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Design and Experimental Validation of an ESP32-Based Multichannel Instrument for Neonatal Physiological Monitoring

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Abstract

This paper presents the design and implementation of a multichannel biomedical instrument capable of the simultaneous digital acquisition and local monitoring of three critical parameters for infant care: Electrocardiogram (ECG), ambient temperature, and humidity. The hardware architecture integrates an AD8232 single-lead heart rate monitor, a DHT11 sensor for environmental data, and an ESP32-WROOM system-on-chip (SoC) which serves as the central processing unit.

Virtual prototyping was established using Fritzing software, while the firmware was developed in C++ within the Arduino IDE framework to handle automated data acquisition and signal processing. The system implements a specific algorithm to detect R-peaks within the QRS complex to calculate heart rate in real-time. Experimental validation conducted on a workbench with a 5-month-old subject demonstrates the instrument's ability to provide stable, real-time data visualization via a virtual USB monitor. The proposed design offers a significant advantage over existing single-channel devices regarding size, cost-efficiency, and the architectural readiness for future IoT-based wireless monitoring.

Keywords: Multichannel Biomedical Instrumentation, ESP32 SoC, Pediatric Monitoring, ECG Signal Processing, Digital Data Acquisition, IoT Healthcare.

INTRODUCTION

A human’s body is well known as a complex biological machine. Under given operating conditions, it involvesa wide variety of biophysical signals, each of which being described by specific time varying waveforms. Most popular examples of biophysical signals encountered in biomedical instrumentation literature are recalled as follows in biomedical engineering literature ([1], [2], [3]): ECG (ElectroCardiGram) from a heart, temperature of a leaving body, neighbourhood skin humidity, EMG (ElectroMyoGram) from muscles; EEG (ElectroEncephaloGram) from a brain, ENG (ElectroNeuroGram) from nerves, ERG (ElectroRetinoGram) from the retina of an eye, EOG (ElectroOculoGram) from the cornea/retina of an eye, MEG (MagnetoEncephaloGram) from the magnetic field of a heart, USG (UltraSonoGram) from a foetus in a mother’s womb, etc.

The biomedical instrumentation engineering has been and remains a relevant attractive field for scientific research opportunities. Beside numerous existing biomedical instrumentation systems, many open problems remained unsolved, e.g.: a) Most bio-instruments encountered are single channel devices [1-6], hence acquiring multiple biological waveforms on a single patient requires distinct instruments, and the whole measurement process is uncomfortable and inefficient; b) A few existing multichannel biomedical instruments [7], might involve greedy investment for possible extension toa Wifi monitoring Terminal; c) Except some papers such as in [8], there is a great lack of research works on biomedical instruments for babies as recommended in [9]. These aforementioned weaknesses arising from the biomedical instrumentation literature, are mayor motivating raisons of this paper.

The pioneering biomedical instrument initiated in this paper is a multichannel instrument for simultaneous measurements and monitoring of baby’s body parameters, i.e., ECG signal, temperature and humidity.

BUILDING TOOLS, METHODS AND EXPERIMENTATION

The schematic diagram of the proposed multichannel instrument is presented in Fig. 1. It consists of 04 main parts numbered from 1 to 6 respectively.

