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Capacitive measurement of infusion fluid volume

***Abstract**. The article presents a system for monitoring fluid during intravenous infusion. The system is based on a capacitive method in which the change in electrical capacitance of the infusion container is converted into the current volume of the fluid. The capacitor pads of the measurement system are integrated into the housing of the container, facilitating easy installation in hospital conditions without significantly altering the dimensions of the infusion set. The system has been tested with target infusion fluids, and the volume measurement error within the entire measurement range is less than 6%. The current fluid volume is displayed on an LED strip to quickly inform the personnel, and the system also has the capability to provide an alarm for low fluid levels.*

***Streszczenie.** W artykule przedstawiono system monitorowania płynu podczas infuzji dożylnej. System bazuje na metodzie pojemnościowej w której zmiana pojemności elektrycznej pojemnika z płynem infuzyjnym przeliczana jest na aktualną objętość płynu. Okładziny kondensator pomiarowego zostały wbudowane w obudowę pojemnika, dzięki czemu instalacja sytemu w warunkach szpitalnych jest łatwa a układ pomiarowy nie zmienia znacząco wymiaru wymiarów aparatu kroplówkowego. System, został przetestowany na docelowych płynach infuzyjnych, błąd pomiaru objętości w całym zakresie pomiarowym jest mniejszy niż 6%. Aktualna wartość płynu jest wyświetlana na pasku LED w celu szybkiego poinformowania personel, dodatkowo układ mam możliwość alarmowania o zbyt niskim poziomie płynu.* (**Pojemnościowy pomiar objętości płynu infuzyjnego)**

Słowa kluczowe: płyn infuzyjny, pomiar pojemności, pomiar objętości, NE555
Keywords: infusion fluid, capacity measurement, volume measurement, NE555,

Introduction

The use of intravenous medications is very common, both during medical procedures and surgeries, as well as during recovery and therapy. The advantage of intravenous injections is that medications and other medical fluids administered in this way immediately interact with the body, producing the expected therapeutic effects within a few seconds, regardless of the patient's well-being and consciousness. In cases where precise administration of medication in a specific time regime is required, infusion pumps are used [1]. However, these devices are expensive and typically limited to surgical and medical procedures. In other cases, drip infusion sets are used. They are common, inexpensive, and highly reliable. However, situations such as air embolism, blood reflux, or tubing disconnection require monitoring of the infused fluid volume to the patient. Additionally, automated monitoring of the infusion process relieves the medical staff and ensures high-quality patient care.

Systems for monitoring intravenous infusion employ various techniques for measuring the fluid volume and perform different functions. Generally, they can be divided into alarm systems and monitoring systems. Alarm systems primarily focus on alerting the medical staff about low fluid levels in the reservoir using audible, visual, or dedicated computer application signals. An example of a low fluid level alarm system is presented in [2], where RFID tags are attached to the fluid containers. The tags gain communication capabilities only when the fluid is below the tag's antenna. The advantage of this solution is the lack of tag power supply requirement and their small size. In [3], a system utilizing the change in capacitance of a capacitor attached to the infusion bottle is presented. In this arrangement, a slotted capacitor is attached at a critical point, and a decrease in the fluid level below the capacitor plates leads to a decrease in capacitance, triggering an alarm.

In monitoring systems, continuous monitoring of the fluid volume or flow is implemented. The volume of the infusion fluid is typically measured using either mass-based or time domain reflectometry (TDR) methods. The mass-based method involves measuring the mass of the container with the infusion fluid using strain gauge load cells. Based on this information, a microcontroller controlling the process calculates the current fluid volume, and when threshold values are exceeded, an alarm signal is sent to the personnel [4, 5]. In the TDR method, the monitored system is stimulated by an appropriate electromagnetic signal, usually a step voltage pulse, which propagates through a probe; any change in impedance causes partial reflection of the propagating signal. The probe, shaped like two strips, is attached to the container housing. In such conditions, the characteristic impedance of the probe depends on the surrounding medium. At the air-liquid interface, a significant impedance change occurs due to the change in dielectric permittivity of the media, leading to a significant change in the reflection coefficient. By analyzing the reflection coefficient change over time, the distance from the probe's beginning to the liquid surface in the container can be determined [6, 7]. Despite its low measurement error, this method is relatively complex to implement.

