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A novel smart instrument for multilevel alerting and multivariable monitoring of urinary absorption process into a textile medium

RACHEL APOLINCE ASSONA NGUEFACK[1], JEAN MBIHI[1*], BRUNO KENFACK[2]

[1]*ENSET, University of Douala, Cameroon*
[2]*Faculty of Medicine, University of Dschang, Cameroon*

Abstract. This paper presents a novel instrumentation device for instantaneous digital acquisition and processing, of the urine flow absorbed by a textile medium. The proposed device is smart version of a basic instrument studied in previous research works. Arduino framework is used as the development tool of the main C++ instrumentation sketch for ESP32 microchip target. The proposed smart device owes its novelty to many relevant factors including a hardware simplicity of the unary sensor, a multilevel alerting strategy, as well as a multivariable monitoring process. In the wireless side, a serial Bluetooth terminal application is used as driver for smartphone-based virtual monitoring of involved output variables. Furthermore, an experimental workbench built for testing the proposed device is presented. Finally, the technical characteristics and experimental results obtained and presented in the paper, show the innovative nature of the proposed device for bioinstrumentation engineering.

Keywords: urinary flow, textile media, smart device, multilevel alerting, multivariable monitoring, Bluetooth terminal Application.

1. Introduction

The urinary detection instruments into textile media (e.g., diapers for babies, women, even urinary incontinent people), have been and remain a growing research topic in bioinstrumentation engineering. The classic types of this class of instruments [1]-[3], are *standalone* electronic devices, involving a local alarm to be activated when the urine quantity inside the diaper, is greater than a given

*Correspondence address: mbihidr@yahoo.fr

threshold. On the other hand, most modern urine detecting instruments involve smart operations [3]-[7], including automated instrumentation tasks and wireless communication capabilities. Fig. 1 shows a simplified block diagram of smart urinary detection devices. They are hybrid electronic instruments consisting of a urine sensor, an analog hardware interface, a digital signal acquisition and processing system, a controlled alarm and a WiFi communication terminal.

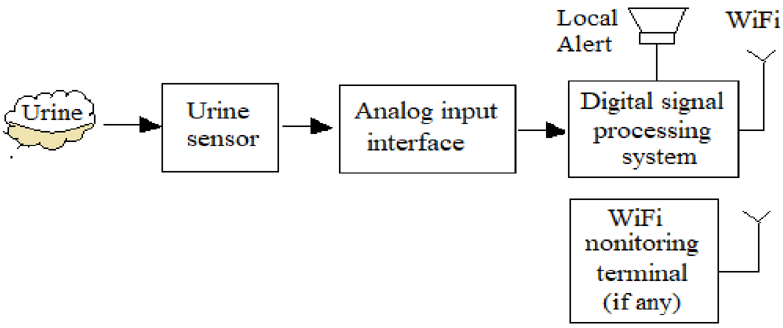


Fig. 1. Block diagram of smart urinary detection instruments.

However, most smart urine detecting instruments involves sensors with *intricate* output quantity, e.g., temperature, wetness, dielectric coefficient, resistivity, electric resistance, etc. In addition, other common weaknesses of existing smart urinary detecting device, are due to hardware interface complexity, single alert threshold, single variable monitoring process, etc. Therefore, in order to overcome these weaknesses, a basic ESP32-based urinary acquisition system, has been studied and successfully tested in our previous works ([8], [9]), where the cumulative urine volume Q (in ml) inside the textile medium, has been used as a suitable direct variable for the sake of better realistic monitoring output. Then, following significant basic works conducted in [8] and [9], the aim of this paper is to present a complete study of a novel type of smart detection instrument of urine flow inside textile media. The next sections of the paper deal with building schemes and tools, experimental study and conclusion.

2. Building schemes and tools

2.1. Overall block diagram

The first design tool of the novel smart urinary detection device is its block diagram depicted on Fig. 2. Its relevant parts are labelled from (a) to (e), where E stands for the power supplied voltage of the local module.

