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PAPER

Design and Comparison of Low-Cost Urine Level Detection Systems for Critical Patients

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ABSTRACT

With the rise in size of the elderly population suffering from urinary incontinence and the number of bedridden patients, individuals providing assistance to the aforementioned groups suffer from the "caregiving burden" due to the time-demanding nature of home health care. The current study proposes a low-cost Internet of Things (IoT)-based urine monitoring system for detecting a critical urine level in a urine collection container and sending an SMS text message to alert the caregiver. Remotely informing the caregiver of the patient's urine level provides freedom of mobility. The proposed system consists of an Arduino microcontroller connected to a sensor measuring system and a SIM800L module with a SIM card. Three sensor measuring systems are suggested: Water Level Sensor, Ultrasonic Distance Sensor, and Weighing Scale Sensor. To compare the performance of the systems, 110 detection recordings from each system are used to construct a confusion matrix. The accuracy, precision, specificity, recall, and F-measure are computed for each system. Numerical and graphical analysis of the measurements show that the Water Level Sensor measurement system (accuracy: 0.96, precision: 0.98, specificity: 0.98, recall: 0.95, F-measure: 0.96) is the most reliable system, followed by the Weighing Scale Sensor (accuracy: 0.93, precision: 1, specificity: 0.936, recall: 0.88, F-measure: 0.93).

KEYWORDS

urine monitoring system, urine level detection, low-cost monitoring system, Internet of Things (IoT), homecare monitoring system, Arduino microcontroller

1 INTRODUCTION

As a result of the medical industry's fast development, as well as due to the general improvement of the living standard, there has recently been a global rise in the human life expectancy and consequently in the size of the elderly population. The number of people aged 65 years and older was 703 million in 2019 and is expected to reach 1.5 billion in 2050 [1]. Considering that most cultures assume responsibility towards patients requiring constant medical care, particularly the

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elderly, this has made senior and long-term care a highly demanding need burdening the working-age people by increasing the number of retired people they have to support [1–3]. Elderly persons generally receive caregiving assistance by family members, who often endure what is known as the caregiving burden due to the demanding nature of caring for someone with mental and physical illnesses [4].

Elderly suffering from conditions such as urinary incontinence as well as bedridden people, who are incapable of caring for their own selves, often require urine bags, which are attached to their bodies with urinary catheters [5]. Urinary incontinence, which most commonly affects old people and diabetic patients, is a debilitating health problem impacting 20 million people worldwide, as declared by the WHO. Defined as the uncontrolled loss of urine from the bladder or accidental leakage of urine, urinary incontinence is caused by the inability of the sphincter muscles to retain urine. Caring for individuals suffering from this challenge, mostly in nursing homes and personal residences, requires frequent attention and is a tedious commitment when compared to other diseases. Failure to closely tend to such patients results in bad smell, leakage, and discomfort [6]. As vesicoureteral reflux (VUR) results in bacterial infection, a urine bag must be emptied at least every four hours and before it attains a certain threshold [5, 7]. The manual inspection that is traditionally used to monitor the urine level is highly time and effort consuming.

In clinical situations where urinary drainage is required, it is achieved with the use of special medical devices known as urinary bladder catheters. Clinical indication for drainage determines the choice of catheter, which may be external (least invasive), transurethral, or suprapubic (most invasive) [8, 9]. Indications for urinary catheters include but are not limited to: urinary incontinence, urinary retention, post-surgery or post-injury management (e.g., pelvic fracture), monitoring of urine output in patients with critical illnesses, medical conditions including neurological illnesses such as dementia and other chronic illnesses, particularly in bedridden patients, as well as terminal care, especially in the elderly [8–11]. In critical care units, a Foley catheter is currently used to connect the bladder of the patient to a graduated container where collection of urine occurs [12]. In fact, among the urethral urinary catheters, the Foley catheter is the one most typically used. It comprises a double-lumen tube traversing the urethra into the bladder [13].

Factors such as water and nutrient intake, exercise, and environmental temperature, among others, influence the characteristics of urine variably. In healthy individuals, urine is pale yellow to deep amber, odorless, pH 4.5 to 8.0, with a specific gravity of 1.003 to 1.032 and an osmolarity of 40–1350 mOsmol/kg [14].

