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Development of an integrated smart monitoring system for enhanced peritoneal dialysis care

Sani Saminu*[a], Abdulrasaq Iliyas[a], Suleiman Abimbola Yahaya[a], Idris Oladele Muniru[a], Taiye Mary Ajibola[a], Morufu Olusola Ibitoye[a], Habib Muhammad Usman[b], and Sanusi Abdulrazaq[c]

[a]Department of Biomedical Engineering, University of Ilorin, Ilorin, Nigeria.
[b]Department of Electrical Engineering, Mewar University, Chittorgarh, Rajasthan, India.
[c]Department of Pharmaceutical and Medicinal Chemistry, University of Ilorin, Ilorin, Nigeria.

Abstract

Kidney removes wastes and extra water from the blood as urine and helps to maintain chemical balance in the body. The kidney controls blood pressure and production of red blood cells. When the kidneys are constrained, waste products and fluid build-up in the body system which causes swelling and bloating. Globally, Kidney disease is a great health challenge affecting millions of peoples at all ages. Dialysis is the removal of waste products and excess fluid from the blood when the kidney failed to function properly. Peritoneal dialysis is a home-based renal therapy for removal of excess fluid from the body for patients with constrained kidney. Integrating recent advancement in telemedicine and Internet of Medical Things (IoMT) into the conventional monitoring systems is a very vital in digital health technologies that improve the remote patient monitoring, empower patients, better care outcomes, and minimize cost related issues. The main aim of this paper is to design and integrate a smart monitoring system for supporting peritoneal dialysis care with the help of a sensor monitoring system and the Internet of Things (IoT) technology. Encompassing sensor integration (weight sensor), web application development/cloud-based platform Internet of Things and an API for notifications of real time data using Nodemailer. Emphasis will be placed on developing user-friendly interfaces for both patients and healthcare providers, ensuring easy access to real-time data, treatment reminders and communication channels. The system's ability to detect such small variations in weight measurements over time demonstrates and supports its suitability for applications requiring precise weight monitoring and management of the dialysate fluid movement in and out of the patient's systems.

Keywords: Kidney; Peritoneal dialysis; Weight sensor; Internet of Things.

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1. Introduction

The kidney controls blood pressure and production of red blood cells. When the kidneys are constrained, waste products and fluid build-up in the body system which causes swelling and bloating [1, 2]. Kidney disease affects the kidneys' ability to clean and filter out the blood. Chronic kidney disease is a long-term condition where the kidney do not work as they should. Without adequate treatments, the damage can get worse and the kidney may eventually stop working [3]. Dialysis is the removal of waste products and excess fluid from the blood when the kidney cannot work properly. Haemodialysis can be done at the centre (Hospital or Dialysis centre) and at home (Peritoneal dialysis) [4].

Peritoneal Dialysis (PD) is a widely used home-based treatment for patients with end-stage renal disease. The success of peritoneal dialysis relies heavily on patient's adherence and effective monitoring to prevent complications [5, 6]. There are two types of peritoneal dialysis: continuous cycling and continuous ambulatory. Continuous ambulatory does not require any machine while continuous cycling requires the use of a dialysis machine that can be used at home.

In-home dialysis has various advantages over hemodialysis, one which is cost of treatment. The major challenges of peritoneal dialysis treatment are the risk of complications such as infection, catheter malfunction, and peritonitis [7]. These complications are as a result of inadequate monitoring and management of the dialysate fluid movement in and out of the patient's systems. Traditional monitoring methods such as manual vital signs recording, manual assessment of dialysate, and physical examination of the catheter site are often time-consuming and prone to human error. To address these challenges, there is a need for the development and integration of a smart monitoring system for enhanced peritonea dialysis care [8].

In the context of PD, one major concern is the risk of peritonitis, a severe complication often linked to poor fluid monitoring and manual methods. Research by [9] and [10] emphasizes the need for advanced monitoring solutions to detect early signs of infection and improve technique adherence in PD patients. The lack of standardized monitoring procedures across regions further supports the need for automated systems that provide consistent and accurate data on patient status.

The use of telemedicine in peritoneal dialysis appears to generally result in a pleasant patient's experience [11]. Increased autonomy [12], fewer hospital visits (saving on travel, expense, and time), higher patients' satisfaction compared to phone contact [10], more confidence and a sense of increased safety [13], less sense of "being a burden" and more time for life [12].