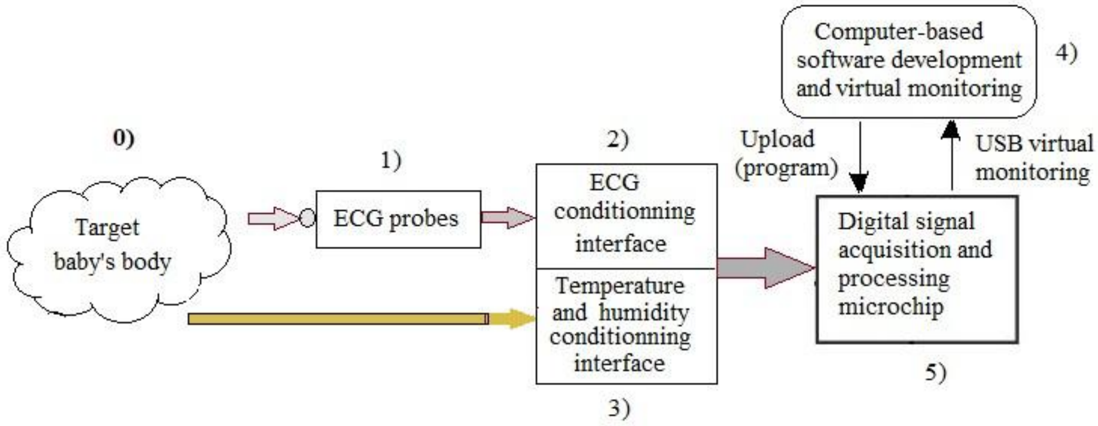


Fig. 1 Schematic diagram of the proposed multichannel digital biomedical instrument

Building hardware and specific software tools

The building hardware tools of the schematic diagram presented in Fig. 1 consist of a few hardware devices and specialized free software tools. Fig. 2 summarises these building hardware modules, e.g.: 1) 03 ECG probes and associated EGC cables with coloured connectors (red, yellow and green); 2) AD8232 ECG conditioning board, offering optimum performances (low noise, common mode rejection, high gain) within 0.5-40 Hz frequency bandwidth (see [10] for details technical details); 3) DHT11 module with build-in temperature sensor for 0-50 ^{o}C range,and humidity sensorswith 20-80 range (see [11] for more technical details); 4) PC/Laptop with preinstalled specific software tools to be listed later; 5) ESP32 WROOM microchip from Espressif;.

Fig. 2 Main building hardware modules

It is worth noting here that DHT11 sensor offers a single digital serial pin for both the temperature and humidity output data. As shown in Fig. 3,a digital output word stream structure is organized into 40 serial bits [11].

Therefore, a direct computing from low level programming of temperature and humidity values for acquired serial bit streams might be highly tedious. Fortunately, DUT11 library yielding low level automated subroutines are used in practice to overcome the difficulty as it will be outlined later.

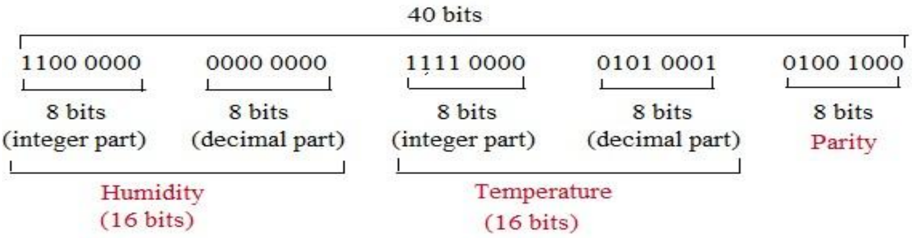


Fig. 3 Bits stream structure of DHT11 sensor output data [11]

It is worth noting also that ESP32 WROOM microchip family offers numerous build-in instrumentation capabilities including [12]: a) dual 32 bits core, reconfigurable multipurpose pins (DIO, DAC, ADC, PWM, I^2S and I^2Cinstrumentation bus);b) PCB antenna, Wifi (802.11, 2.2-2.5 GHz, access point or client mode or both);c) Bluetooth (BLE, 4.2 version); d) ready to use on-board Hall sensors; e)capacity touchelectrodes; f) up to 32 MB flash memory; g) enable and reset buttons;h) 3.2 V power supply and more. For these relevant technical raisons, ESP32 microchip family has increasingly becomes the most attractive choice for ambitious and innovative instrumentation projectsas in [12], [13], [14],[15} and [16].

On the other hand, the specific software tools required for design or real time programming tasks are described in Table 1.

Table -1 Specialized software tools

Specific software tools	**Version**	**Technical relevance**
Fritzing	0.9.3b	Virtual prototyping of the instrument
Arduino IDE	1.8.12	C++ sketch programming
Arduino DHT11 sensor Library	1.4.2.zip or Adafruit version 1.1.4	To be installed into Arduino IDE/C++
ESP32 WROOM driverfor Windows	CP210x_Universal_Windows10_Driver.zip	To be installed into Windows 10
ESP32 WROOM library for Arduino	https://dl.espressif.com/dl/package_esp32_index.json	To be installed from Arduino IDE
AD8232 library for Fritzing	Heart_Rate_Monitor_demo.fzz	To be installed into Frotwing

Methods

The relevant need at this methodological subsection is to show how the virtual prototyping model of the proposed biomedical instrument has been implement and in both virtual and real worlds.