Normally, the daily urine volume produced by the kidneys ranges between one and two liters, with a minimum requirement of 500 mL/day excreted to ensure body waste removal. In the case of severe dehydration, renal disease, blood loss, diarrhea, cardiogenic shock, or kidney disease, urinary output drops below this level in a condition known as oliguria (300–500 mL/day). Anuria, on the other hand, is characterized by almost no urine production (<50 mL/day) due to conditions such as a kidney failure, enlarged prostate, or obstruction resulting from kidney stone or tumor. Polyuria occurs in situations such as diabetes mellitus, diabetes insipidus, sickle cell anemia, kidney disease, excess caffeine or alcohol, specific drugs such as diuretics, or excessive water intake and is characterized by elevated levels of urine production exceeding 2.5 L/day [12, 14, 15]. Generally, elderly people void 100–200 mL of urine at a time [10].

In our changing world, many automated systems are becoming reliable on the Internet of Things (IoT) [16]. In addition, a serious decline in the prices of IoT devices has been noted [17]. Therefore, smart technologies based on IoT have rapidly developed, resulting in an extensive range of advanced technological applications in various areas of life [18]. IoT, as a framework permitting the connection and communication between various sensors, devices, and systems, utilizes technology to monitor patients at all times and relay data about their health statuses. By utilizing an Internet connection, IoT improves communication between healthcare providers and patients. Through its precise and automatic data collection, IoT could have a growing influence on healthcare services, particularly for older people [1].

For instance, in 2010, a study proposed a system capable of automatically measuring, using a weight scale, the urine output of a critical care patient and sending the data to a personal computer (PC) by Bluetooth [19]. Another similar system, involving two different collectors and reed switches, was built for the same purpose in 2011 [20]. Later, in 2014, a urine bag monitoring system, equipped with a sensing accelerometer and a load cell, was presented by Cheng et al. to monitor all information of interest from the urine bag on a PC with the aid of the wireless ZigBee transmission technology [2]. Via Wi-Fi and a tension sensor, Chen et al. were capable of designing a real-time urine bag monitoring system of low cost in 2022 to record the event of urine volume exceeding a specific threshold [5]. In addition, an integrated circuit was built to aid in the hospital setting for urine output monitoring, through a study conducted in 2023, using a strain gauge load cell and the Wi-Fi network to collect data and display needed information on a mobile application [21]. Also, in 2023, Özer et al. created a urine drainage bag monitoring system to measure the weight of urine and warn, through Bluetooth communication, when the weight of the bag reaches a critical value [22].

On another note, some urine monitoring systems usually used in the market may cost up to $5000, which is not within everyone's reach, especially in less developed countries. Moreover, some monitoring devices lack practicality as they are very sensitive to external environmental factors [21].

For this paper, a comparative study was conducted to investigate the quality of three low-cost Arduino microcontroller-based measuring systems used for detecting a critical threshold of the urine volume in a container attached to a catheter and for notifying the caregiver from a distance. The three systems differ from each other by the major sensor used to detect a critical volume of the urine before the urine container fills up completely. Accordingly, the main purpose of this study is to propose the most effective prototype that can alleviate the burden of constant monitoring of the patient's urine bag, thus enabling caregivers to be notified about urine volume remotely, providing them the freedom of being distant from the patient while still being capable of taking care of their loved ones when required.

2 MATERIALS AND METHODS

In our study, the main proposed IoT-based urine monitoring system consists of the relatively low-cost Arduino Uno R3 microcontroller connected to one of the three sensor measuring systems (to be compared) used to detect an adjustable threshold of urine level and to the SIM800L module with a cell phone SIM card that are used to send a short message service (SMS) text message through the global system for mobile (GSM) network (see Figure 1). Controlling the communication between the different components of the system occurs through the Arduino Integrated Development Environment (IDE) software platform. The cost of the proposed system does not exceed 50 USD with low maintenance costs, which is relatively affordable.