Smart monitoring systems are being used in various healthcare applications, such as monitoring vital signs, medication adherence,

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*Corresponding author. Email: saminu.s@unilorin.edu.ng and disease progression. The use of smart monitoring systems has shown promising results in improving patient outcomes and reducing healthcare costs. In the context of peritoneal dialysis, smart monitoring systems can provide valuable information on the patient's fluid status, dialysis adequacy, and potential complications such as infections and peritonitis. A service-oriented, sensor cloud-based architecture for smart monitoring of water environments is termed "SmartWater," [14]. This system can be adapted for the monitoring of peritoneal dialysis fluid and can provide real-time data on fluid volume, composition, and temperature.

Real-time devices, monitoring devices and remote control can be made possible by the combination of a sensor monitoring device and internet of things (IoT) technologies. A smart monitoring and controlling system for household appliances was built by [15] using LoRa-based IoT. For COVID-19 patients, [16] suggested an Internet of Things-based smart monitoring and emergency alarm system. Another area of peritoneal dialysis care that could be observed by smart monitoring devices is patient adherence to treatment guidelines. A smart monitoring and controlling system for agricultural pumps was created by [17]. It makes use of LoRa IoT technology to monitor pump performance and regulate water flow. This method could also be applied in a home-based dialysis system to reduce the prevalence of infections in the patient undergoing the treatment.

It was reported by [18] that amyloid-beta plasma levels in humans and attenuates Alzheimer-associated phenotypes in an APP/PS1 mouse model. This finding suggests that PD may have neuroprotective effects, and a smart monitoring system that can track and monitor patients' cognitive function and detect early signs of neurological decline may help improve patient outcomes. The limited resource settings went through some challenges in providing renal replacement therapy to patients with chronic kidney disease [19]. A smart monitoring system that is cost-effective and easy to use may help improve access to PD in these settings and improve patient outcomes.

This research will offer important insights into the development and use of IoT-based smart monitoring systems for medical purposes. It can be modified to monitor patients with chronic kidney diseases by offering real-time monitoring and early detection of potential difficulties. The development and integration of a smart monitoring system for better peritoneal dialysis care can raise the standard of care for patients with chronic kidney disease. Remote monitoring and control of dialysis fluid and other medical equipment can be made possible by the integration of smart alarm systems and the Internet of Things.

2. Materials and methods

This section focuses on the design process of integrating smart monitoring system for enhanced peritoneal dialysis care. The study involved two stages: the design of the sensor system into the peritoneal dialysis bag and the transmission of the dialysate flow parameters into the cloud-web based Internet of Things couple with the notification alert system.

The system's components and functions which illustrates the data flow and decision-making processes to control events within the system are shown in Fig. 1. Fig. 2 provides a clear representation of how different parts of the system interact and work together to ensure efficient management of events in the proposed system.

2.1. Weight sensor

The sensor network is the main component of the system as it captures and transmits data from the patient's PD bag to the cloud-based platform. The sensor was used to measure the weight of the PD bag as the dialysate is flowing into the peritoneum. This study demonstrates that sensor networks can be used for continuous monitoring and data collection. Initially, an Ultrasonic sensor was the proposed sensor to be used for the system. Ultrasonic sensors rely on the sound waves; therefore, it struggles with surfaces that absorb sound like soft fabrics or foam, or surfaces that have complex shapes, causing irregular reflections. The material of the bag can affect the accuracy of the ultrasonic sensor. The dialysate fluid bag is made of a material that absorbs sound and it is very flexible. It distorts the sound waves leading to inaccurate measurements. Irregular shapes or folds in the bag can also affect the readings. Therefore, after implementation on the bag it was discovered that an ultrasonic sensor cannot monitor the bag fluid (dialysate solution) from outside unless it is exposed to the fluid without any interference. Exposing the sensor to the fluid can lead to contamination and risk of infection of the dialysate solution. This development leads to the use of a weight sensor instead of an ultrasonic sensor.