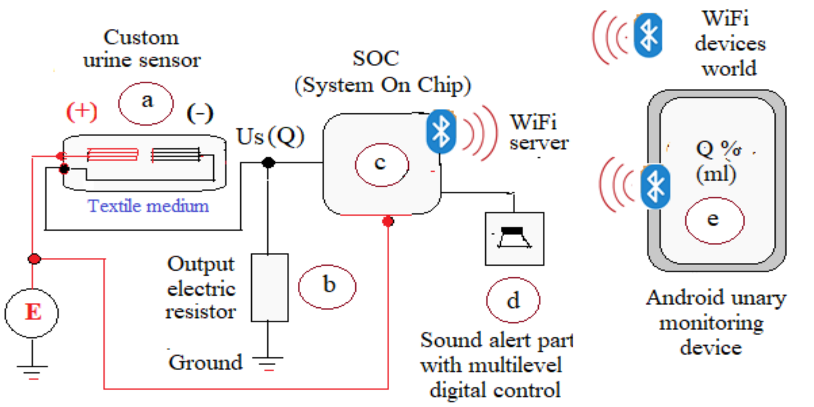


Fig. 2. Block diagram of the novel urinary detection/monitoring device.

2.2. Custom dual probes as urine sensor

It is worth noting in Fig. 2(a) that each of dual (positive and negative) urinary probes, is a think electric conductive wire, which can be easily printed or sewed on the textile layer. For an initial urine quantity Q = 0, the textile medium is dry and behaves as an open switch within the electric mesh {E, (+) probe, textile medium, (-) probe, resistor, ground}, in which case the output voltage Us(Q) = 0 V. Otherwise, a wet state of the textile medium due to a cumulative urine quantity Q inside the textile medium, incurs a corresponding output voltage Us(Q).

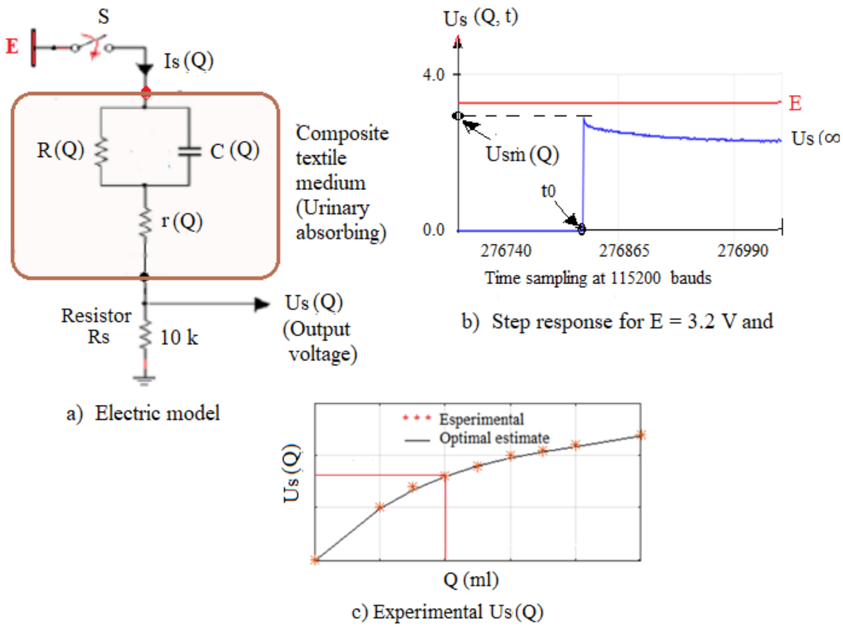


Fig. 3. Electric model and experimental behavior of a simple urinary sensor initiated in [8].