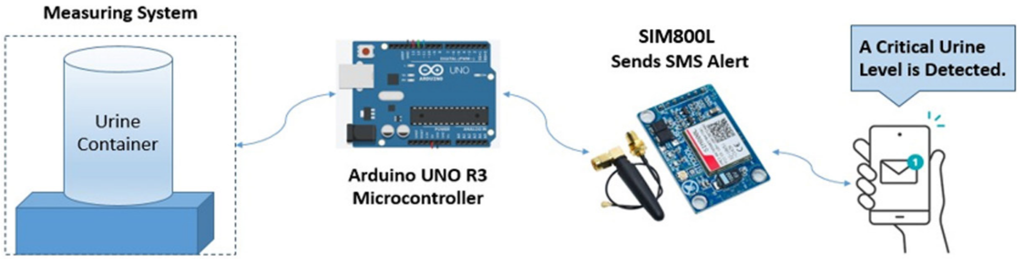

Fig. 1. The proposed IoT-based urine monitoring system

For practicality reasons, the liquid used in our measurements is water instead of urine. Considering that 95% of urine consists of water and the density of human urine (1.003–1.032 g/mL) is very close to the density of water (1.000 g/mL), this exchange has no effect on the results of the current study.

The main concern in our study is to compare the performance of three different sensor measuring systems: the water level sensor, the ultrasonic distance sensor, and the weighing scale sensor. The three systems were selected based on the following criteria: low cost, suitable range of measurement, and more availability in the market.

It is important to note that the mechanism of sensing for each measuring system is unique.

- **Measuring system 1: Water Level Sensor.** The Water Level Sensor, with a measuring range of four cm, consists of five bare power copper lines interlaced with five bare sense copper lines in a manner where two consecutive power lines have a sense line between them. When dry, in the normal condition, sense and power lines are unconnected. They get connected when the sensor is immersed in water and form a bridge. The water level covering the sensor affects the resistance, where an increase in the water level results in a decrease in the resistance and eventually an increase in the conductance. The water level is determined by the output voltage generated by the Water Level Sensor, which is proportional to the resistance (see Figure 2).

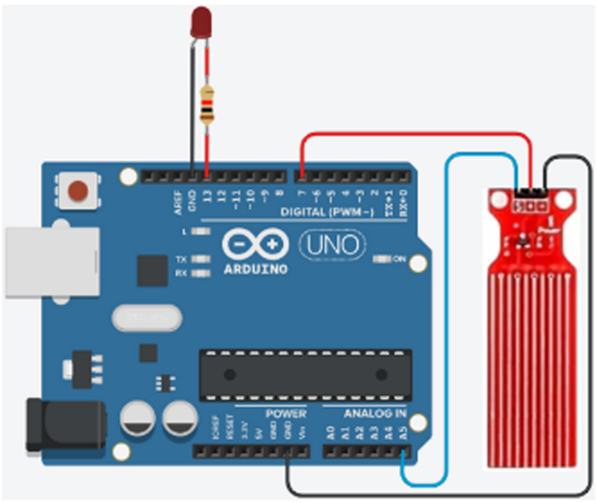

Fig. 2. Water Level Sensor measuring system

- **Measuring system 2: Ultrasonic Distance Sensor.** For the Ultrasonic Distance Sensor, the HC-SR04 sensor, which has a measuring range of 2 cm to 400 cm, is used in this study. It consists of two ultrasonic transducers: an emitter and a receiver. An ultrasound wave is emitted and received back after being reflected by an obstacle, which here is the water surface. Knowing the speed of ultrasound in air (about 343 m/s) and the time duration between sending and receiving the ultrasonic signal, the distance between the water surface and the Ultrasonic Distance Sensor can be calculated (see Figure 3).