The resulting virtual instrument model build in Fritzing software platform is depicted on Fig. 4, where all hardware modules are mounted on a virtual electronic board.

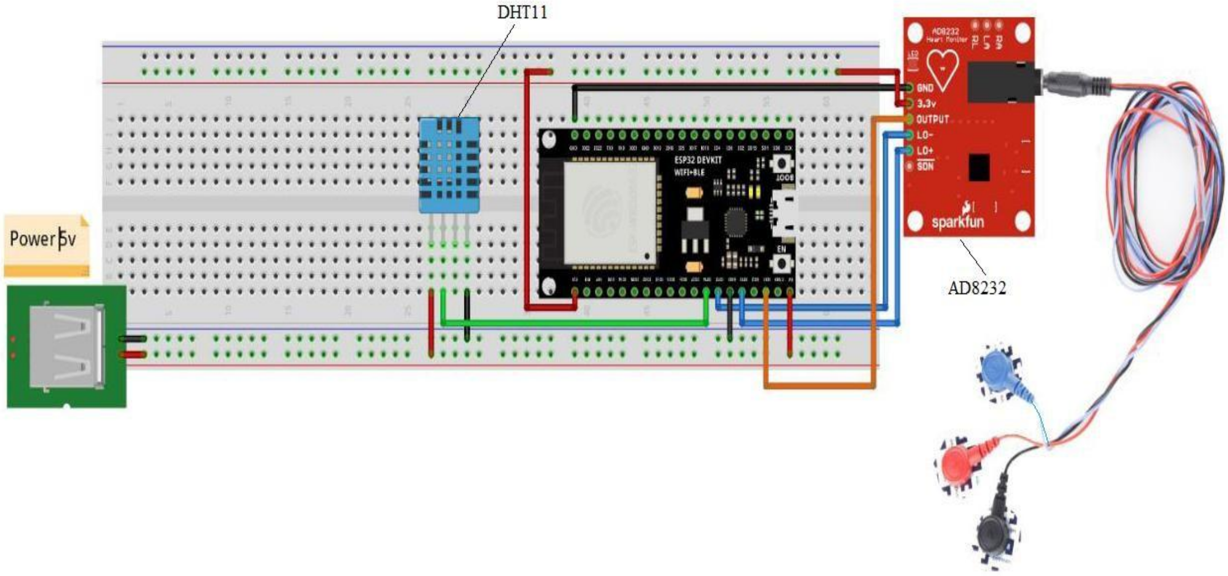


Fig. 4 Virtual prototyping model of the proposed biomedical instrument under Fritzing

In the next step, the second relevant need is to outlined the flowchart from which the automated instrumentation tasks might be coded at programming time as a set of C++ sketch to be compiled into Arduino IDE/C++ framework. A brief list of instrumentation tasks to be automated via programming for further real time processing by ESP32 WROOM are:

- Digital acquisition of input temperature and humidity from corresponding DHT11 ADC pins;
- digital acquisition of ECG samples from corresponding AD8232 ADC pins; Digital signal processing (DSP) of sampled signals according to target goal;
- Monitoring of DSP results on virtual Arduino IDE monitor via USB data transfer process at 9600 bd.

It is worth noting that the related DSP process subroutines take into account physical constraints and numerical analysis needs associated with each input channel. Fig. 5 show the main flowchart associated with the aforementioned instrumentation tasks to be further implemented as a source C++ sketch.