For brief recall needs, Fig. 3 shows relevant preliminary results published in [8], [9]. Theses results outline an electrical model of the unary absorbing textile medium (see Fig. 3a), as well as a sample of the corresponding response Us(Q, t) under a step control voltage E (see Fig. 3b), and the *steady input/output characteristic* Us(Q, ∞) in Fig. 3c given a dry state of the medium at initial time t_0. In addition, for a constant value of Rs, e.g., Rs = 10 kΩ, and given a suitable choice of t_∞ given t0 in Figure 3b, then unknown parameters r(Q),, R(Q), C(Q) of the sensor electric circuit recalled in Figure 3a, can be computed according to the set of steady equations (1) as developed earlier in [8]:

$$\begin{cases} r(Q) = Rs\dfrac{(E - Usm(Q))}{Usm(Q)} \\ Us(\infty) = \dfrac{Rs}{Rs + r(Q) + R(Q)}\, E \Rightarrow R(Q) = Rs\dfrac{E}{Us(Q,\infty)} - (Rs + r(Q)) \\ C(Q) = \dfrac{(Rs + r(Q) + R(Q))}{R(Q)\left(Rs + r(Q)\right)\ \log\left(\dfrac{R(Q)}{a\ (Rs + r(Q))}\right)}(tr(Q,\infty) - t0) \end{cases} \tag{1}$$

Following [9], the overall steady characteristic of Us(Q) could be rigorously computed from a experimental sample (2), with appropriate size M = 10, and suitable sampling period ΔQ_m, e.g., ΔQ_m, = 10 ml.

$$\{(Us(0), Q(0)), ((Us(1), Q(1)), \ldots, (Us(m), Q(m)), \ldots, (Us(M), Q(M))\} \tag{2}$$

Furthermore, an input-output steady characteristic Us(Q) given by (3) and its reverse function Q(Us) reported in (4), can be automatically computed from experimental data (2) as in [ ], using Matllab/CFTool framework.

$$Us(Q) = p_1Q^3 + p_2Q^2 + p_3Q + p_4 \tag{3}$$
$$Q(Us) = q_1(Us)^3 + q_1(Us)^2 + q_3Us + q_4 \tag{4}$$

On the other hand, unlike most modern urinary detection/monitoring schemes recalled in Fig. 1, the overall analog interfacing circuit which operates upstream the downstream digital processing part, is reduced to a piece of think and high precision custom sensor, without any explicit hardware interfacing circuit.

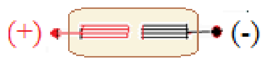
2.3. Digital acquisition and signal processing

It is also worth noting that, for the sake of minimal size and cost constraints, the ESP32 microchip used for digital signal processing communication tasks. As a significant profit, it provides embedded input-output instrumentation resources, and remote server/client communication capabilities, for Bluetooth monitoring terminals. Obviously, software tools are required for the development of instrumentation and WiFi service routines, and for the deployment of serial Bluetooth terminal applications.

2.4. Technical specifications of hardware tools

The whole hardware tools retained for a prototyping realization of the proposed novel bioinstrumentation device, are summarized in Table 4.

Table 1. Building hardware tools.

Label (Fig. 2)	**Type and Image**	**Relevant Characteristics**
E	USB power supply pin	3.2 V
(a) Textile medium with custom probes		02 think electric wires (printed/sewed on textile)
(b) Resistor		Resistance Rs = 10 kΩ Power = 1/4 Watt
(c) SOC DSP core	 ESP32 WROOM-32D	- Dual core, 80-240 MHZ - 2.6 $\leq$ Vcc $\leq$ 3.8 V - 2.5 to 2.5 GHz frequency - WiFi 802.11 b/g/n - Configurable ports (as analog or digital input/ output, PWM), 3.3V - Embedded Bluetooth or BLE 4.0 - Arduino IDE/C++ driver
(d) Sound device	 Universal active Buzzer	16 Ohms, 2 Khz, 3 V
(e) Remote Android terminal	Smartphone 	Samsung Galaxy Note 10^{+}

2.5. Software development and deployment tools

In the ESP32-WROOM-32 .side, Arduino IDE/C++ with a few preinstalled special libraries, are used to develop the application to be compiled and uploaded into ESP32, for real time instrumentation needs and Bluetooth communication services. Fig. 4 shows the flowchart of the main C++ sketch required for automation needs.

