

Design and Validation of an ESP32-Based Digital Instrument for Real-Time Urine Volume Monitoring in Composite Textile Diapers

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Abstract

This paper introduces a novel biomedical digital instrument designed for the acquisition and local monitoring of urinary volume within a hydrophilic composite textile medium composed of cotton and Luffa cylindrical fabrics. The system utilizes a specialized sensor that transduces cumulative urine volume (Q) into an output voltage (U_s) under a controlled supply voltage. Third-order polynomial models characterizing the nonlinear relationships between voltage and volume were analytically derived from experimental data using MATLAB's Curve Fitting Tool.

The analog signals are digitized and processed using an ESP32 system-on-chip (SoC), chosen for its high performance and IoT capabilities. A custom C++ application developed within the Arduino IDE facilitates real-time signal processing and visualization. Comparative analysis confirms that the digital signals displayed on the virtual monitor accurately mirror the analog waveforms captured by a storage oscilloscope, validating the instrument's effectiveness for low-cost, high-quality smart diaper applications.

Keywords: Biomedical Instrumentation, ESP32 SoC, Smart Textiles, Urinary Incontinence Monitoring, Digital Signal Processing, MATLAB Curve Fitting.

INTRODUCTION

Urinary absorption diapers are widely used through the world in any population class, e.g., babies, women, elders and numerous persons affected by urinary incontinence. A few types of hyper absorbing diapers may cause skin cancer when wearing them for long time wetness period [1]. In order to ever come this problem, it is necessary to frequently change the diaper if is very wet. However, when and how can a person recognize a very wet diaper without looking or touching inside? This relevant question has motivated the apparition of diapers equipped with yellow bands, having the ability to turn into red under over wetting states [2]. Even in this case, a person who is far from the diaper wearer cannot observed any change in the diaper color state.

Fortunately, most modern diapers are smart products, i.e., they are equipped with embedded urinary sensors, allowing to automatically detect the urine volume Q inside the diaper, and then sent an alert signal to the wearer, if Q achieves a given overflow threshold. In most cases, the alert system is extensible to target remote persons via wireless transmission technology.

Ideally speaking, any modern microcontroller can be used for both digital signal processing tasks and wireless transmission transactions. However, a suitable choice of a microchip might yield lower building cost and better operational performance as it will be seen later in section II of this paper.

In these aforementioned cases, the urinary sensor is designed according to an equivalent physical quantity to be captured as image of the urine volume inside the diaper. As an implication, widely used equivalent physical quantity considered in existing urine sensors are: electric resistance ([3], [4], [5]), electric capacitance [6], thermal change [7], photo electronics [8], pressure [9], and wetness ([10], [11]).

However, most of these equivalent physical quantities require greedy realization and real time processing costs. In other to overcome these practical difficulties, a new urine sensor initiated and well tested in [12], is founded on the *output*

voltage image resulting from the electric effect of the cumulative urine inside the diaper. Therefore, the main aim of this paper is to use that simple urine sensor, as a basic module for the development of a pioneering urinary digital detection device in smart diapers. The remaining sections of this paper deals with research material and method, results and discussions, and conclusion.