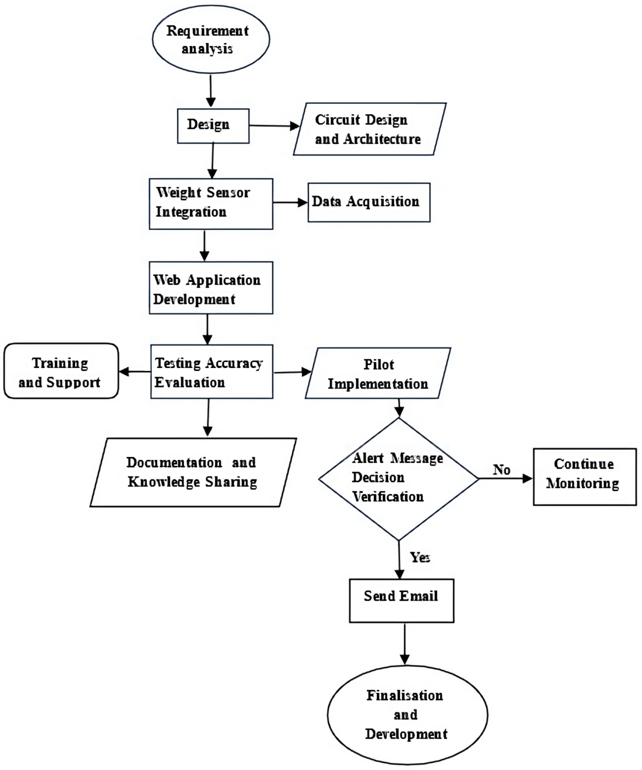


Figure 1: Flow chart of the proposed peritoneal dialysis monitoring system.

A weight sensor with load cell is a transducer that converts a mechanical force into an electrical signal. These sensors are widely used in various applications where accurate measurement of weight is necessary. They operate based on the principle of strain gauges which change resistance in proportional to the applied force, allowing the weight sensor to measure the force accurately.

2.2. HX711 load cell amplifier

HX711 is a precision 24-bit analog-to-digital converter (ADC) designed specifically for weigh scales and industrial control applications to interface directly with a bridge sensor. The HX711 not only amplifies the low-level signal from the load cell but also converts it into a digital signal that can be processed by a microcontroller. It has a unique properties of low power consumption that provide stable and accurate reading.

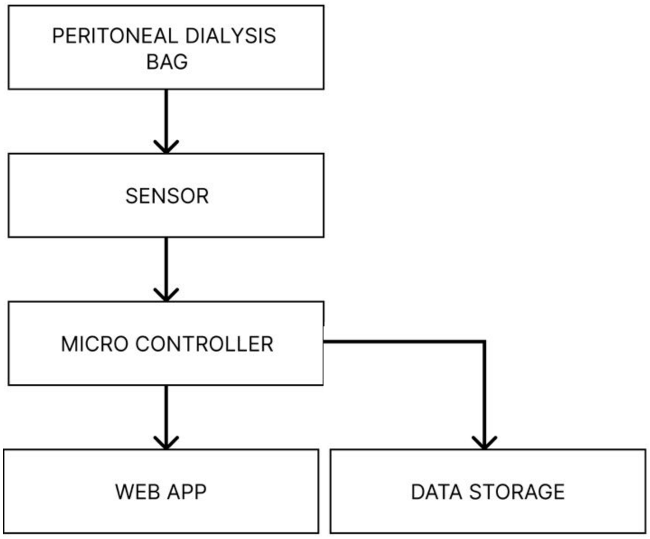


Figure 2: Block diagram of the proposed peritoneal dialysis monitoring system.

2.3. ESP32 overview

The second component of the proposed smart monitoring system is the microcontroller. The microcontroller used is an ESP32 which is responsible for transmitting and processing data from the sensor network to the cloud-based platform for analysis. The microcontroller system is essential for the timely and accurate transmission of data.

The ESP32 is a powerful and a versatile microcontroller developed by Espressif Systems. It is widely used in IoT applications due to its robust feature set which includes WiFi and Bluetooth connectivity, multiple GPIO pins and support for various protocols and sensors. In this work, ESP32 was used to receive data from the load cell amplifier and also to send data from to the cloud-based website through its Wi-Fi feature by sending and getting post request.

3. Implementation steps of the hardware integration/connection

A 12V battery which was regulated by LM7805V voltage regulator was connected to power the NodeMCU (ESP32 microcontroller). This serves as the power supply backup. Fig. 3 shows an overview of the circuit diagram of the proposed design and Fig. 4 shows the simulation circuit diagram.

3.1. Overview on the NODEMCU (ESP32) programming measurement of the weight

The load cell was paired with an HX711 amplifier to measure the weight of objects. The ESP32 microcontroller processes the weight data and transmits it to a web server. This system is particularly useful for applications requiring precise weight measurements and remote data monitoring.

