Wi-Fi based Integrated System for the Monitoring of Heart Rate and Peripheral Capillary Oxygen Saturation

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***Abstract* - This work illustrates an integrated system comprising a low-cost Embedded device connected with a finger–type Photoplethysmography (PPG) array sensor to estimate Heart Beats per minute (HR) and Peripheral Capillary Oxygen Saturation (SpO2) parameters and a web based application that receives them via Wi-Fi for further processing and visualization through Message Queuing Telemetry Transport (MQTT) internet protocol.**

In conventional PPG signal sensing approaches, the finger-type PPG sensor probe is being utilized while Wireless Personal Area Network (WPAN) technology, mainly Bluetooth Low Energy (BLE), is used to transmit the data to a gateway acting as an intermediate.

The low-cost Embedded and microcontroller-based device that processes the signals collected by the finger-type Photoplethysmography (PPG) array sensor, extracts both HR and SpO2 parameters, and ultimately transmits them via Wi-Fi to a web-based application. The web-based application, which is a dedicated tool in the hands of the physicians, features an interface that allows both continuous monitoring and recording of patients corresponding parameters.

***Index Terms*—embedded devices, photoplethysmography, HR, SpO2, Wi-Fi**

I. INTRODUCTION

In recent decades, developments in the field of Engineering have laid the ground for innovative partnerships between health industries that wished to optimise their products and services. Given the expertise, industry expectations have grown seeking new solutions for process automation, improvement of the existing ones and introduction of new services. Health sector is afflicted by a variety of problems, such as the lack of financial resources, staff and organization, leading to adverse circumstances for patients and workers. Engineering has so far provided quite many solutions for the improvement of quality of healthcare services. Amongst them is the creation of artificial organs, supportive machines and systems for the patients, platforms for patient records and others that consistently facilitate the staff's work.

In this work, we introduce a low-cost integrated system ideal for monitoring patients' health in the Hospital Emergency department (ED). The system's purpose is prioritisation of patients based on their condition and not on their arrival order. Continuous monitoring of patients' certain bio parameters helps avoiding misdiagnoses and enables decongestion of ED allowing physicians to save valuable time and space allotting them for more severe cases.

The implementation of the system includes the design of a wireless wearable device, which consists of a Wi-Fi microcontroller and a Photoplethysmography (PPG) array sensor. The device accrues vital signals from patients and by applying signal processing on the photoplethysmograms, it extracts important parameters for the assessment of their health. The calculated parameters are sent via Wi-Fi to a web-based application using the Message Queuing Telemetry Transport (MQTT) protocol. In this case the two parameters used for monitoring are Heart Beats per minute (HR) and Peripheral Capillary Oxygen Saturation (SpO_2), as the combinatorial knowledge of these two values allows the diagnosis of dangerous incidents such as ventricular fibrillation, pulmonary edema, increased internal bleeding, respiratory problems or inadequate oxygenation of peripheral tissues.

The second part of the system's implementation includes the development of a web-based application that receives the parameters from the device, demonstrates them in real time in the format of tables and charts and allows downloading the history of the procedure. The web-based application was developed using the MERN technologies (MongoDB, ExpressJS, ReactJS and NodeJS) and practically it is the physician's interface with the system.

II. RELATED WORK AND SIMILAR PRODUCTS

Wearable health monitoring systems have become very popular in the recent years, due to the fact they have evolved in terms of technology and cost. Their features have made them attractive for use on patients in ED environments and hospital clinics in general. For example, they are lightweight, they can be directly applied to the patients without causing discomfort, they are power and network efficient, they can record and possibly process a variety of patient's vital signs.
Several wearable devices are based on the method of PPG, which is a simple and low-cost optical technique that can be used to detect blood volume changes in the microvascular bed of tissue. Due to its non-invasive nature, it is often used to take measurements at the skin surface and has been adopted as the main method for SpO_2 and HR measurements.