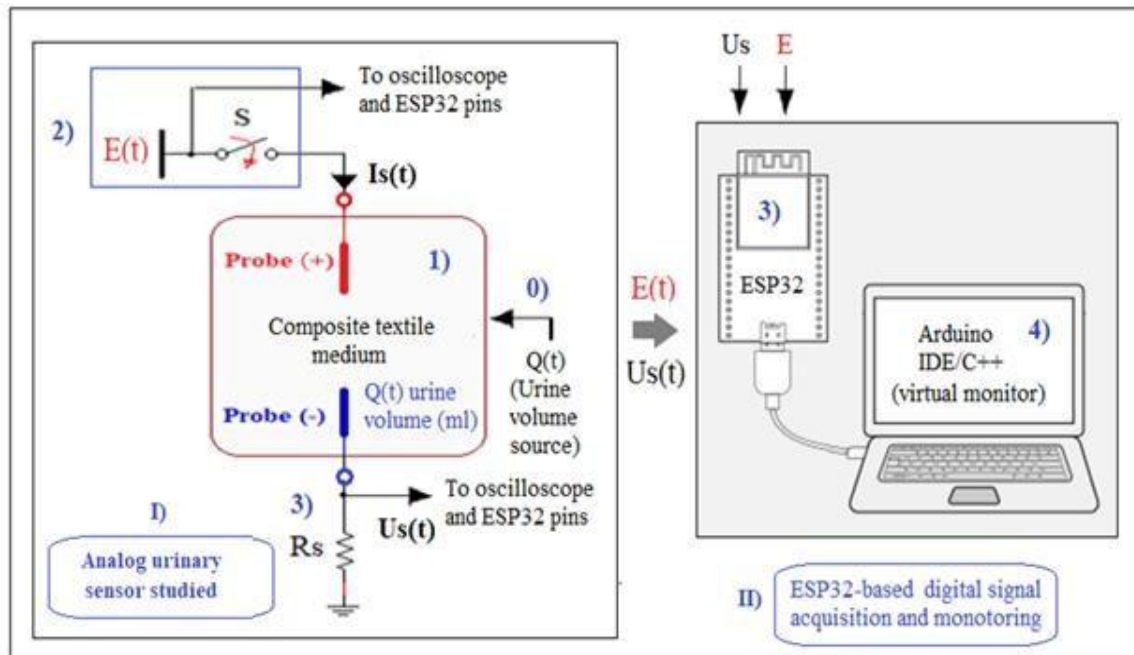


Fig. 1 Block diagram of the ESP32-Based urinary digital detection instrument

TOOLS AND METHOD

The block diagram of the urinary digital detection instrument initiated in this paper is presented in Fig. 1. It consists of two main parts I and II.

Recall on urinary sensor

Given the urinary sensor architecture and its operating principle, it is worth noting that:

- $Q_u(t)$ stands for the cumulative urine volume inside the composite textile medium at time t , with initial condition $Q_u(t) = 0$ if the whole textile medium is absolutely dry, and the switch S associated to the supply voltage $E(t)$ is closed;
- $I_s(t)$ is the electric current resulting from the conductive effect of the wet textile medium containing an urine volume $Q_u(t)$;
- $U_s(t)$ is the voltage image of $Q_u(t)$, which is a simple output signal to be detected and processed.
- The general operating law between $U_s(t)$ and $Q_u(t)$ is modelled by an electrodynamic differential equation, or by a first order lead/lag transfer function, with a short transient time period; equivalently;
- The static model $Q_u(t) = g(U_s(t))$ can be easily built at design time from combined experimental and analytical methods;
- $E(t)$ is a DC electric supply voltage of the sensor. It is not always a constant, since it is usually a battery, involving over time voltage decreasing;
- The resistance $R_s = 10 \text{ k}\Omega$ is quite suitable.

Fig. 2 presents a sample of real analog signals displayed on the oscilloscope screen for an experimental step response of the analog urinary sensor. Note that the transient time is less than a second. Then, it is shown how a static model $U_s(Q)$ or $Q(U_s)$ equivalently, can be analytically computed from associated experimental data using *Matlabcftool* (curve fitting tool).

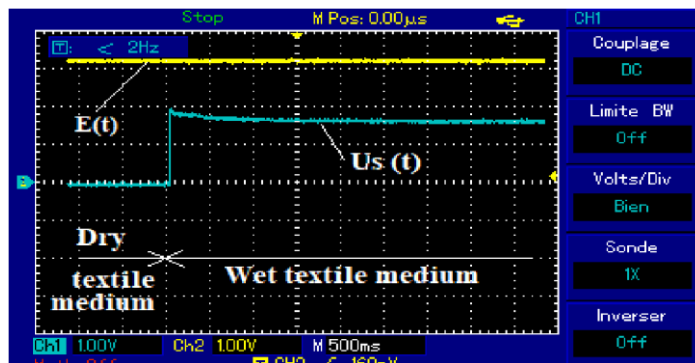


Fig. 2 Sample of analog signals $E(t)$ and $U_s(t)$ for the urinary sensor (under $Q = 40$ ml).

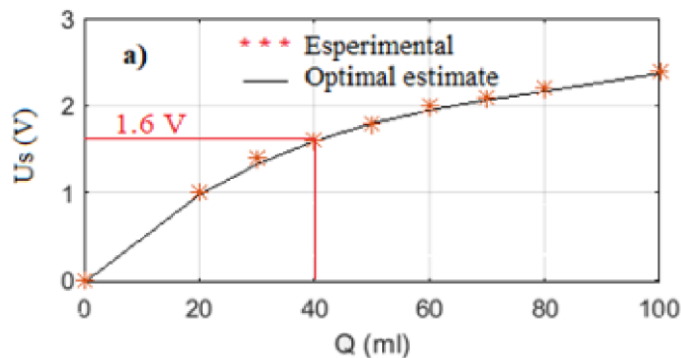


Fig. 3 Static model of $U_s(Q)$ developed in [14].