3.1.1. Preparation of data

- Measure the weight using a sensor (e.g., load cell and HX711 amplifier).
- Convert the measured weight to a required format (e.g., percentage).

After the hardware connection has been made, the codes were uploaded through the Arduino Integrated development environment (IDE).

3.1.2. Data processing of the weight obtained

This section presents an overview of how the data collected from the load cell are being converted into percentage using a mathematical formula before it is processed into output on the cloud-web based platform.

Weight percentage is calculated using equation (1)

$$\text{weight percentage} = \frac{\text{measured weight}}{\text{max bag weight}} \times 100 \tag{1}$$

ESP32 microcontroller was utilized to interact with a web server via HTTP POST and GET requests. This enables remote monitoring and control capabilities, making the ESP32 an integral part of IoT applications. The following methodology outlines the steps required in sending and receiving data between the ESP32 and a web server.

Sending POST requests A POST request was used to send data to a web server. The ESP32 sends weight data as a JSON payload. The data received from the HX711 load cell amplifier was formatted into a JSON file in the Arduino IDE to Json file.

Sending GET requests A GET request was used to retrieve data from a web server. It was used for fetching configurations or updates.

3.1.3. Post Request Server

ServerName as used in the programming implementation specifies the address of the web server that the ESP32 communicates with to send and receive data. The URL defines the specific endpoint on the web server where the ESP32 sends data (e.g., weight measurements) or requests information (e.g., configuration data). It facilitates communication between the microcontroller and the web server.

3.1.4. Creation and integration of the cloud web-platform

The cloud-based Internet of Things (IoT) platform is used to store, analyze, and visualize data from the sensor network. The platform can be used to display real-time data to healthcare providers and patients, enabling them to make informed decisions quickly. The primary purpose of IoT is to make the systems work without human intervention or follow a self-reporting mechanism in real-time.

The website was created and hosted on onrender website with the meta name of www.bn-health.onrender.comwith the title name of Water Tank Level. The front end was done with javascript and backend on Node.js server. More deatails on the website is embedded and stored in a GitHub link (`https://github.com/nurmandev/water-level/blob/main/server.js`).

The website is a platform where the patient going through the care will register his details (username, name, age, height and weight). It includes a dashboard where the flow tank measures and updates the data received from the microcontroller the API created. It updates the physician in charge the real time reading/flow of the peritoneal bag and it also notifies through the encoded physician Gmail on the flow level.

The platform offers a user-friendly interface for patients and healthcare providers to access real-time data through a dashboard as shown in Fig. 5. Additionally, healthcare providers can retrieve patient information via a GET request API `https://bn-health.onrender.com/dashboard` or by login the patient username and password. `https://bn-health.onrender.com/endpoint` is the POST request handler for the ESP32 microcontroller. The platform's dashboard provides real-time updates on the fluid levels.

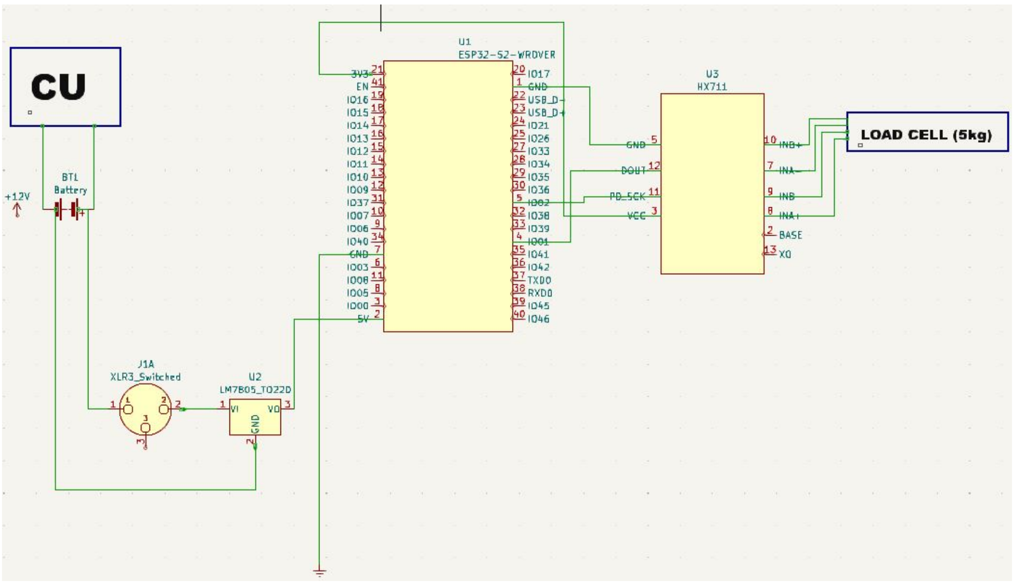


Figure 3: Circuit diagram of the sensor system, NodeMCU(ESP32) and the power supply unit.