A. *Wearable devices used for measuring HR and PPG*

Some commercially available wearable health monitoring systems are listed below.

i. Wrist Pulse Oximeter by Berry utilizes a pulse oximetry optical sensor for HR and SpO2 measurements. The wearable is small, lightweight, and available for home use as well as clinics in long-term and comfortable monitoring. Data can be transmitted from app to Android Phones and iPhones via BLE [1].

ii. Biostrap provides biometric insights using PPG and a pulse oximeter of clinical quality. It keeps track of HR, Heart Rate Variability, SpO_2, Respiratory Rate, in-depth sleep tracking, basic activity tracking and more. All data are synced and downloaded to smartphone via iOS and Android Apps [2].

iii. Nonin Onyx Vantage 9590 finger Pulse Oximeter is a portable device which measures and displays SpO_2 and HR of patients. It is intended for spot-checking of adult and pediatric patients on digits (fingers, thumb, toes) in a wide range of environments including hospitals, clinics, long-term care facilities, skilled nursing facilities, emergency medical services, and home healthcare services [3].

B. *Internet of Things connectivity protocols*

The broadcasting of the IoT devices is achieved via wires or wirelessly through a communication network. The appropriate connectivity protocol should be chosen, taking into consideration power consumption limitations and bandwidth restrictions. Here are some popular data IoT protocols:

i. Constraint Application Protocol (CoAP) is a web transfer protocol created for constrained nodes, like low power sensors and constrained networks in IoT. It enables IoT nodes to communicate with each other over the Internet. CoAP runs on devices that support UDP protocol, in which client and server communicate through connectionless datagrams. In a similar way of the HTTP, the CoAP is able to carry different types of payloads and to integrate any data format of the user's choice [4].

ii. Message Queuing Telemetry Transport (MQTT) is the protocol mostly used amongst IoT devices and it is based on the client – server model functioning on top of the TCP/IP. MQTT minimizes data packets, transmits data fast and consumes less energy. It includes a subscriber, a publisher and a broker. The publisher collects the data and sends it to subscribers. Consequently, the broker tests publishers and subscribers and checks their authorization. It's the real time interaction between the devices on a wide area network that makes MQTT an ideal protocol for IoT applications [4].

iii. Representational State Transfer (REST) is based on HTTP. REST technology uses bandwidth efficiently thus making it suitable for internet usage. It is used to fetch or give some information from a web service. All communication is done via REST API using HTTP requests. Regularly there is a REST server, which provides access to the resources, while REST clients access and modify them. Every resource is identified by a global id, which is generally the Universal Resource Identifier (URI). In a REST based architecture there are five methods which are commonly used i.e., POST, GET, PUT, PATCH and DELETE. These correspond to create, read, update, and delete (or CRUD) operations respectively [5].

Both the MQTT and the CoAP work well with low power and network constrained devices. Thus, the choice depends on the application use case special requirements. Based on our use case requirements, such as the bandwidth and power consumption, MQTT protocol is adopted.

III. SYSTEM ARCHITECTURE

Our proposed integrated system follows a modular design both at hardware level (physical components) as well as at behavioral level (operational components). This section is divided into three subsections. The first subsection presents how the low-cost embedded device and the PPG array sensor is implemented at the hardware level, the second subsection reveals the firmware configuration of the embedded device and the web based application, while the third subsection details the system performance and the energy consumption aspects.

A. *Physical Components*

At the hardware level, the physical constituents of our proposed system follow the composition depicted in Figure 1. Different function blocks are defined:

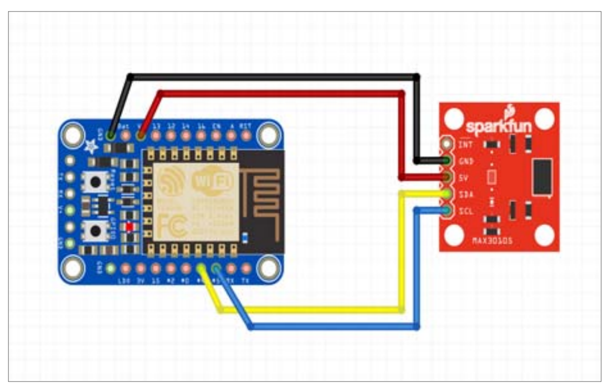


Figure 1. Embedded Device Physical Constituents

i. Adafruit Huzzah ESP8266 Breakout

The Adafruit ESP8266 breakout is a low cost module, which contains the ESP8266 processor. The ESP8266 is a System On Chip (SoC), developed by the Chinese company Espressif for IoT systems. It is a complete Wi-Fi system, incorporating a 32 bit 80MHz microprocessor, 64 KB of RAM, 96 KB of RAM, 4 MB SPI Flash Memory and a Wi-Fi transceiver. The module can operate as a stand-alone system, capable of running various applications due to the large size of the external Flash memory. Therefore, in this project ESP8266 is being used as the main processor of the device and provides the Wi-Fi connectivity to the system [6].