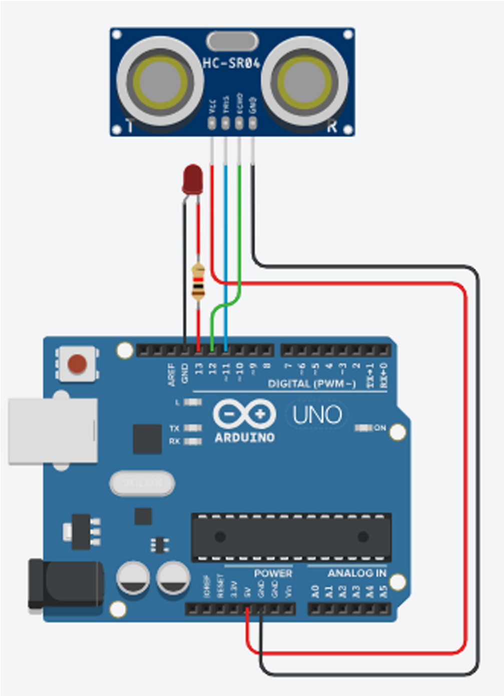

Fig. 3. Ultrasonic Distance Sensor measuring system

- **Measuring system 3: Weighing Scale Sensor.** This Weighing Scale Sensor measuring system involves a 20 kg load cell, with a measuring range of up to 20 kg, connected to the HX711 analog-to-digital converter. When the water load is applied to the strain gauge load cell, the gauge strains a slight amount proportional to the output voltage. Then, the 24-bit HX711 converts the small changes in strain from the load cell into changes in the output voltage, thus allowing the detection of the required amount of water (see Figure 4).

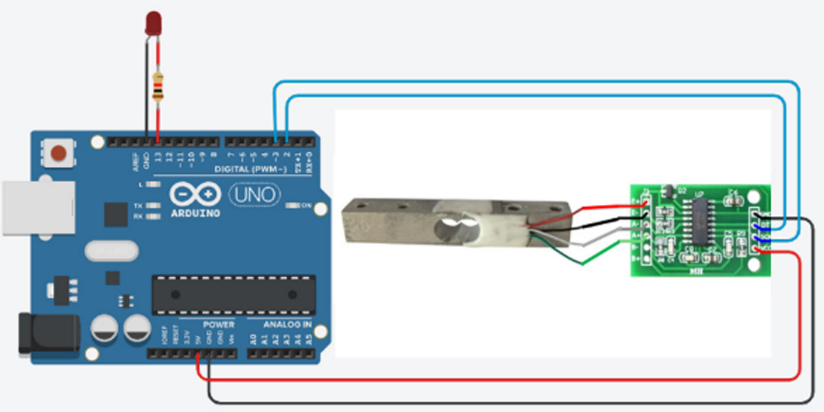

Fig. 4. Weighing Scale Sensor measuring system

As for the measurement procedure, one of the three measuring systems is connected to the remaining components of the whole proposed system (the Arduino UNO R3 microcontroller and the SIM800L module with a SIM card). A threshold value is chosen for the liquid level detection. This threshold is adjustable according to the volume of the container used for urine collection, taking into consideration the patient's urine output that might be affected by age, the type of disease, and/or medications taken. In the current study, the container used for water collection fills up to 1200 mL, and the threshold for water level detection is taken to be 900 mL (75% of the container's whole volume), which simulates the average real-life urine example requirements.

Increments of 20 mL of water are added gradually from 800 mL to 1000 mL. At each new volume reached, the measurements from the three proposed systems are recorded simultaneously. This is possible as the systems are mounted together on the liquid collection container for standardization reasons that are crucial for valid comparison among the systems (see Figure 5). The gradual increase in volume allows recording 11 measurements. This process is repeated 10 times, resulting in a total of 110 recordings for each of the three urine level detection systems.

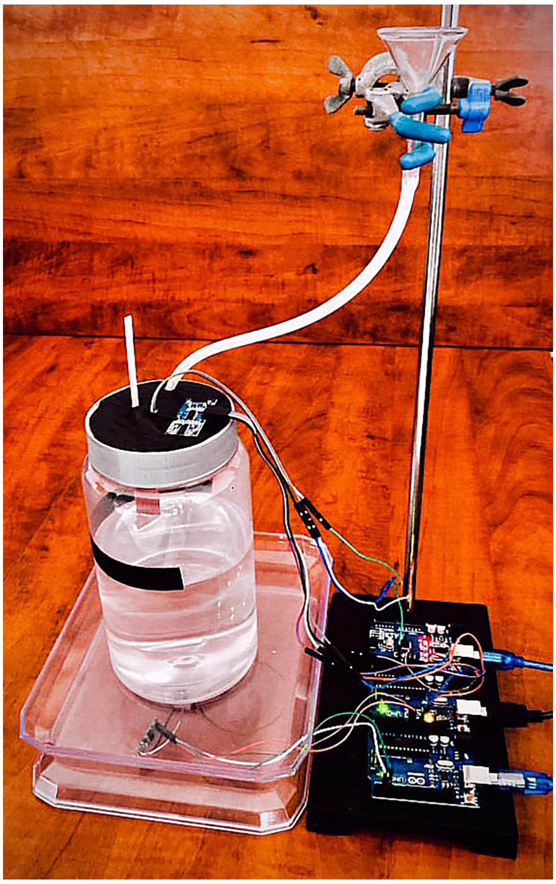

Fig. 5. The three proposed measuring systems mounted together on the liquid collection container during the recordings of the current study