ESP32-based digital signal acquisition and monitoring

The ESP32 in Fig. 3 (part II), is a latest SOC (system-on-chip) device from *Espressif* Manufacturer. Compared to most SOC devices, it offers lower size, lower cost, higher degree of pins reconfigurations, higher types of standard instrumentation bus (I²S, I²C, USB), build-in Bluetooth (4.2 version, BLE types and Wifi (802.11, 2.2 to 2.5 GHz) modules, dual processing core, and a wider set of free tutorials for IoT development technology, etc. In addition, its driver for Arduino IDE-C++ programming is quite free. Therefore, it is the best choice for the development of IoT (Internet of Things) devices. opportunities.



Fig. 4 ESP32

In Fig. 6 (part II), a laptop computer is connected to the ESP32 via a USB port. It can be used at both development time and real time signal processing. Assuming that an Arduino IDE-C++ is preinstalled, then the laptop is used at development time for programing, compiling and downloading the target C++ program to the ESP32 application memory. In real time, it is used as a virtual plotting monitor of real data samples $\{E(kT_0), U_s(kT_0)\}$ received from the ESP32 via a USB cable, where T_0 is the sampling period, k being the sample index.

The flowchart of the target Arduino C++ application is presented in Fig. 5, and Fig. 6 shows the workbench image used experimental and testing needs.

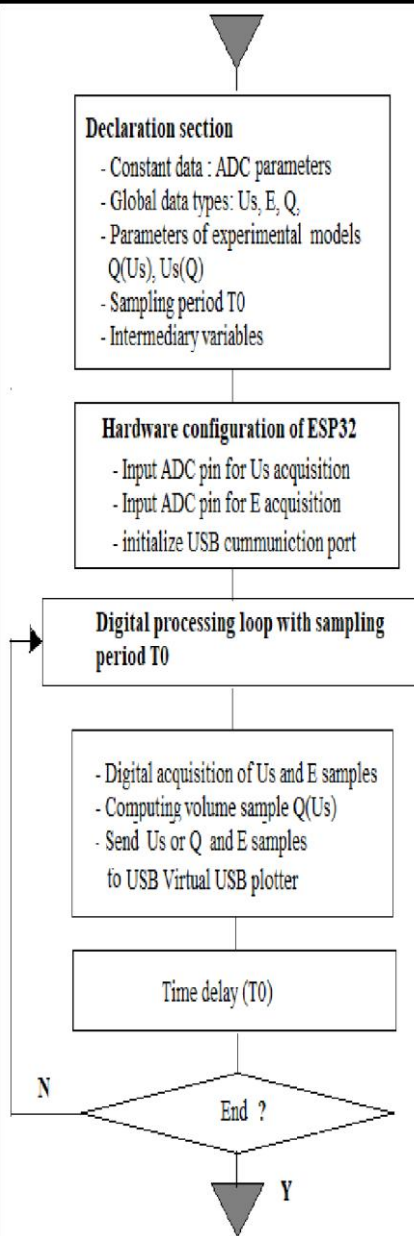
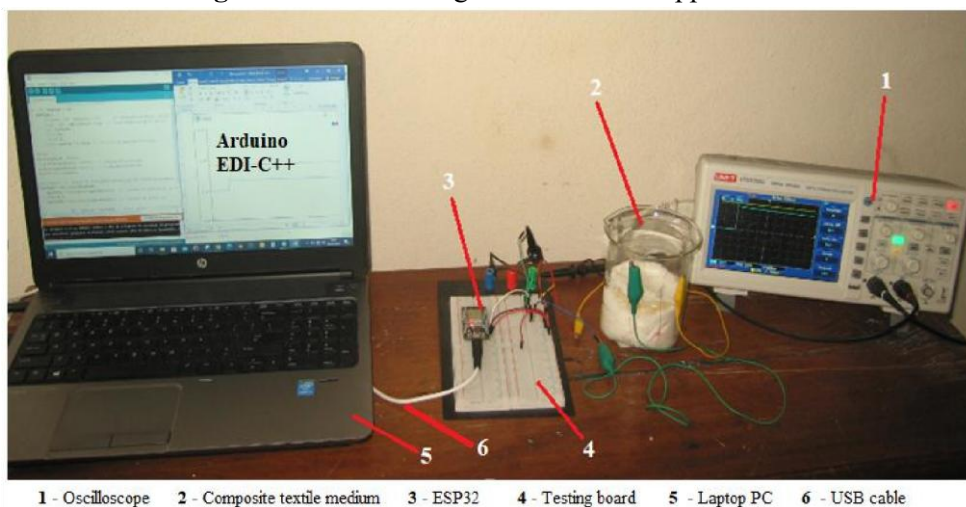