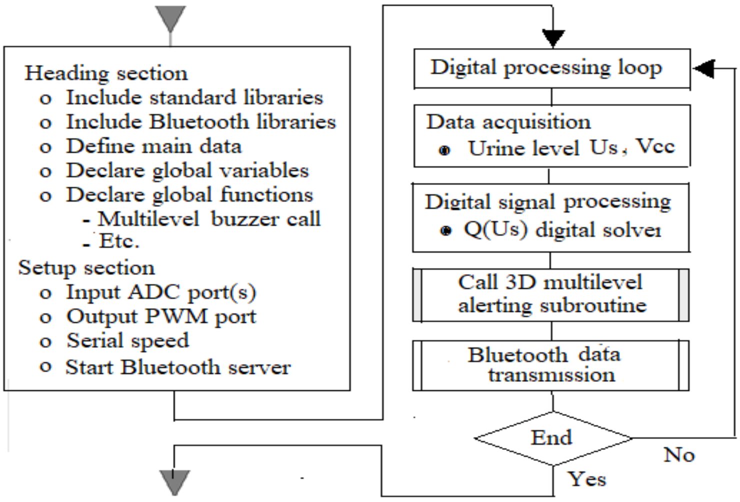


Fig. 4. Flowchart of the main Arduino C++ sketch for automation needs.

The *multilevel urinary alerting process* outlined in Fig. 4 is implemented as an Arduino C++ subroutine, according to a decision function Z = f(Vcc, Q) defined by (5). Obviously, the graphical morphology of (5) implemented using Matlab digital computing resources, is a 3D virtual model shown in Fig. 5.

$$Z = f(Vcc, Q) = \begin{cases} 2.7\ \mathrm{V} \le \mathrm{Vcc} \le 3.8\ \mathrm{V} \\ \begin{cases} 0 \le Q < 20\ \%, & \mathrm{Z} = 0 \\ 20\ \% \le Q < 80\ \%, & \mathrm{Z} = \mathrm{m} \\ 80\ \% \le Q \le 100\ \%, & \mathrm{Z} = \mathrm{M} \end{cases} \end{cases} \tag{5}$$

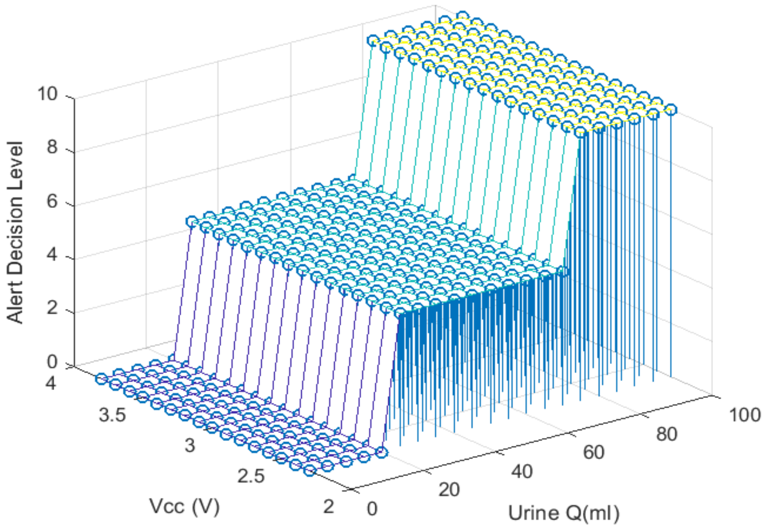


Fig. 5. Virtual 3D model of the multilevel urinary alerting process.

Fig. 6 shows a partial screenshot of the main Arduino C+ sketch associated with the flowchart depicted on Fig. 4, with real time implementation under Arduino/IDE C++.

Fig. 6. Partial screenshot at compiling time of main C++ sketch under Arduino/IDE 1.8.12.