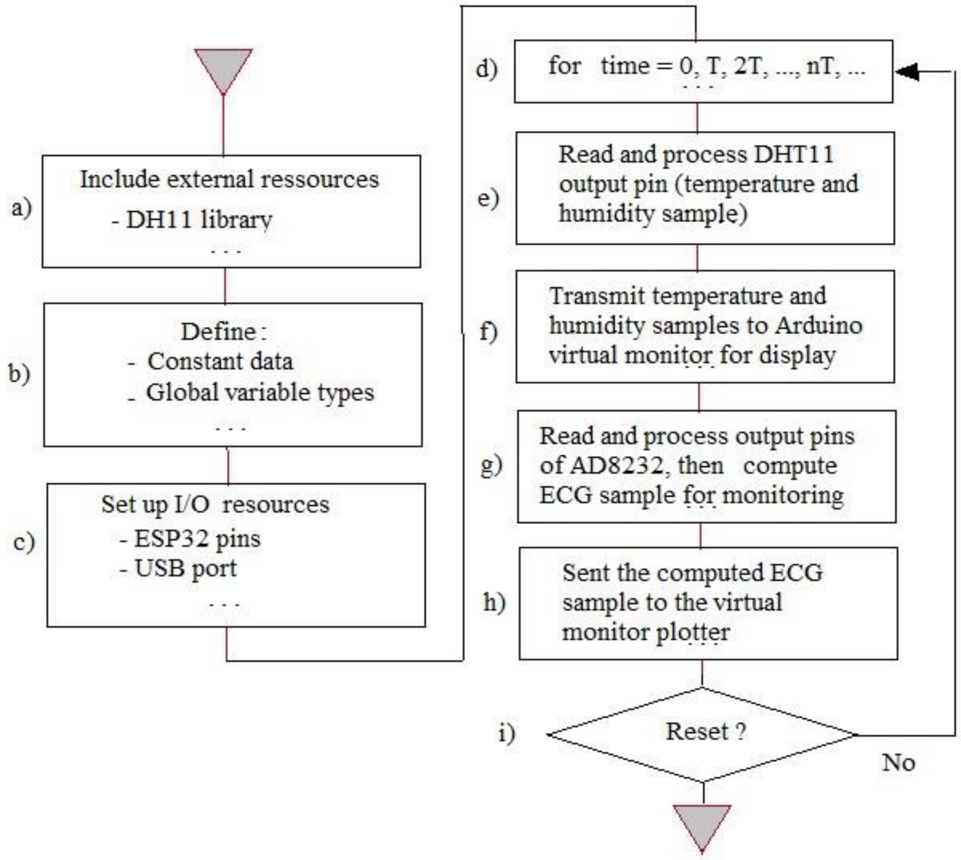


Fig. 5 Flowchart of the ESP32-based automated instrumentation tasks

The set of first steps {a, b, c} are heading tasks associated with external libraries, data types dictionary and hardware setup respectively. Then, the remaining sequential steps {d, e, …, i} are periodic tasks according to a digital processing loop logic, with time period .T (ms). In digital signal processing practise, a suitable value of T is dictated by Nyquist's sampling frequency [17], which is at least 2 times the maximum frequency required to process all tasks and delays involved within the loop. However, an occurrence of a reset signal initializes of the whole digital-based automated system.

A second relevant information to be outlined in depth in Fig. 5 is the numerical computing policyof ECG samplesgiven digital values acquired from AD8232 output pins. In this paper, the computing algorithm used is organized into 5 steps as follows:

1) A threshold is fixed for a digital R wave sample;
2) The R wave is detected on the basis of the time index for which the acquired is greater to the given threshold level;
3) The digital gap between time indices values are computed (R-Rinterval).
4) A mean of last sixteen interval R-R is computed.
5) The heart rate frquency is determined according to relationship (1).

$$Heart\_Rate = \frac{60000}{AVG(R\text{-}R\ interval)} \quad (1)$$

where AVG stands for the average operator.

Fig. 6 shows the main heading section of C++ sketch as viewed under Arduino IDC/C++ platform.