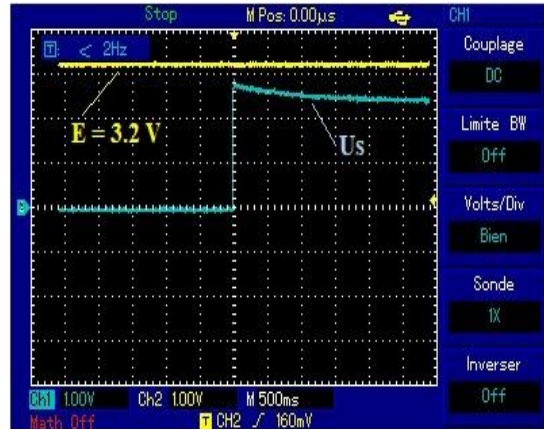
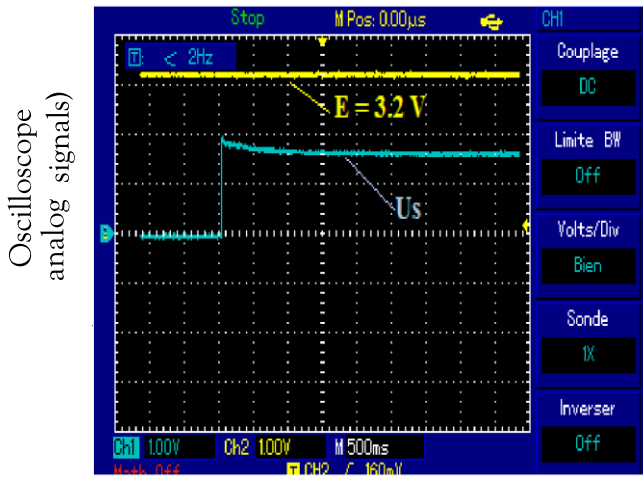
Fig. 5 Flowchart of target Arduino C++ application



1 - Oscilloscope 2 - Composite textile medium 3 - ESP32 4 - Testing board 5 - Laptop PC 6 - USB cable

Fig. 6 Workbench of a the proposed ESB32-based digital instrument for urinary data acquisition from a textile medium

- b) $Q_u = 100 \text{ ml}$, $U_s = 2.4 \text{ V}$, $U_{sm} = 2.6 \text{ V}$, $T_r = 2 \text{ s}$
 a) $Q_u = 40 \text{ ml}$, $U_s = 1.6 \text{ V}$, $U_{sm} = 2 \text{ V}$, $T_r = 1 \text{ s}$



- c) $Q_u = 40 \text{ ml}$, $U_s = 1.6 \text{ V}$, $U_{sm} = 2 \text{ V}$, $T_r = 1 \text{ s}$ d) $Q_u = 100 \text{ ml}$, $U_s = 2.4 \text{ V}$, $U_{sm} = 2.6 \text{ V}$, $T_r = 2 \text{ s}$

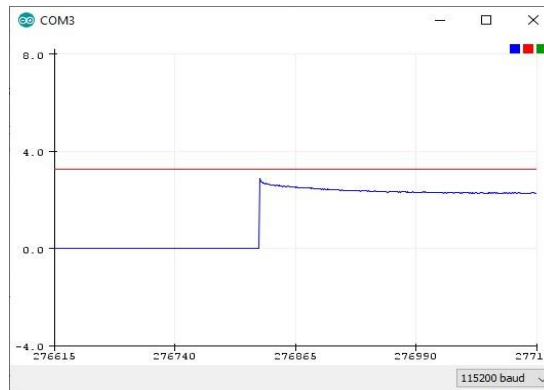


Fig. 7 Sample of signals ($E(t)$, $U_s(t)$) and their corresponding digital waveforms