The current volume of the infusion fluid can also be estimated based on the flow measurement in a drip set. Two dominant methods of drop counting are employed: the optical method and the capacitance method. In the optical method, a light source, often in the form of an LED, and a photodetector measuring the intensity of radiation are attached to the drip set. The falling droplet reduces the intensity of light reaching the detector, allowing for drop counting and determining the amount of milliliters that have been drained from the full container [8 – 10]. In the capacitance method, capacitor overlays in the shape of half cylinders are applied to the drip chamber. The falling droplet changes the electrical permittivity of the dielectric between the overlays, resulting in a momentary increase in the electrical capacitance of the system. This enables the calculation of the number of drops fallen over time and the current volume of the fluid in the container [11]. To increase accuracy, fusion methods are employed. In [12], simultaneous measurement of the container mass and drop flow using an optical method is observed. In [13], a system combining optical and capacitance sensors for simultaneous drop flow measurement is proposed.

In summary, methods based on container mass measurement are relatively simple to implement and exhibit good measurement accuracy. However, they increase the size of the drip stand, which can be inconvenient for the medical staff. TDR-based methods have the lowest measurement error but require a complex measurement system and data processing. Methods based on drop counting monitor infusion with high resolution but require calibration for each specific flow rate setting.

This article will discuss an intravenous infusion monitoring system using a capacitance-based method that covers the entire container. The construction of the system, its functions, and tests with an analysis of the obtained results will be presented.

Structure of the Measurement System

The described measurement system is designed to meet the following requirements:

- Continuous monitoring of the infusion process
- Alarm notification for reaching the empty threshold
- Easy installation in medical conditions
- No need for additional data processing
- Compatibility with different fluid containers
- Compact size, low weight, and low cost

Considering these requirements, the decision was made to implement a capacitance-based method. The structure of the measurement system is presented in Figure 1.

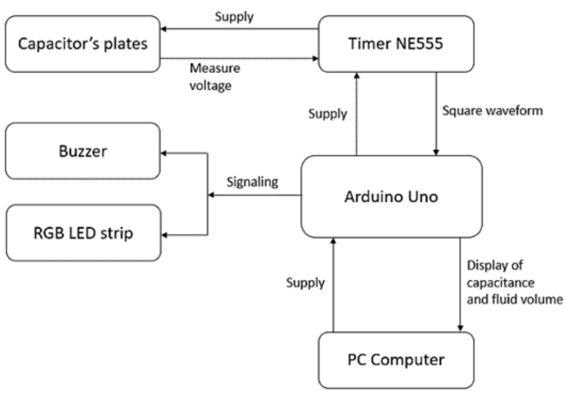

Fig. 1. Block structure of the measurement system.

The managed system was based on the popular Arduino Nano module, which contains the AVR ATmega328 microcontroller. An important element of the measurement system was the measurement capacitor, whose capacitance depended on the current volume of the infusion fluid in the container. The NE555 timer allowed for the determination of the capacitor charging frequency based on the generated square wave, and thus the measurement of the capacitance of interest. To visualize the current volume of the infusion fluid in the container, an RGB LED strip with eight diodes was used. This solution was chosen to improve readability compared to a small display, such as an OLED, allowing for a quick assessment of the current fluid volume in the container. Additionally, a 5V 12mm THT Buzzer was utilized to alert the medical personnel when the alarm threshold was exceeded. When the volume of the infusion fluid falls below the specified value, the Buzzer generates a continuous sound signal until the fluid volume is increased by replacing the container with a full one.

Two different fluid containers were used in the study: Bottle I with a total height of 210 mm and a width of 56 mm, and Bottle II with a total height of 195 mm and a width of 45 mm.

Therefore, a key aspect was to develop the shape and dimensions of the measurement capacitor. Initially, a slotted capacitor was employed, consisting of two aluminum foil strips measuring 86x10 mm with a 1 mm gap. Although this capacitor was easy to install, it exhibited a low capacitance in the range of 5.3 pF when the container was filled to 81%. Such a low capacitance measurement yielded inaccurate results, thus this shape was eliminated. Subsequently, a flat capacitor was constructed, with copper foil overlays measuring 110x30 mm placed on opposite sides of the container (48 mm), as shown in Figure 2.