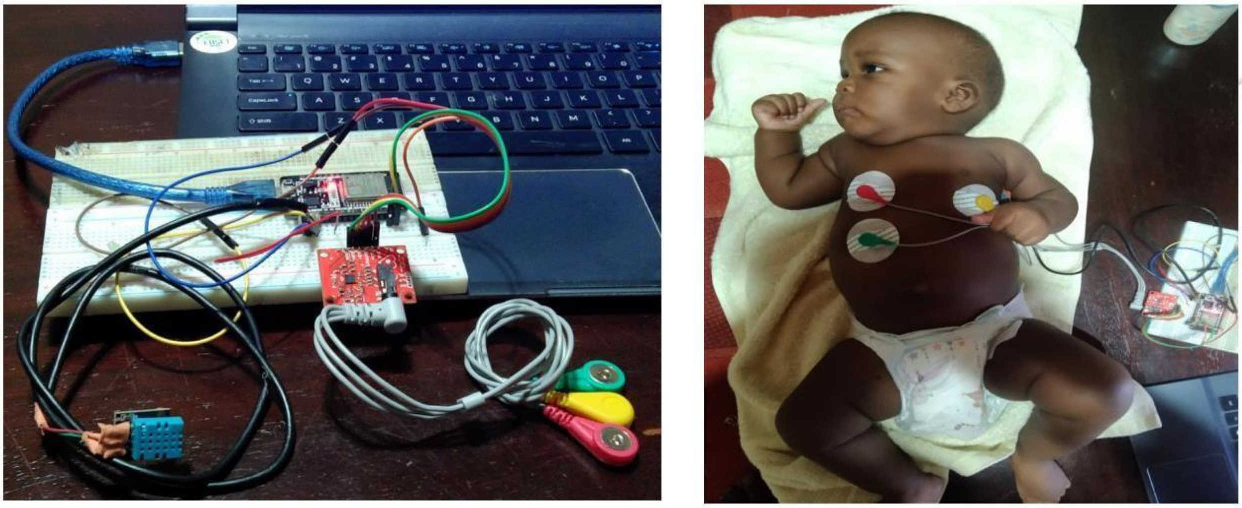
```
#include <dht11.h>
#define DHT11PIN 4

dht11 DHT11;
float temperature = 0 , humidite = 0 ;

#define PI 3.141592
unsigned  int  temps=0;
unsigned  int  Minute=0;
unsigned  int  entree=0;
unsigned  int  entreen1=0;
unsigned  int  entreen2=0;

float filtre;
float filtren1;
float filtren2;
float derivation;
float derivation1;
float derivation2;
float derivationABS;

unsigned int centi;
unsigned int centiST;
float ST;     //seconde
unsigned int periode;

bool flag=0;
bool flag1=0;
bool flag2=0;

unsigned int BPM;
unsigned int average;
const int numReadings = 120;
int readings [numReadings];
int readIndex = 0;
long total = 60;

        float a1=1;
        float a2=1;
        float detectionfiltre;
        float detectionfiltren1;
        float pentedetection;
        float sortie;
        float sortie1;
        float sortie2;

void setup() {
  // initialize the serial communication:
  Serial.begin(9600);
  pinMode(10, INPUT); // Setup for leads off detection LO +
  pinMode(11, INPUT); // Setup for leads off detection LO -

 }
```

Fig. 6 Heading section of the C++ sketch under Arduino IDE/C++ platform

Experimental Research

At this study step, the set of Figures form Fig. 1 to Fig. 5, appears to be a sufficient techical knowledge base, from which a complete experimental workbench can be surely designed and built in order to prove the realistic feaisibility and good quality of the proposed multichannel biomedical instrument for babies. The image sample of the resulting experimental workbench is presented in Fig. 7.

The complete isolated workbench shown in Fig. 7a, is a real world realization of theFrizing-based virtual instrumentation systemealier presented in Fig. 4. Ti is worth nothing that all the building hardware modules depicted ealier in Fig. 2 are quite visible, including real wiresfor signal transmission among parts. On the other hand, Fig. 7b shows an experimental session where the ECG electrodes are appropriately connected to a 05 month old baby's. Then a few minutes are sufficient to automatically complete a biomedical data acquisition session.



a) Experimental isolated workbench *b) Experimental workbench connected to a target baby*

Fig. 7 Experimental workbench of the proposed biomedical instrument

RESULTS AND DISCUSSIONS

Fig. 8 shows a sample of real times values of both temperature and humidity, as displayed on the Virtual monitor screen under 9600 bd USB communication protocol.Of course, it is expected that during a few milliseconds of time interval, neither temperature nor humidity characteristics may notsignificantly vary.