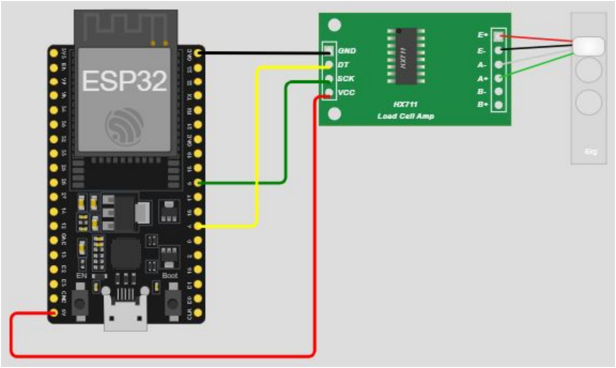
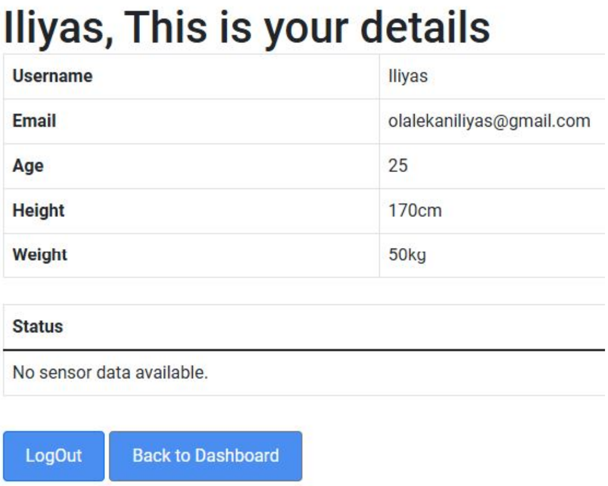


Figure 4: Simulation Circuit diagram of the weight sensor (HX711 amplifier and 5kg load cell) and the NodeMCU(ESP32).



Iliyas, This is your details

Username	Iliyas
Email	olalekaniliyas@gmail.com
Age	25
Height	170cm
Weight	50kg

Status
No sensor data available.

Figure 5: Patient's information dashboard.

3.1.5. API integration for GET request

A GET request API was created with Node.js and integrated it with an ESP32. An Express.js, a web application framework for Node.js was deployed to handle HTTP requests after a basic server was set up. This server will include routes to handle GET requests. The route processes incoming requests and send back a JSON response or any other data format required by the ESP32.

To implement the GET request handler, a define routes in Express.js server which will be responsible for handling the incoming GET requests from the ESP32 and responding with the necessary data. After setting up the server and routes, the Node.js server was tested on Thunder Postman in the Visual code before deploying it finally in the designed website for the project to test the GET request endpoints.

3.1.6. Integration of the notice alert system

The design and implementation of a notification system to alert healthcare providers on real-time fluid movement into the peritoneum of the patient or deviations from the expected treatment parameters. Nodemailer was integrated into the project by setting up a development environment with Node.js and initializing a new project. Nodemailer is a module for Node.js that allows you to send emails easily.

After a directory was created, the mailer was set up by creating a service credential with my email which is abulrasaqiliyas@gmail.com in form of Simple Mail Transfer Protocol (SMTP) just like Gmail. This transporter thereby handles the email sending process. In the Node.js server, an endpoint or function was created to handle email sending. This will involve defining a route that listens for incoming requests, constructs the email details (such as the recipient, subject, and body), and uses the transporter to send the email. The email functionality was tested by running it on the Node.js server and triggering the email sending function. This ensures that the emails are being sent and received correctly.