ii. PPG sensor board MAX30105

The PPG sensor board MAX30105 is a powerful sensor for detecting reflected light, which allows measuring of heart rate and oxygenated blood, or detection of smoke and distance if combined with other components. Its advantages lie in the following areas:

- High sensitivity for detecting a wide variety of sizes
- Very small size 5.6mm x 3.3mm x 1.55mm, which makes it extremely handy
- Built-in glass cover for optimum performance
- Very low consumption:
  -Scheduled sampling rate and power consumption for energy saving
  -Very low shutdown current (standard value of 0.7 mA)
- Resistance to movement
- Operating temperatures from -40 ° C to +85 ° C
- Excellent ability to reject ambient light

MAX30105 is equipped with 3 internal light emitting diodes (LEDs), photodetectors, optical elements and low noise electronics to dispose ambient light. LEDs emit red, infrared and green light. Specifying the mode of the sensor, determines the LEDs that take part in each operation. In the current system, Mode 2 is being used to emit Infrared and Red light for the purpose of HR and SpO_2 calculation [7].

The ESP8266 and MAX30105 boards communicate through SPI communication. Specifically, the GPIO pin 4 of ESP8266 is connected with the SDA pin of MAX30105 and the GPIO pin 5 with the SCL pin respectively. As for the power supply, the sensor is powered by 5 Volt through the V+ pin of ESP8266.

B. *Operational Components*

At the software level, the components of our proposed system comprise the following:

i. Firmware Adafruit board

The main operations implemented by the proposed system are the collection of PPG signals through the sensor, the processing of the signals for extraction of HR and SpO_2 and the wireless transmission of the parameters.

Initially, infrared and red signals are collected continuously from the sensor and result in two clear PPG waveforms. A 21-point moving average filter is used for high frequency cut-off due to noise removal. HR calculation is done by identifying the positions of successive peaks from IR PPG. Subsequently for each pair of peaks, beats per minute (BPM) is calculated using the type $BPM = Fs * 60 / d$, where Fs is 25 Hz and d the time difference between two successive peaks. Finally, HR is computed as the average value of all BPM. SpO_2 is calculated using the type $SpO_2 = -45.060 * R * R + 30.354 * R + 94.845$, where $R = (AC_R / DC_R) / (AC_{IR} / DC_{IR})$. The AC components are computed as the difference between maximum and minimum values and the DC components as the mean values of the PPG waveforms.

ESP8266 connects easily to a local network and transmits the parameters over Wi-Fi using the MQTT protocol.

ii. MQTT

MQTT is described by OASIS as a lightweight messaging protocol designed to enable low computing and low storage devices such as IoT microcontrollers to communicate in unreliable or low bandwidth areas. The protocol runs over TCP/IP and is based on a machine-to-machine (M2M) publish/subscribe communication model.

In the current case, the bio parameters HR and SpO_2 and the ID of the device are published as a message in specific topics at the MQTT broker: *broker.hivemq.com*. In order to receive the published messages, the application connects to the same broker, subscribes to the same topics and receives the messages in real time. The procedure for the data's transmission is shown in Figure 2

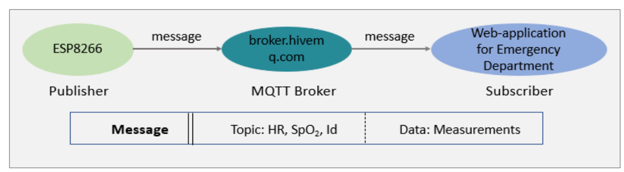


Figure 2. Data transmission through MQTT protocol

iii. Web based App

The Web based Application was developed so that physicians can monitor in real time the compiled biomedical parameters of the patients. The technologies used for the backend are NodeJS and ExpressJS and respectively for the frontend ReactJS. The MongoDB database is used to store data from patients. As indicated earlier, the application receives the data through Wi-Fi using the MQTT protocol and stores them in the database. The current state of the device is displayed on a table which is updated upon the arrival of every new measurement. All of the aggregated data since the device's commenced operating, is shown in a chart in Figure 3.