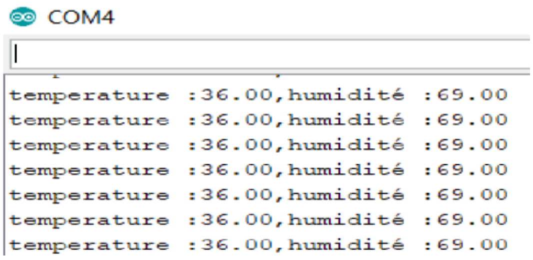


Fig. 8. Experimental samples of temperature and humidity

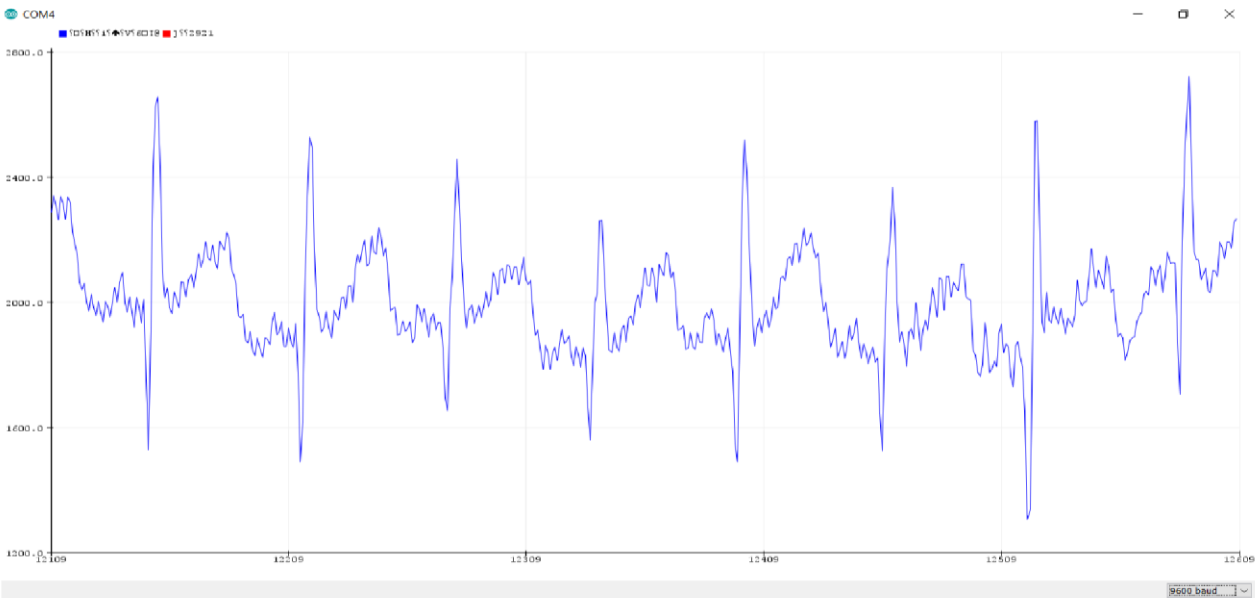


Fig. 9. Experimental sample of baby's ECG

Fig. 9 shows an experimental sample of a baby's ECG on the screen of the Virtual USB Arduino monitor. It is a great challenge to see that, under a permanent agitation of baby's body, the crude ECG waveformprovided by the proposed instrument is quite satisfactory. However, the quality might be improved using a low-pass digital filter.

CONCLUSION

The multichannel biomedical instrument developed in this study represents a significant advancement in low-cost pediatric monitoring technology. Through rigorous design and workbench testing, the system demonstrated high flexibility and operational fidelity in acquiring ECG, temperature, and humidity data simultaneously.

Unlike traditional bulky instrumentation, this ESP32-based solution offers a compact, scalable architecture. While the current iteration utilizes local USB monitoring, the results validate the hardware's potential for advanced applications. Future work will focus on implementing digital low-pass filtering to further reduce signal noise and leveraging the ESP32's wireless capabilities to transition from local monitoring to remote Android-based IoT telemetry.

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