Finally, integrating this email functionality with ESP32 in the project by making HTTP requests to the Node.js server endpoint that handles email sending. This setup allows the ESP32 to trigger email notifications or alerts based on specific events or conditions which was programmed. It was programmed that if the weight percentage is less or equal to 10%, the water is low. If the weight percentage sent from the microcontroller is greater than or equal to

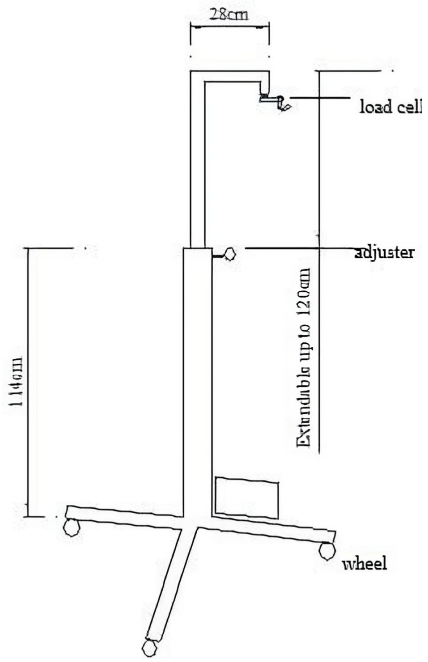


Figure 6: 2D design of the peritoneal dialysis stand.

Figure 7: Complete design and construction of the peritoneal dialysis stand.

70%, the water is full. Fig. 6 and Fig. 7 show the complete 2D design and the completed constructed peritoneal dialysis stand. While Fig. 8 and Fig. 9 show the pictorial depiction of when the Gmail notification was triggered by the device.

3.2. Flow rate based on weight changes

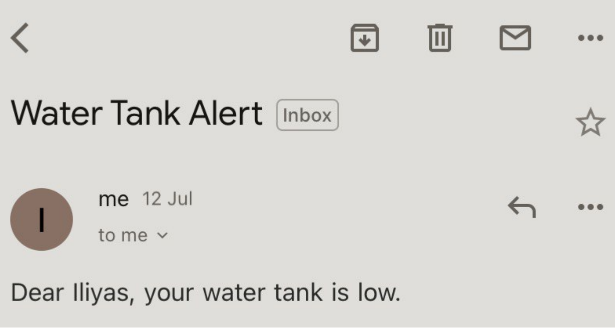
The system already monitors the weight of the dialysate bag over time, the flow rate can be estimated using the rate of change in weight. This utilizes the time-stamped weight data to infer the flow rate.

Although the current system does not directly measure fluid flow rate, it estimates the rate indirectly by analyzing the change in the bag's weight over time. The flow rate is calculated using the formula Flow Rate = $\frac{\Delta \text{weight}}{\Delta \text{time}}$ leveraging time-stamped weight data. This approach provides additional insights into the dialysis process without requiring hardware modifications, enhancing the system's functionality while staying within the scope of the project.

This study focuses on the measurement of the dialysate bag's weight to monitor fluid levels during peritoneal dialysis. While the system effectively tracks changes in the bag's weight, it does not currently measure the fluid flow rate. Incorporating flow rate measurement could provide additional insights into the treatment process, such as detecting obstructions or irregular fluid flow. However, this enhancement was deemed beyond the scope of the current project due to resource and technical constraints.

4. Results and discussion

Peritoneal dialysis (PD) is an effective method to manage chronic renal disease. However, a strict schedule of exchange can lead to peritonitis which is a severe complication that affects long-term success of PD. A smart monitoring system developed in this work can help to overcome these limitations by providing accurate data on the patient's health status, reducing the risk of peritonitis, and improving outcomes. This section will summarize the findings from several test carried out on the development and integration of a smart monitoring system for enhanced peritoneal dialysis care.

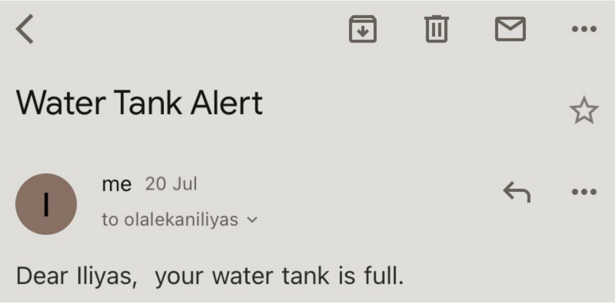


Water Tank Alert Inbox

I me 12 Jul
to me

Dear Iliyas, your water tank is low.

