case of a tilted IV drip chamber. In common practice, IV drip chambers are often not perfectly vertically suspended but rather tilted at a certain angle. Consequently, the location where the water drops appear in the CP plane shifts closer to the walls of the IV drip chamber. To assess the sensitivity (ΔC_con and ΔC_pro) of the two sensors, we conducted simulations by systematically varying the position of the water drop along the X and Y axes of the CP plane of the IV drip chamber, as illustrated in Figure 6.

The simulation results depicted in Figure 6 demonstrate the variable sensitivity (ΔC_con_X and, ΔC_con_Y) exhibited by the conventional sensor along the radial X and Y directions. Such variations in sensitivity compromise the reliability of the conventional capacitive sensor. Additionally, due to comparatively weaker sensitivity along the X-axis, the performance of the conventional sensor can further deteriorate when the drop size is decreased at faster infusion rates. In contrast, the novel proximity capacitive sensor demonstrates similar and superior sensitivity (ΔC_pro_X and, ΔC_pro_Y) across all radial directions as illustrated in Figure 6. These sensitivity profiles ensure precise drop counting, irrespective of the drop size for different infusion rates.

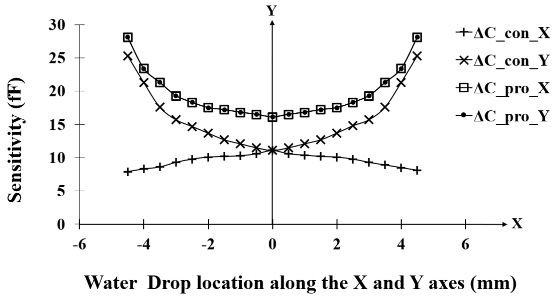


Figure 6: Sensitivity concerning water drop position along the X-axis and Y-axis in the CP plane.

During intravenous (IV) infusion, a residual volume of liquid with fluctuating level is consistently present within the IV drip chamber. The capacitance of the sensor is the function of the electric field which comprises both the field between the electrodes and the fringing field as shown in Figure 4. An increase in the liquid level in the IV drip chamber alters the electric field, resulting in the corresponding changes to the sensor's capacitance. Consequently, the volume of liquid which is expressed as its level (or height) within the IV drip chamber emerges as another significant factor influencing the sensitivity of the capacitive sensors. Simulations were conducted by systematically varying the height of the water within the vertically suspended IV drip chamber. The sensitivity of the two sensors (ΔC_con and ΔC_pro), determined by positioning the water drop at the center of each sensor in the CP plane is depicted in Figure 7.

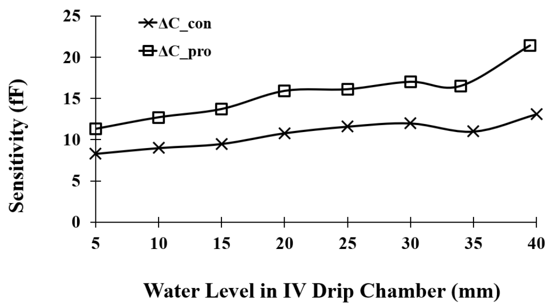


Figure 7: Sensitivity concerning water level within the IV drip chamber.

As illustrated in Figure 7, the capacitive sensors exhibited varying sensitivities to the changes in the liquid volume within the IV drip chamber. Regardless of the liquid volume in the IV drip chamber, the proposed asymmetrical proximity capacitive sensor consistently maintained 1.5 times higher average sensitivity compared to the conventional one. Furthermore, the results indicate that when the liquid level rises to encroach upon the sensor, the sensitivity of both sensors increases. However, the proposed proximity capacitive sensor retains its superiority over the conventional sensor even in such conditions.

A standard drip chamber with a drip factor of 20 drops/ml is commonly used in IV drip administration. However, drip factors ranging from 10 to 60 drops/ml are also used for dedicated IV drip administrations. Variations in the drip factor influence the diameter of the liquid drops forming in the IV drip chamber (Flack et al., 1975; La Cour et al., 1965). Faster drip rates yield smaller drops that potentially affect the sensitivity of capacitive sensors. To evaluate the sensitivity of asymmetrical electrodes-based conventional and proximity sensors, we conducted simulations by systematically varying the water drop diameter, corresponding to the different drip factors. During simulations, the liquid drop was positioned at the point of maximum sensitivity, as identified in Figure 5(b). The sensitivity (ΔC_con and ΔC_pro) of the conventional and proposed capacitive sensors across various drip rates by varying the drip factor is illustrated in Figure 8.