The following capacitance values were obtained for the capacitor constructed in the above manner:
Container filled to 81%: C = 53.9pF
Container emptied to 18%: C = 4.3pF

In this case, the capacitance of the capacitor C is a parallel combination of two capacitors C1 and C2, where their capacitance depends on the level of the infusion fluid. The infusion fluid used is a 0.9% saline solution of sodium chloride (NaCl). The relative permittivity of such a solution is approximately εr2=80. The infusion fluid often contains medications and vitamins, but they have a negligible effect on the electrical permittivity.

$$(1)\ C = C1 + C2 = \frac{\varepsilon o * \varepsilon r1 * w * h1}{d} + \frac{\varepsilon o * \varepsilon r2 * w * h2}{d}$$

Where: εo - electric permittivity of vacuum εr1 - electric permittivity of the bottle enclosure and air εr2 - electric permittivity of the bottle enclosure and infusion fluid h1 - height of the air level on the capacitor lining height of the infusion fluid level on the capacitor lining w - width of the capacitor lining (30mm) d - distance between the linings (56mm)

To facilitate the installation of the system in a hospital environment, a universal housing with built-in capacitor plates was created.

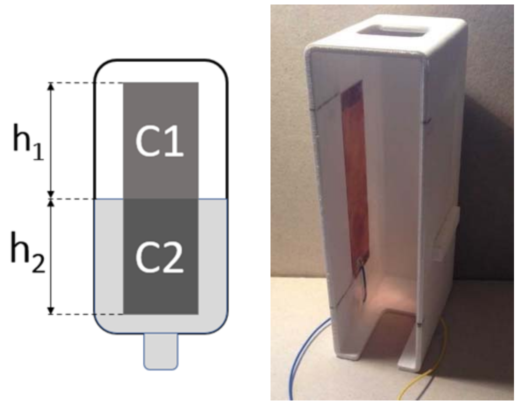

Fig. 2 Structure of the measurement capacitor, and the housing

The first algorithm for measuring electrical capacitance utilized an Arduino Uno module and the Capacitor library. This library enables capacitance measurement within the range of 0.2 pF to 100 μF without the need for additional components. However, due to a large variation in measured capacitance values, this solution was abandoned.

In the algorithm implemented for the development of the measurement system, the frequency of capacitor charging was measured instead of the time, as the latter occurs very rapidly. The operational algorithm of the system is presented in Figure 3.

The first step of the program involved measuring time using the micros() function. This function returns the number of microseconds that have elapsed since the Arduino was powered on. The implementation of the micros() function involved reading the current time in microseconds, assigning the measured value to a variable, and calculating the difference between the current time and the stored time. Finally, the current time was stored by assigning it to another variable.

After storing the current time, the charging frequency of the tested capacitor was determined based on Equation 2.

(2) $$f = \frac{n}{t}$$

Where: f - frequency of capacitor charging processes, expressed in [Hz] n - number of rising edges, [-] t - duration of one charging period, expressed in [s]

After determining the frequency, the capacitance of the tested capacitor is calculated, and the obtained electrical capacitance is converted into the current volume of the fluid in the container. In the next step, selected data is displayed on the Serial Monitor, allowing for easy reading and analysis of the results. At the end of the loop, a condition is checked - whether the measured volume of fluid is less than the alarm threshold. If the infusion fluid volume is less than or equal to 110 ml, the user will be alerted by activating the buzzer.

The last step is to display the current value of the infusion fluid volume in the container using an RGB LED bar. By turning on/off the corresponding number of RGB LEDs, the variable responsible for the number of rising edges is reset. After this operation, the program returns to the beginning of the loop.

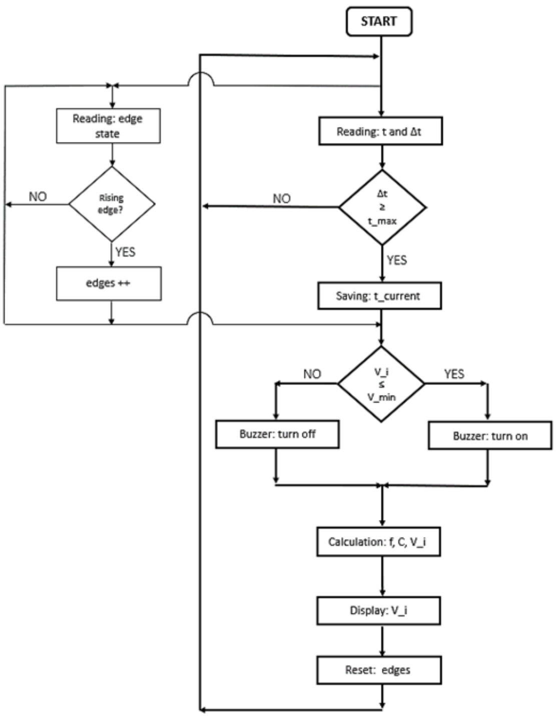

Fig. 3. Block structure of information flow and measurement execution in the system

One of the stages of testing the developed system was to determine the range of measured electrical capacitance values. Based on the collected measurements, it was found that the measurement range of the system ranged from 3.3pF to 100nF.