The resulting performance data, as displayed beneath the compilation windows, are summarized as follows:

- Program size = 969260 octets (73% of maximum program memory);
- Global variables = 31344 octets (9 % of maximum memory for variables).

From these results it is obvious that a great amount of ESP32 resources remain available for further extensions the main C++ sketch.

In the smartphone side, however, a suitable *Serial Bluetooth Terminal Application* should be installed and deployed, for Bluetooth monitoring. The *Serial Bluetooth Terminal* used in this research work is a high performance freeware tool, available for transactions on fast downloading [10].

2.6. Overall workbench

Fig. 7 shows a real workbench image, built for rigorous experimental study of the proposed smart urinary detection and monitoring device. This workbench shows how the whole building parts described earlier in Table 1 are practically organized and connected. It is worth noting that a real urine sample has been used for conducting the whole experiments. In addition, it is worth nothing that an USB cable is useful for the following purposes :

- DC power supply source, with stable nominal output voltage Vcc = 3.2 V;

However, if the ESP32 chip is powered from a custom DC power voltage, then the use of USB cable would become unnecessary;

- Uploading the compiled main C++ sketch to the ESP32 WROO-32 memory;
- Real time data transfer between ESP32 microchip and Arduino virtual monitor or plotter.

Fig. 7: Workbench of the prototyping SUDAM Device

3. Experimentation study

3.1. Experimentation methodology

The experimentation works have been organized into the following steps:

1) Step 1 - Install and connect the workbench parts as shown in Fig. 7, given that the textile medium is initially dry, i.e., the absorbed urine quantity Q = 0 ml.

In which case the initial electric current flow through the resistor Rs (or equivalently the related output voltage Us) is zero.
2) Step 2 - Upload the main Arduino C++ sketch into ESP32 program storage memory;
3) Step 3 - Find and start the Serial Bluetooth Terminal application which should be preinstalled into the smartphone as shown in Fig. 8. Then, select the connected target Device name, e.g., AKEMBI SUDAM Dev.