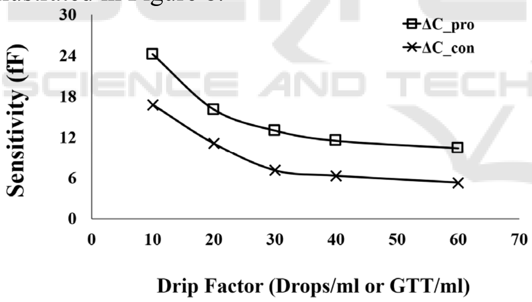
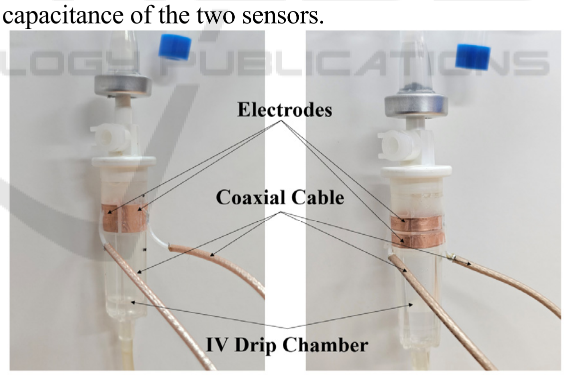


Figure 8: Sensitivity concerning various drip rates in IV drip chamber.

The radii of the spherical water drops used in the simulations depicted in Figure 8 for 10, 20, 30, 40, and 60 drops/ml were 2.9, 2.3, 2.0, 1.8, and 1.6 mm, respectively. As illustrated in Figure 8, the sensitivity of both capacitive sensors decreased with increasing drip rate. However, the proposed proximity capacitive sensor demonstrated 1.7 times higher average sensitivity than the conventional one across all drip rates. Figure 8 illustrates the results obtained by using the asymmetrical electrode configurations, specifically optimized for a 20 drops/ml drip factor. Notably, the proposed proximity capacitive sensor's sensitivity remains robust across a range of drip rates, suggesting its potential for broader application.

5 PROTOTYPE MEASUREMENT

To validate the simulation results, we implemented the prototypes of the asymmetrical type conventional, and the proposed proximity capacitive sensors as illustrated in Figure 9. Adhesive copper tape, readily affixed to the IV drip chamber, was utilized to fabricate the electrodes of two sensors using the optimized dimensions obtained via simulations. To measure the capacitance between the electrodes, we employed the AD7150, a capacitance-to-digital converter (CDC) manufactured by ANALOG DEVICES, capable of achieving a sensitivity of up to 1 femtofarad (fF) (Analog Devices). Coaxial cables of identical lengths with SMB connectors were employed to establish a connection between the electrodes of the sensor and the AD7150 capacitance evaluation board. AD7150 offers a diverse range of operational modes for capacitance measurement. We used the adaptive mode with the positive threshold for capacitance measurements (Zhang et al., 2011). We deployed standard normal saline fluid drip with the IV drip chambers. Based on the crossing location of the saline drops in the CP plane four distinct scenarios were established to evaluate the capacitance of the two sensors.



(a) **Conventional Sensor** (b) **Proposed Sensor**

Figure 9: Implemented prototypes of two asymmetrical capacitive sensors for sensitivity measurement.

Figure 10 presents the waveform of the capacitance variations measured using the accompanying software of the AD7150 evaluation board (Analog Devices) with a standard 20 drops/min IV drip having a drip factor of 20 drops/ml. All capacitance measurements presented in Figure 10 were acquired with the partially filled IV drip chambers. The proposed proximity capacitive sensor consistently exhibited higher capacitance values than the conventional sensor across all measurement scenarios. Figure 10(a) illustrates the baseline capacitance of each sensor, measured in the absence of a saline drop. Subsequently, the capacitance of vertically suspended IV drip chambers was measured using a similar drip factor (20 drops/ml), as depicted in Figure 10(b). These capacitance readings were measured along the central axis, with positive spikes indicating the presence of a saline drop at the CP plane (CP). Figures 10(c) and 10(d) showcase the capacitance measurements obtained by manually tilting the IV drip chamber along the X-axis and Y-axis (selected according to Figure 4), respectively. In these cases, the saline drops crossed the CP plane by contacting the cylindrical wall of the chamber.

A comparative sensitivity analysis of the conventional and proposed capacitive sensors in three measurement scenarios is provided in Table 1. The asymmetrical electrode-based proposed proximity capacitive sensor exhibited 1.3 times higher sensitivity than the conventional one. The measured sensitivity values are closely aligned with the simulated results. The tabulated sensitivity profiles unequivocally demonstrate the superior performance of the proposed proximity sensor implemented with asymmetrical hollow cylindrical electrodes.