The next stage of testing involved determining the measurement error of the electrical capacitance values measured by the developed system. For this purpose, a series of reference capacitance measurements were carried out in the range of 3 to 91pF. The relative error for the tested capacitance values is presented in Figure 4.

Based on the collected results, it was determined that the smallest error occurred for a capacitor with a capacitance of 91.10pF and was 0.25%, while the largest error value was obtained for a capacitor with a capacitance of 11.70pF, which was 2.56%. Such error values are acceptable for assessing the volume of infusion fluid.

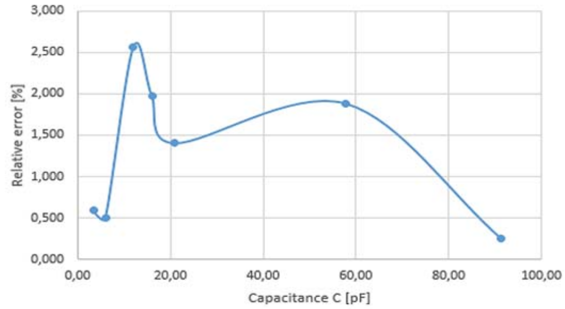

Fig. 4. Relative error as a function of measured capacitance.

As part of the project implementation, the system was calibrated, which involved scaling the measured electrical capacitance values to the corresponding volume of infusion fluid in the specific container. To achieve this, capacitance characteristics were first established as a function of the volume of infusion fluid. Then, an approximation was performed on the collected measurement points, allowing for the determination of polynomial coefficients of the function. This function was designed to estimate the current volume of infusion fluid in the container. Below, the tables of five measurement series are presented separately for the studied system during the infusion fluid emptying

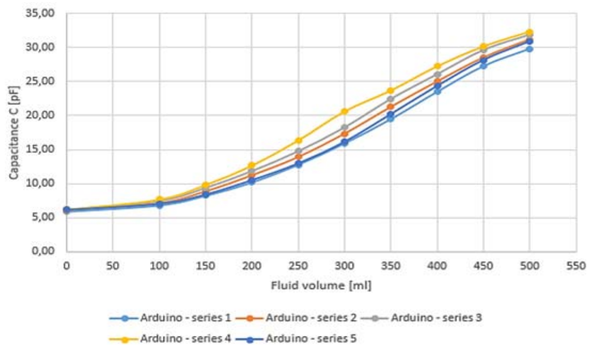

Fig. 5 Summary of five series of measurements for a circuit containing an Arduino and an NE555 timer.

At the end, an approximation was performed based on the measurement data collected during the emptying of the infusion fluid bottle. The general form of the applied approximation is as follows (3):

(3) $p(x) = p_1 x^n + p_2 x^{(n-1)} + \cdots + p_n x + p_{(n+1)}$

A cubic approximation was implemented, utilizing a third-degree polynomial. In the case of the collected measurements, it exhibits a very small error. The transposed function that allows for determining the volume of fluid as a function of the capacitance of the measuring capacitor is described by the equation 4 and shown in Figure 6:

(4) $p(x) = 0.0458x^3 - 2.8234x^2 + 68.5262x - 304.2507$

Below, there is a photo of the implemented system and a screenshot.

As part of the tests conducted on the developed system, a characteristic of the measured volume values was created, using the implemented system, as a function of the nominal-to-real volume values (Fig8). Additionally, the relative error values for the measured values were determined.

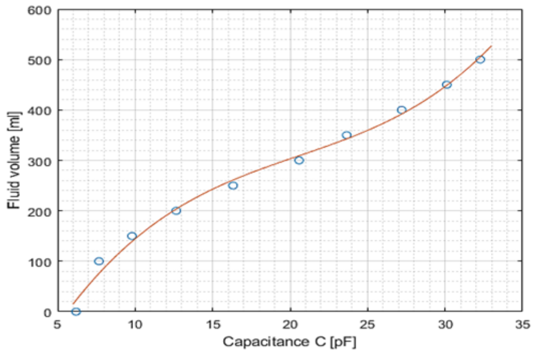

Fig. 6. Plot of the function of infusion fluid volume in relation to electrical capacity.