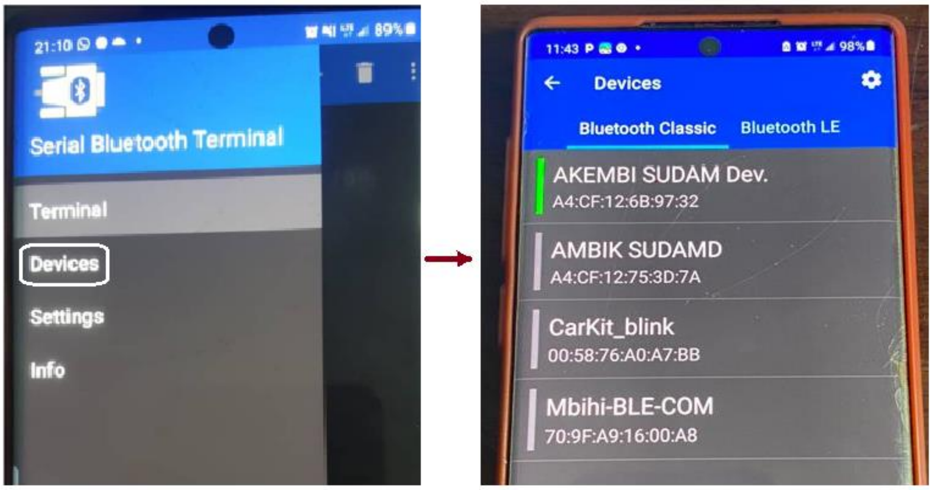


Fig. 8. Preliminary steps for running Serial Bluetooth Terminal Application

4) If the selected target device is not detected, then the detection process remains active. Otherwise, the target output characteristics associated with the multivariable monitoring state as transmitted by ESP32 chip via Bluetooth, are instantaneously displayed on the smartphone-based virtual monitor from initial conditions Q = 0 and Us = 0 dictated by the dry state of the textile medium;
5) At any discrete time, each urine quantity increment ΔQ thrown inside the textile medium, incurs an output voltage increment ΔUs. As an implication, for each cumulative urine quantity Q inside the textile medium, the corresponding steady output voltage Us is sent to the smartphone for visual monitoring. Therefore, the fast transient behavior of the urine diffusion process of Q is not taken into account during data collection required for building the steady model Us(Q);
6) An experimental sample {Q, Us} with size N is manually recorded during the previous step, given each known input Q and the corresponding output Us observed on the monitor screen;
7) Analytic models of Us(Q) and Q(Us) functions, given associated experimental sample{Q, Us} presented in Fig. 9, can be easily built using Matlab/CFTool;

8) Return to the main C++ Sketch, for updating implementing or updating the Q(Us) model to be computed. Then, apply the digital multilevel alarm control to the local buzzer;

9) Send via Bluetooth transactions of three output variables {Us, Q, Vcc}, to the smartphone for visual monitoring.

10) Under normal operating conditions where the ESP32 microchip is supplied by an external standalone Vcc battery, the USB link to the a Laptop becomes unnecessary.

3.2. Experimental results

The first expected result obtained in practice, witch cannot be outlined visually here on a physical paper, is the realistic nature of multilevel alarm levels provided by the electronic buzzer, under real time variations within the corresponding urine range [0 20% 80% 100%] ml, for the cumulative urine quantity Q (ml) absorbed into the wet textile medium.

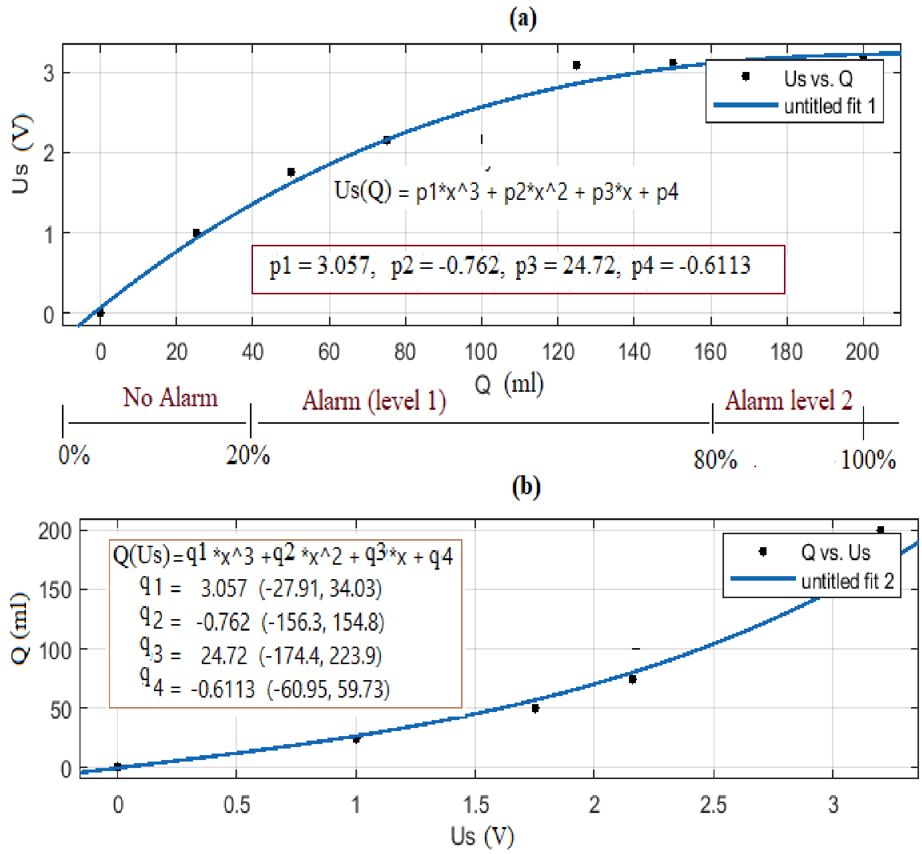
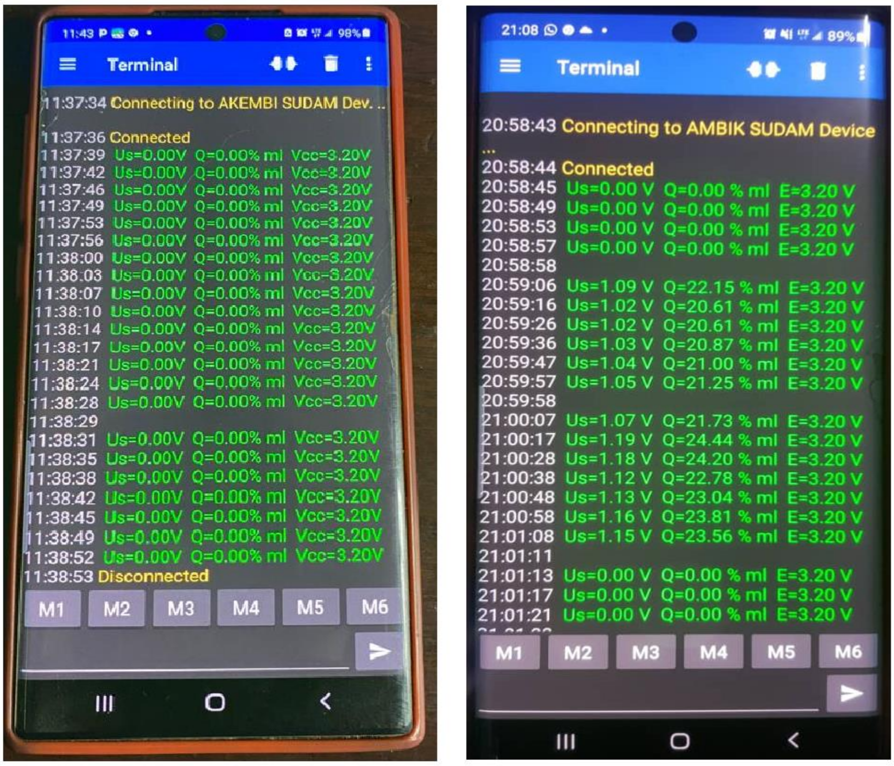