The liquid level detection is recorded relative to the chosen threshold level for detection. A urine level detected by a system is recorded as a positive (P) detection; otherwise, if there is no detection by the system, the result is recorded as a negative (N) detection. Moreover, each of the three proposed systems may detect the threshold of interest at different liquid levels, which means that the detection of each system at a certain liquid level may be either a true (T) detection or a false (F) detection. Consequently, one of four possible recordings for each system at a specific liquid level could be recorded: a urine level detected at the threshold level or higher is recorded as a true positive (TP) detection, a urine level detected below the threshold level is recorded as a false positive (FP) detection, a urine level not detected at the threshold level or higher is recorded as a false negative (FN) detection, and a urine level not detected below the threshold level is recorded as a true negative (TN) detection (see Figure 6).

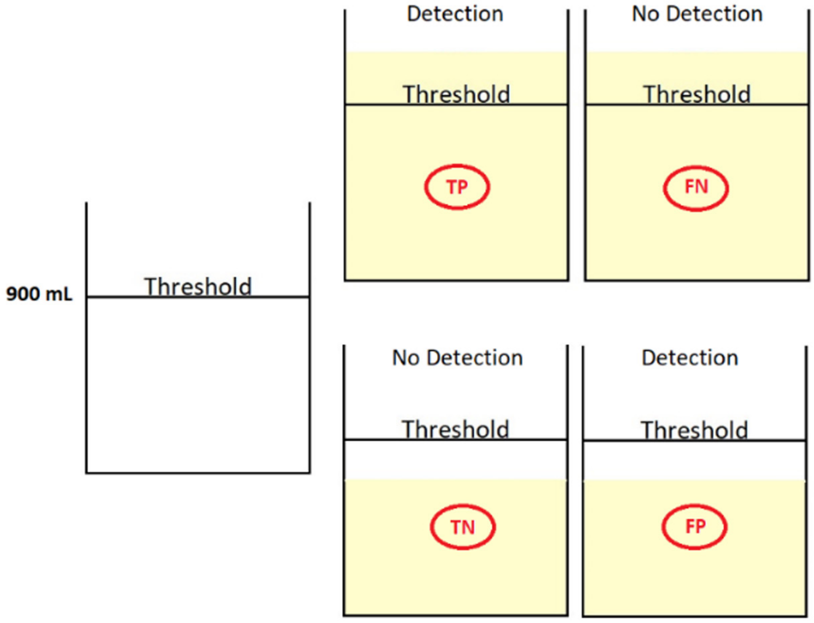

Fig. 6. The four possible recordings by the system at a specific urine level relative to the threshold level

At the end of the measuring process, after all the detections are recorded, a confusion matrix is constructed for each of the three proposed measuring systems in order to compare their performance. This comparison is applied according to computed measures of accuracy, precision, specificity, recall, and F-measure. Accuracy indicates how close a measurement is to the true value; in other words, it indicates the rate at which the measuring system is correct (see Eq. 1). On the other hand, *precision* refers to how close results are to one another (see Eq. 2). Regarding specificity, it is the proportion of TN detections out of all actual negative cases (TN and FP) (see Eq. 3). Likewise, recall measures how often the detection system correctly identifies TP detections out of all actual positive cases (TP and FN) (see Eq. 4). The F-measure is often used to evaluate the performance of the detection system on a scale of 0 to 1 (where 1 indicates a perfect detection system), in an attempt to balance precision and recall of the system (taking the coefficient β of relative importance of precision and recall as 1) (see Eq. 5).

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN} \quad (1)$$

$$Precision = \frac{TP}{TP + FP} \quad (2)$$

$$Specificity = \frac{TN}{TN + FP} \quad (3)$$

$$Recall = \frac{TP}{TP + FN} \quad (4)$$

$$F\_measure = \frac{(1+\beta^2).Recall.Precision}{\beta^2.Recall + Precision} \quad (5)$$

3 RESULTS

After recording the water level detection measurements from the three proposed systems (Water Level Sensor, Ultrasonic Distance Sensor, and Weighing Scale Sensor) in the form of TP, FP, FN, and TN, a confusion matrix is constructed for each system showing the frequency of each of the four possible outcomes (TP, FP, FN, and TN) (see Figure 7).