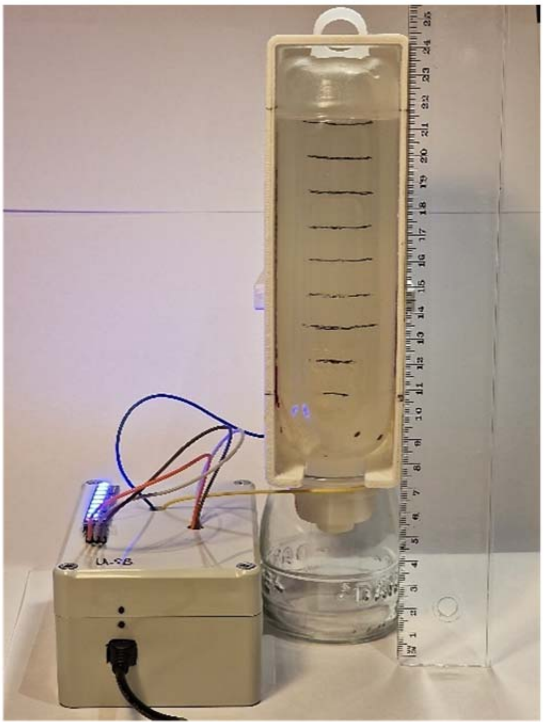
Fig. 7. The executed system

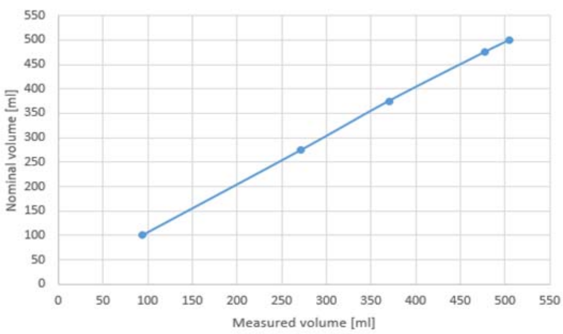

Fig 8 The measured value of fluid volume as a function of actual volume.

As you can see from Table 1, the developed system exhibited an error within the range of 0.4% to 1.5%. An exception occurred when there was 100 ml of fluid remaining in the bottle, where the error value was 6%. Based on this, it can be concluded that the performed approximation displayed high accuracy. Furthermore, the relationship between the measured fluid volume and the nominal volume was linear.

Another test involved signaling using RGB LEDs and a buzzer. When the fluid was depleted, one LED remained illuminated. The buzzer was activated when the volume value reached approximately 110 ml. The conducted tests demonstrated the proper functioning of the LED bar and the buzzer alarm.

Table 1 Final calibration data and measurement error

Point	Nominal Volume	Measured Volume	Relative Error
-	[ml]	[ml]	[%]
1	500	505	1.00
2	475	477	0.42
3	375	370	1.33
4	275	272	1.09
5	100	94	6.00

Conclusion

As part of the implemented project, a sensor was developed for measuring fluid volume based on copper adhesive tapes. Furthermore, a measurement system was created utilizing the NE555 timer, which indirectly measures the volume of the infusion fluid and directly determines the frequency of capacitor charging and its capacitance value. To enhance the usability of the system, a housing was designed and constructed, incorporating capacitor plates and allowing for the placement of a fluid reservoir.

Within the scope of this study, a series of measurements were conducted to establish the relationship between the current volume of the infusion fluid and the corresponding electrical capacitance value. Additionally, the measurement range of the implemented system and the relative error values for selected capacitance values were determined. Finally, functionality tests of the system were performed, including an RGB LED strip indicating the fluid level in the reservoir and a buzzer providing an alarm when the minimum allowable fluid volume is exceeded.

The tests show that the error of infusion fluid volume measurement is less than 6% for the entire measurement range. Above 40% filling, the error is less than 2%. Such accuracy meets the application requirements all too well. Measuring hysteresis was observed during testing, but considering that in the target conditions the system works only when emptying the IV fluid container, it is not significant.

Currently the system is being prepared for hospital tests, after which it will be extended by a network interface so that the current value of the volume of infusion fluid, which in addition to visualization on the LED bar is issued to the serial port of the microcontroller, is transferred to the database.

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