Table -1 Characteristic of Workbench modules

No	Type	Model	Qualities
1	Oscilloscope	UTD2052CL	50 MHz, 500 MS/s, storage memory, USB connector for graphics saving
2	Composite textile medium	Cotton and Luffa layers	Sweetness, high urine absorption capacity
3	SOC device	WROOM32	IoT technology
4	Testing board	White	-
5	Laptop PC	DELL	2.40 GHz, Win 10
6	Android cable	USB	115000 bauds
7	Arduino	IDE-C++	1.8.12

The technical characteristics of the workbench modules presented in Fig. 6 are provided in Table 1. On the order hand, it is worth noting that:

- The total sampling period T (ms) of the ESP32-based digital processing loop, is a sum of times due to sequential tasks (i.e. digital computing T_d, USB communication T_c, and downstream delay T₀ (or sampling period equivalently)).
- The target C++ application embedded into ESP32 application, offers 216 Ko memory size according to the C++ compiler specifications, and the adopted sampling period is T₀ = 10 ms.
- In each real time digital processing loop, available sampled signals are sent to Arduino virtual monitor via an Android USB cable for textual or graphical visualization.

RESULTS AND DISCUSSIONS

However, each result presented in Fig. 7 deals with the step response over time of the composite textile medium for a fixed absorbed urine volume Q (ml). In smart diapers design, the static models between urine volume Q and its corresponding output image (i.e. U_s in our case) is more relevant, for signal acquisition and processing tasks. In this paper, the static analytical laws U_s(Q) and Q(U_s) are established in MATLAB/Cftool framework from their experimental data, according to third order polynomial shapes (1) and (2) respectively.

In Fig. 8, the graphs of experimental data and related analytical least square estimates are plotted for the sake of better visual comparison. As straightforward results, the direct urine absorption law (1) describes a static input-output model of the urine volume sensor, while its reverse function given by (2) is needed in the executable application program, for reliable reconstruction needs of the associated urine volume Q (ml) to be sent to a virtual terminal monitor. Of course, the urine volume samples Q (in ml) are physically more realistic than their related voltage samples U_s (in volt).

$$U_s(Q) = p_1 Q^3 + p_2 Q^2 + p_3 Q + p_4 \tag{1}$$

with

$$p_1 = 2.625e - 06, \quad p_2 = -0.0006439$$

$$p_3 = 0.0621, \quad p_4 = 0.002241$$

and

$$Q(U_s) = q_1 (U_s)^3 + q_2 (U_s)^2 + q_3 U_s + q_4 \tag{2}$$

with

$$q_1 = 10.87, \quad q_2 = -21.64 \quad q_3 = 30.97, \quad q_4 = -0.03052$$

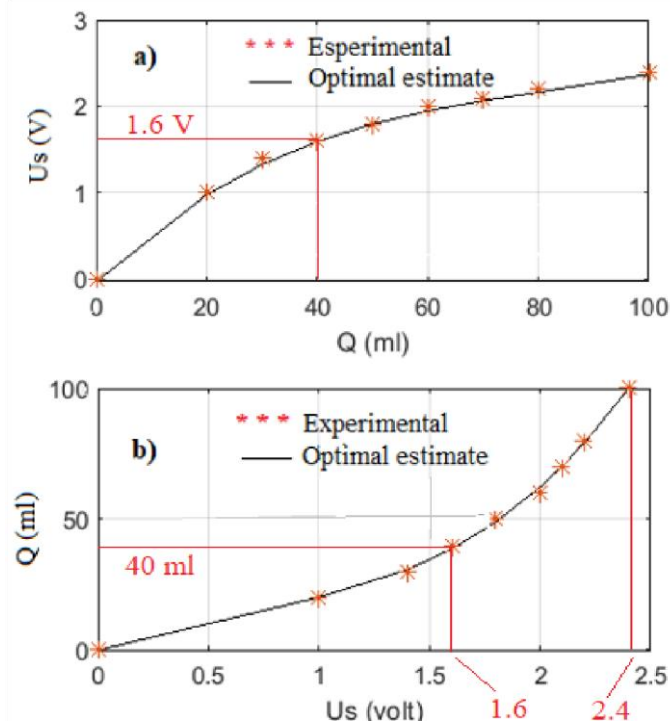


Fig. 8 Third order polynomial models of U_s(Q) and Q(U_s)

Fig. 9 shows how digital values of an arbitrary urine volume (e.g. Q = 65 ml), can be easily displayed on Arduino virtual USB plotter. Minor fluctuations observed might result to combined effects of both urinary diffusion noise through the

urine absorbing medium, and to a suboptimal choice of the sampling period $T_0 = 10$ ms. However, a simple first order IIR (infinite impulse response) filter can be used is necessary, to cancel these aforementioned noisy effects.