Measuring System 1
Water Level Sensor

TP=57	FN=3
TN=49	FP=1

Measuring System 2
Ultrasonic Distance Sensor

TP=58	FN=2
TN=39	FP=11

Measuring System 3
Weighing Scale Sensor

TP=53	FN=7
TN=50	FP=0

Fig. 7. The confusion matrix for each proposed measuring system

With the purpose of comparison of the performance of the proposed measuring systems, the confusion matrices of the systems allow the calculation of the measures of interest: accuracy, precision, specificity, recall and F-measure (refer to Table 1).

Table 1. Accuracy, precision, specificity, recall, and F-measure of measuring systems

Measuring System	Accuracy	Precision	Specificity	Recall	F-Measure
Water Level Sensor	0.96	0.98	0.98	0.95	0.96
Ultrasonic Distance Sensor	0.88	0.84	0.78	0.96	0.89
Weighing Scale Sensor	0.93	1	0.936	0.88	0.93

In order to analyze the performance of the measuring systems regarding the first positive outcome detected by each system while gradually increasing the volume of water (with increments of 20 mL) in the liquid collection container, the first-time P detections are graphically presented for each system over 10 trials (see Figure 8).

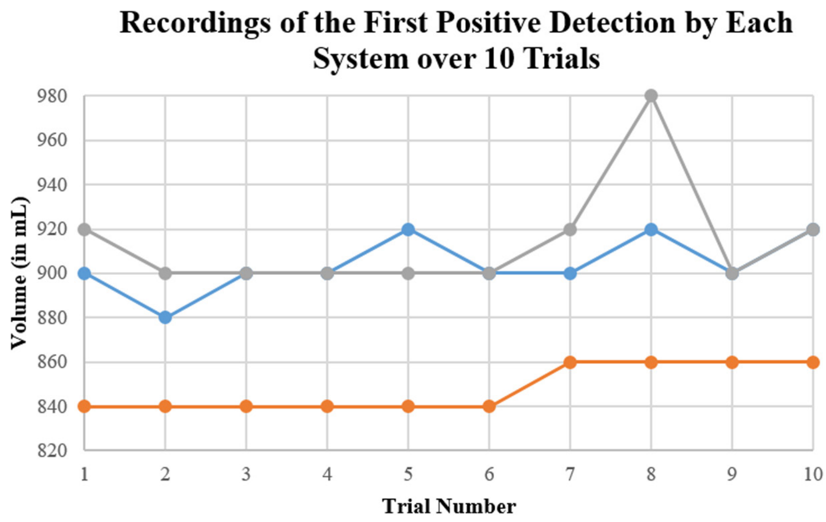

Fig. 8. Recordings of the first positive detection by each of the three proposed measuring systems: Water Level Sensor (Blue), Ultrasonic Distance Sensor (Orange), and Weighing Scale Sensor (Grey)

During the measurement procedure, each system may detect a positive outcome at a certain volume of water, and then it may give a negative outcome at a higher volume. Therefore, further visual analysis of the performance of the systems is required. After encoding a N detection of the water level relative to the specified threshold level by 0 and a P detection by 1, the average of all detections over 10 trials at a certain same volume is computed for each system. Consequently, we are able to graphically study how consistent the recordings from each system are (see Figure 9).