Fig. 9. Experimental models of Us(Q) and Q(Us).

The first relevant results to be shown in this section are the experimental steady models of Us(Q) and Q(Us). They are presented if Fig. 9, where Us(Q) and Q(Us) are plotted in Fig. 9a and Fig. 9b respectively. A third order polynomial models are adopted for the sake of better precision in the parameters estimation process within Matlab/Cftool, and for the need at real time of a fart digital computing of Q(Us) samples, given Us values associated with the cumulated urine quantity inside the textile medium.
The second relevant result is a sample of real time urinary data observed on the smartphone-based monitor as illustrated in Fig. 10, from initial conditions dictated by the dry state of the remote textile medium.



Dry textile medium (Left image) and wet textile medium (right image)
Fig. 10. Sample of urine monitoring data on a smartphone.

4. Conclusion

The novel type of smart urinary detecting and monitoring device presented in this research paper, outlines new keys concepts, e.g.: a) urine absorption capacity; b) multivariable urinary process; c) multi-thresholds alarm control strategy; d) multimode monitoring process. In addition, compared to existing types of smart urinary detection devices, it involves better intuitive custom sensor, more miniaturized hardware, more rigorous building models, better precision, higher number of output characteristics, lower overall size and more flexibility. Furthermore, for an industrial prototyping instrument under development and complete characterization, the power supply source for ESP32 chip, is a 3.2 V miniature battery recommended for e-textile applications. Finally, it would have as expected a significant impact factor on further researches and manufacturing activities, of smart generations of diapers for children, elders and urine incontinence persons.

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