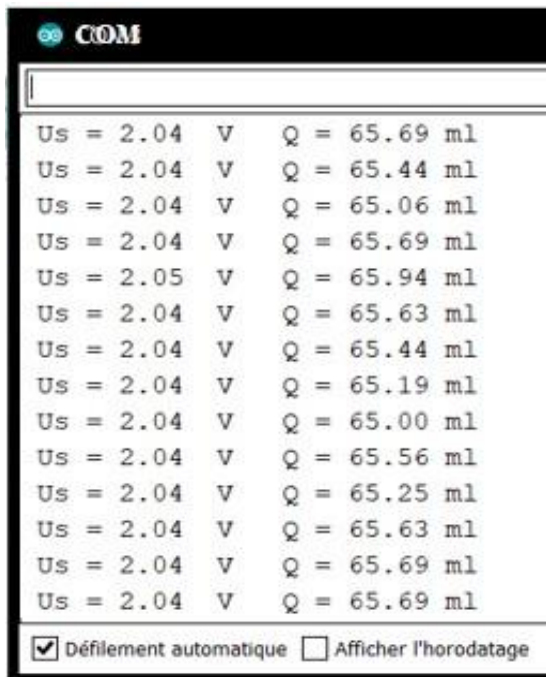


Fig. 9 Us and Q values in Arduino USB virtual monitor

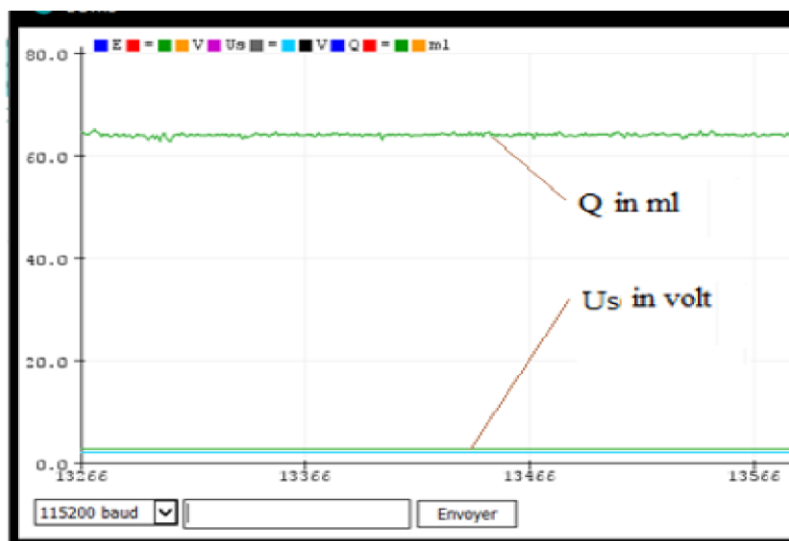


Fig. 10 Graphs of involved digital signals on Arduino virtual plotter

In Fig. 10, the graphs of digital signals $U(n)$ and $Qs(n)$ are visualized on Arduino USB virtual plotter, where n being the index of sampled data, within the integer range $13266 \leq n \leq 13566$ with length 300 samples.

Finally, the most relevant scientific merit of this paper, has been to develop and build a first pioneering well tested prototyping biomedical digital instrument, from a simple analog urinary sensor.

CONCLUSION

This study successfully demonstrated a pioneering biomedical instrument for the digital acquisition and monitoring of cumulative urine volume in multilayer composite textiles. The developed ESP32-based prototype combines structural simplicity with high operational flexibility and measurement fidelity.

The validation results indicate a high degree of accuracy in volume reconstruction using polynomial modeling, suggesting that this technology is a viable foundation for the next generation of cost-effective, wireless smart diapers for incontinence management. Future work will focus on extending these capabilities to wireless remote monitoring systems to further improve patient care.

Conflicts of Interest: All authors declare that they have no conflict of interest associated with this research work.

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