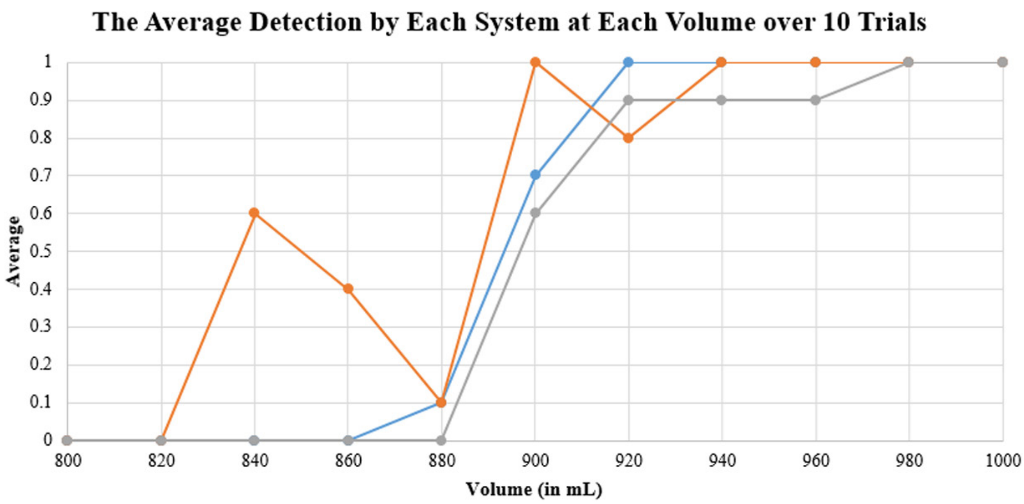

Fig. 9. The average detection (0: negative detection – 1: positive detection) by each of the three proposed measuring systems: Water Level Sensor (Blue), Ultrasonic Distance Sensor (Orange), and Weighing Scale Sensor (Grey)

4 DISCUSSION AND CONCLUSION

Improving quality of life worldwide is a commandment to go further in healthcare technology and invest in study and innovation in medical technologies such as wearable and assistive health devices [23]. Aiming to find solutions to common health problems, urinary home care technologies caught our attention.

Urinary incontinence is known as an involuntary leakage of urine, which is a common condition, especially among elderly individuals. Functional incontinence occurs when physical or cognitive impairments prevent a person from reaching the toilet in time. It is common in seniors with mobility issues or dementia [24].

Several traditional means are used for bedridden patients, such as disposable adult diapers, first created by the American inventor Marion Donovan in 1946. Diapers need special care to avoid rash, infection, bedsores, and bumps. Furthermore, several factors must be taken into consideration, such as good absorbency and leakage protection [25]. Bedpans are other assistive forms used for bed-confined individuals, but they are also surrounded by complications such as constipation and discomfort [26]. Moreover, urine bags, also known as urinary drainage bags or catheter bags, are commonly used. These need to be emptied periodically or replaced according to medical guidelines to minimize the risk of infection [5]. This is due to the fact that urine reflux, also known as VUR, can have significant implications for bedridden patients, especially those with compromised mobility.

All the previously mentioned means of urine healthcare assistance require the constant need to have a family member by the patient's side. Add to that the embarrassment factor and the loss of dignity due to inadequate patient privacy, which negatively affects the patient's psychology.

For all these reasons, it is crucial to choose adult incontinence aid methods that prevent the traditional side effects of bedridden urine management in the aim of maintaining patient comfort and health. Furthermore, in order to relieve the patient's family from the caregiving burden, technologies that support home care for the elderly and offer personalized assistance that addresses the patient's physical, emotional, and social needs are of our interest. In this context, urine level detection sensors can be integrated with a urine collection container to provide precise detection of a critical urine level and send an SMS to a caregiver's personal mobile phone device.

In the current study, we propose a low-cost urine monitoring system with the aim of the detection of a critical threshold of urine volume. Our presented system consists of an external urine collection container attached to a catheter. A microcontroller (Arduino UNO R3) is connected to a sensor and SIM800L with a SIM card to send an alerting SMS text message to the caregiver's mobile phone when the critical urine level is attained on the patient's side (see Figure 1). In order to recommend the most effective system, we conducted a comparative study on three possible sensor measuring systems: Water Level Sensor Measuring System (see Figure 2), Ultrasonic Distance Sensor Measuring System (see Figure 3), and Weighing Scale Sensor Measuring System (see Figure 4). The performance of the three systems is compared according to their measures of accuracy, precision, specificity, recall, and F-measure. Moreover, graphical interpretation of the first positive outcome detected by each system while gradually increasing the volume of liquid in the collection container (see Figure 8) and the average of all detections over 10 trials at a certain volume (see Figure 9) is performed to further investigate the performance of the systems.