Figure 8: Water tank below 10% indicating low fluid level.



Water Tank Alert

I me 20 Jul
to olalekaniliyas

Dear Iliyas, your water tank is full.

Figure 9: Water tank above 70% indicating high fluid level.

Table 1: Tabular representation of the weight reading in kg, ml and the float percentage.

S.N	Volume of the bag (mL)	Weight of the bag (kg)	Float percentage
1.	500	0.5	100
2.	350	0.35	70
3.	250	0.25	50
4.	125	0.125	25
5.	50	0.05	10

Several tests were conducted on the developed monitoring system which involves the operation of the weight measurement system based on the ESP32 and interaction with a website server for data processing and sending emails. The system was functioning correctly and efficiently hence, achieved all the goals of the project.

4.1. Calibration of the load cell

The calibration factor is used to convert the raw data from the HX711 into meaningful weight measurements. The maximum weight of the bag is 500 ml, which is equivalent to 0.5 kg. therefore, the Maximum weight of the load cell is 5 kg.

After calibrating the load cell with a known weight of 0.5 kg equivalent to the weight of the bag, the raw reading of the HX711 is 0.001 kg after series of measurement without load on the load cell. Using the calibration formula (Eq. 2):

$$\text{Calibration Factor} = \frac{\text{known weight}}{\text{measured weight}} \tag{2}$$

Calibration Factor = $\frac{0.5}{0.001}$
Calibration Factor = 500
Hence, 500 is the calibration factor or value of the load cell.

4.2. Float percentage of the measured weight

The float percentage represents the weight measured by the load cell as a percentage of the target weight (0.5 kg).

This percentage is useful for monitoring how full or empty the bag is relative to its intended capacity. For instance, if the bag is supposed to be 0.5 kg when full, and the load cell measures 0.25 kg, the percentage will be 50%, indicating the bag is half full.

This percentage is sent to the cloud web-server (https://bn-health.onrender.com) through the POST-request and GET-request, providing real-time feedback on the bag's content.

Different values of float percentage shown in Table 1 was calculated for different measured weight of the bag of 0.5 kg, 0.3 kg, 0.25 kg, 0.125 kg, and 0.05 kg with the maximum weight of the as 0. 5 kg using Eq. 3.

$$\text{float percentage}=\frac{\text{measured weight}}{\text{maxBag weight}}\times 100\% \tag{3}$$

The value that triggers low water volume email notification.

4.2.1. Methods of data acquisition and operation of the smart monitoring system

As shown in Fig. 10, the data from monitoring device (ESP32 and weight sensor) and normal saline bag flow into the urinary bag were provided on a timely basis of delay of 30 seconds by combining the Internet of things and peritoneal bag flow. The process was supervised and recorded in Table 2. The peritoneal dialysate was obtained after weighing with a 5 kg load cell and HX711 amplifier during the process. Then, the data of normal saline bag (weight, time taken and float percentage) were transmitted to the real-time background system for peritoneal dialysis through the mobile network.

Table 2: Statistic of test and data obtained.

S/N	Weight	Time(s)	Flow percentage
1	0.50	0	100
2	0.46	30	92
3	0.40	60	80
4	0.34	90	68
5	0.27	120	54
6	0.21	150	42
7	0.16	180	32
8	0.12	210	24
9	0.10	240	20
10	0.08	270	16
11	0.05	300	10

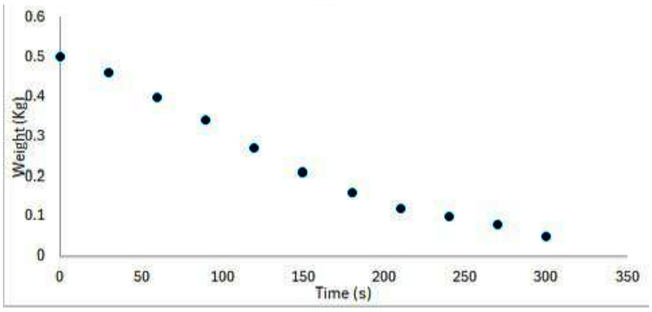


Figure 10: Graphical plot of weight in kg and time of the peritoneal bag process.

Statistic of the time against weight A statistical analysis was applied to peritoneal time and filtration rate using Microsoft excel with the results evaluated, as shown in Table 3.

Range The range is the difference between the maximum and minimum values in the dataset.