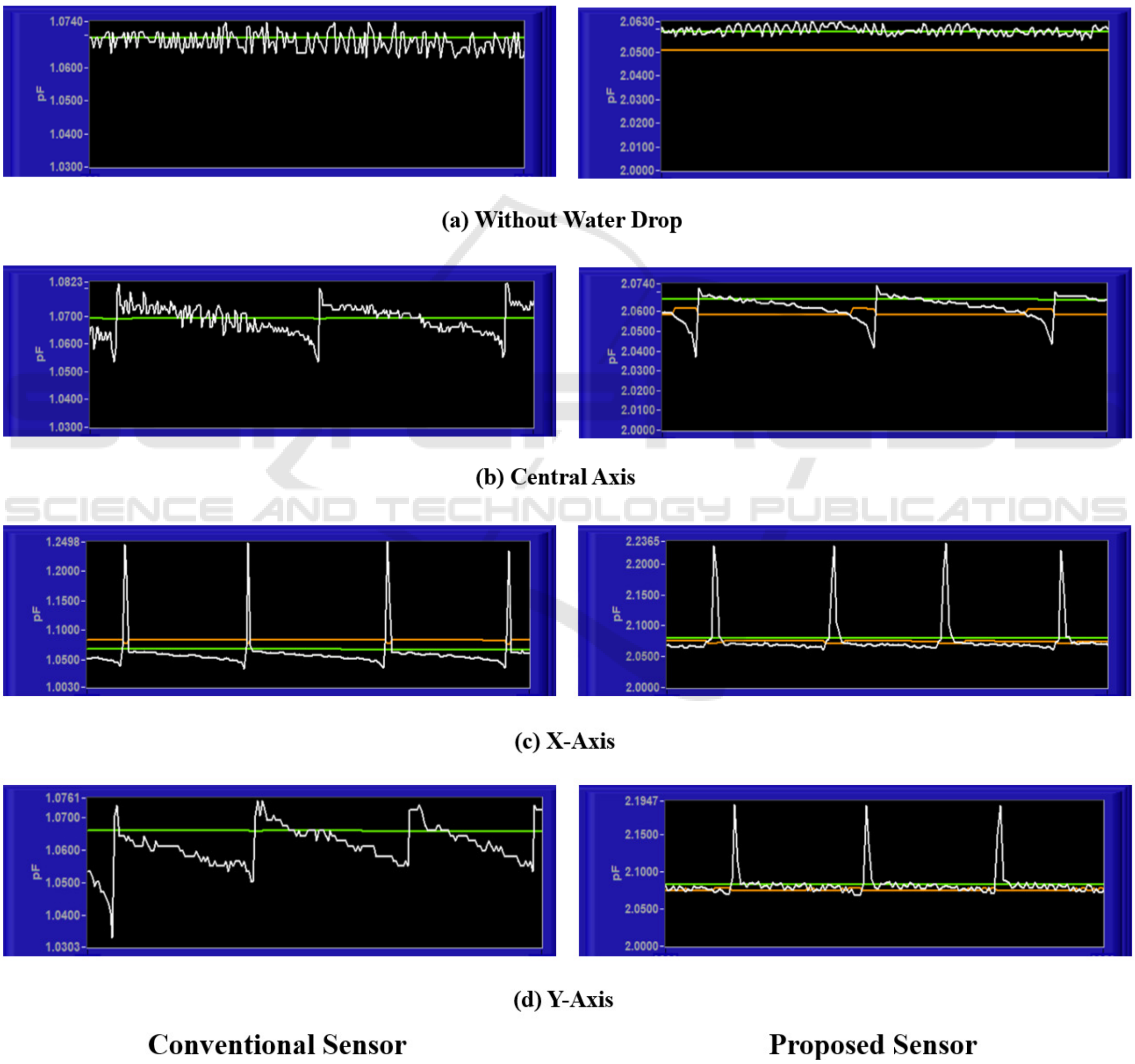


Figure 10: Measured capacitance of the two sensors using AD7150 evaluation board.

Table 1: Measured sensitivity of capacitive sensors.

Drop Crossing Location	Conventional (fF)	Proximity (fF)
Central Axis	8.3	11
X-Axis	2.1	173.5
Y-Axis	175.8	131.7

5 CONCLUSIONS

This paper presents a novel proximity capacitive sensor designed to monitor intravenous (IV) drip infusion administration. The proposed sensor consists of two coaxial asymmetrical hollow cylindrical copper electrodes of finite thickness. This proposed configuration generates a longitudinal electric field within the IV drip chamber, enabling proximity capacitance detection. Employing electrostatic simulations, we demonstrated that the novel proximity capacitive sensor overcomes the issue of non-uniform sensitivity across various radial directions, a limitation commonly encountered with conventional capacitive sensors. Moreover, we established that the proposed proximity capacitive sensor exhibits superior sensitivity for drop detection compared to conventional capacitive sensors under diverse physical conditions pertaining to the IV drip chamber orientation. The study presented in this paper focused on the commonly used 20 drops/min IV drip chamber with 20 drops/ml drip factor. The results however indicate that the proposed asymmetrical electrodes-based proximity capacitive sensor offers more accurate and reliable performance than the conventional one across various drip factors.

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