Results show that the Water Level Sensor (Measuring system 1) is the most reliable system, followed by the Weighing Scale Measuring System (Measuring system 3). Table 1 shows that measuring system 1 has the highest accuracy (96%), specificity (98%), and F-measure (96%), measuring system 3 has the highest precision (100%), and measuring system 2 has the highest recall (96%). Moreover, one can notice that measuring system 2 shows the lowest accuracy, precision, specificity, and F-measure among the three investigated systems, and the computed measures for measuring system 1 (Water Level Sensor) are all 95% or above, which is a promising advantage over the other two systems (Weighing Scale Sensor and Ultrasonic Distance Sensor) (refer to Table 1).

As for the visual analysis of the performance of each system, it is noticed that, when taking into consideration the first positive detection by each system while gradually increasing the volume of liquid, the Water Level Sensor and the Weighing Scale Sensor were able to record a positive detection for the first-time, six times out of 10 trials, at exactly the specified critical threshold of 900 mL. The other four recordings were all detected very close to the threshold (900 ± 20 mL) by the Water Level Sensor, while three recordings were detected very close to the threshold (900 ± 20 mL) and one recording farther from the threshold (at 980 mL) by the Weighing Scale Sensor. As for the Ultrasonic Distance Sensor, all first-time positive detections were far from the critical threshold (at 840–860 mL) (see Figure 8). Similar results were obtained when taking into account the average of all detections over 10 trials at a certain volume. An ideal system is supposed to always return a 0 outcome (negative) until shifting to the case of always returning a 1 outcome (positive) when detecting the critical liquid threshold. The graphical result obtained by the Water Level Sensor is the closest to the ideal scenario, followed by the Weighing Scale Sensor. On the contrary, the graph of the Ultrasonic Distance Sensor is unstable with many fluctuations (see Figure 9).

Consequently, all numerical measures and graphical interpretations show that the most reliable sensor to be integrated in our proposed system is the Water Level Sensor. Results also show that the Weighing Scale Sensor is very reliable, while the Ultrasonic Distance Sensor is not suitable for such systems. On another note, it is crucial to mention practicality considerations, where external factors may affect the performance of the sensor measuring system. For instance, the Water Level Sensor is very sensitive to any possible vibration of the urine in the container, causing this sensor to be splashed with even a little amount of liquid, thus resulting in a false positive detection of the critical urine level. On the other hand, the Weighing Scale Sensor is less problematic regarding this issue, which might turn it into a more preferable sensor choice for similar proposed systems. Furthermore, efforts could be made to improve the design of the urine collection system in order to minimize possible external effects on the results of the measuring system. For example, a heavier or fixed collection system can be proposed.

In comparison to systems proposed by previous studies, such as the systems proposing the wireless communication to be performed via Bluetooth, Wi-Fi, or ZigBee [2, 5, 21, 22], our proposed system is based on data communication through the widely used GSM network. As for the purpose of the designed system, our study is similar to those suggested by Chen et al., Lee et al., and Özer et al. [2, 21, 22] regarding the use of a weighing load cell measuring sensor.

In conclusion, this study proposes a low-cost IoT urine level detection system, controlled by an Arduino microcontroller, that gives the freedom of mobility to caregivers of critical patients by sending an alerting text message (SMS) about a critical urine level to their cellular phones with the aid of the SIM800L module. Our current investigation shows that the best sensor to detect the critical urine level is, in the first place, the Water Level Sensor. This might be due to the fact that the Water Level Sensor is very sensitive, thus highly accurate, to the direct contact of even a small drop of water that eventually lowers the resistance of the sensor. The second studied sensor whose performance shows very good reliability is the Weighing Scale Sensor.

Improvements to the current proposed system can be done in the direction of minimizing external factors negatively affecting the detections of the system.

For instance, using waterproof measuring sensors can be investigated, such as waterproof ultrasonic distance sensors.

Furthermore, since our world is progressing toward implementing numerous IoT solutions in a smart house with sensors and devices interacting to deliver useful information [27], studies in the future can be performed with the aim of providing such solutions to the caregivers of critical patients at home. For instance, a urine monitoring system can be constructed to continuously measure the urine level and provide helpful information to the caregiver when being at a distance from the patient. For such a system, it is preferable to use the Weighing Scale Sensor, which is capable of continuously measuring the level of urine, over the Water Level Sensor, which has a measuring range limited to 4 cm.

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