Range = Maximum Value–Minimum Value

Average (mean) The average (mean) is the sum of all values divided by the number of values.

$$\text{Mean} = \sum \frac{\text{weight}}{N} \tag{4}$$

Where N is the number of observations.

Standard deviation The standard deviation is a measure of the amount of variation or dispersion in a set of values.

$$\sigma = \sqrt{\frac{(x_i - mean)^2}{N-1}} \tag{5}$$

Where x_i represents each individual value, and N is the number of observations.

Variance The variance is the square of the standard deviation.
Variance = σ^2

$$\sigma^2 = \frac{0.2553}{10} \tag{6}$$

Table 3: Descriptive statistics of weight and time of the normal saline bag used in place of peritoneal bag.

	Range	Minimum Value	Maximum Value	Average Value		Standard Deviation	Variance
	Statistics	Statistics	Statistics	Statistics	Standard Error	Statistics	Statistics
Weight in kg	0.45	0.05	0.5	0.2445	0.0506	0.1597	0.0255
Time of peritoneal dialysis (s)	300	0	300	150	31.5	99.5	9900

Standard error The standard error is the standard deviation of the sample mean, calculated as:

$$\text{Standard Error} = \frac{\sigma}{\sqrt{N}} \tag{7}$$

The complete statistical result was tabulated and presented in Table 3.

The decreasing trend in weight measurements over time demonstrates that the load cell and HX711 amplifier integrated with the ESP32 are effective in capturing weight changes. The system's ability to detect such small variations supports its suitability for applications requiring precise weight monitoring. Relatively low standard deviation and standard error indicate that the measurements are consistent and reliable, which is critical for monitoring systems where accuracy is essential.

However, this study emphasized the clinical practical value of reviewing the results of equations. Furthermore, the weight of peritoneal dialysate bag can be predicted on the basis of historical data in the future, which is not widely used in the actual treatment.

4.3. System's accuracy

The system's accuracy was evaluated through calibration and testing of the load cell sensor with the HX711 amplifier. During calibration, a reference weight of 0.5 kg (equivalent to the dialysate bag) was used to determine the calibration factor, ensuring precise weight measurements. The results demonstrated an error margin of ±1% in weight measurement, which is within an acceptable range for medical applications. The statistical analysis of test results showed an accuracy of 98.2 % and a low standard deviation of approximately 0.159 kg were obtained, indicating consistency in measurements across multiple trials.

Furthermore, the system's data transmission was tested for reliability, with all data packets successfully sent to the cloud platform over a 24-hour period without any loss. These findings validate the system's capability to provide accurate and real-time weight monitoring for peritoneal dialysis care.

5. Conclusion

This project developed and integrated a smart monitoring system for enhanced peritoneal dialysis. This system leverages an ESP32 microcontroller to interface with a load cell sensor and transmit data to a cloud web-based platform. The server processes the data and sends notifications using Nodemailer when the fluid bag of 0.5kg reaches a predetermined level. The testing and analysis validated the system's functionality, accuracy and reliability therefore, achieving the project objectives. The float percentage represents the weight measured by the load cell as a percentage of the target weight (0.5 kg). This percentage is useful for monitoring how full or empty the bag is relative to its intended capacity. This percentage value is sent to the cloud web-server through the post request and get request, providing real-time feedback on the bag's content. By continuously optimizing and improving the system, peritoneal data may now be studied with greater precision and a wider range of applications than before. This is especially true for peritoneal dialysis data to minimize the complications as a result of inadequate monitoring and management of the dialysate fluid movement in and out of the patient's systems. In order to increase the curative impact, peritoneal medical services are being developed and applied with the goal of improving peritoneal medical services, identifying real-time treatment data transmission, fostering doctor-patient communication, and improving the mode of follow-up. Furthermore, as it develops, peritoneal data reliability and integrity are ensured, significantly lowering the possibility of data loss and omission and offering solid support for diagnosis and therapy. Our mission is to support the dissemination of knowledge on the use of telemedicine system data for automated diagnosis and treatment. Despite the fact that the remote system still has certain drawbacks and restrictions, our goal is to encourage data management that is thoughtful rather than merely treating it like a tool. Future studies may explore the integration of flow sensors to complement weight-based monitoring and further improve system functionality. Also, the possible future advancements can be aimed at increasing the security level, convenience and expandability of the system.

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