C. *System Performance*

i. Firmware / Software

No embedded operating system is used. ESP8266 is programmed for HR and SpO_2 extraction from MAX30105 in Arduino's integrated development environment (IDE). Arduino IDE is an application written in Java for easy hardware programming, such as microcontrollers. Arduino's programming language is based on Wiring and IDE design in

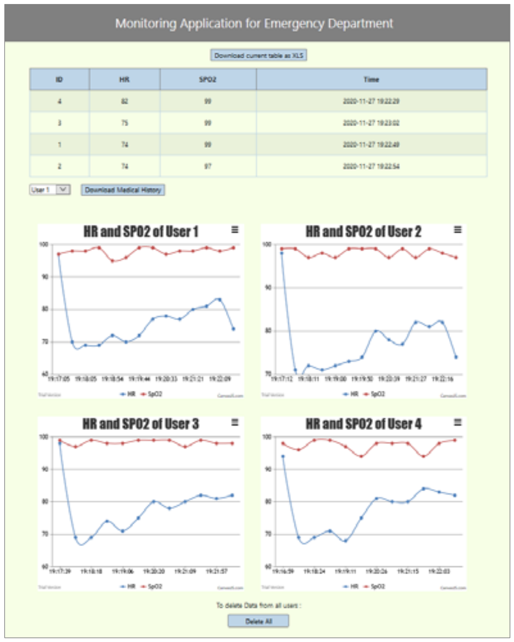


Figure 3.GUI of Monitoring Application for the ED

Processing language and is available for Windows, Linux and Macintosh OSX operating systems.

The web application developed to display the data is of MERN type, which means that the four technologies used are MongoDB, ExpressJS, ReactJS and NodeJS [8]. MongoDB is a NoSQL, open-source, cross platform, organized in documents database written in C++. NoSQL databases are designed to overcome the limitations of traditional relational database technology (RDBMS). Instead of tables, MongoDB stores data in collections. Each collection retains one or more documents with different fields, which is not provided by the relational databases. The data is stored in BSON format, a binary JSON format. This format provides additional data types and is efficient in many programming languages. NodeJS is a server-side environment of Javascript running on the Javascript V8 engine, the core of Google Chrome. V8 and NodeJS are mostly implemented in C and C++ focusing on performance and low memory consumption. Unlike most modern environments, a server operation is not implemented by multithreading to serve simultaneous requests, but by an asynchronous event-based model that makes the application non-blocking. NodeJS includes a huge variety of packages for several purposes, which can be installed using the npm or yarn package manager. ExpressJS is the most well-known framework of NodeJS, specifically designed to create one-page, multi-page and hybrid web applications. It is also installed using npm. ReactJS is a Javascript library created by Facebook and used for the User Interface (UI) design of an application. The main features of React are:

- It is organized in Components which could be considered as simple reusable functions. React uses small Components coming together to create larger ones for both the same and other programs.
- It uses JSX (Javascript XML) code. React incorporates HTML code into the Javascript file via JSX code. The JSX's syntax has the same features as the HTML and is a very useful and easy-to-use tool that describes exactly how the UI will look like.
- It implements a Virtual DOM. Virtual DOM is a representation of the real DOM as a lightweight copy but without being able to display its objects on screen. It works as follows. Each time the JSX code changes, the Virtual DOM is updated promptly. Once the update is completed, React compares the resulting updated Virtual DOM with its previous version and identifies exactly which nodes have changed. It then applies the changes to the real DOM and therefore to the screen.

The web application is developed in Visual Studio Code environment.

ii. Cost Aspects

The integrated system presented in this paper is a low-cost system both in terms of initial purchase and further use. Esp8266 and MAX30105 are available on the market at a low price. Additionally, the operating costs of the system are minimal as only a Wi-Fi connection is required.

IV. Small – Scale Demonstration

The measurement procedure commences by placing the finger on the sensor. MAX30105 emits Red and Infrared light and continuously receives samples, from which the IR and Red PPG are extracted. The device is deactivated in case it does not receive samples for more than 30 seconds. To reactivate the device a reset of ESP8266 is needed. Two clear PPG waveforms are shown in Figure 4.

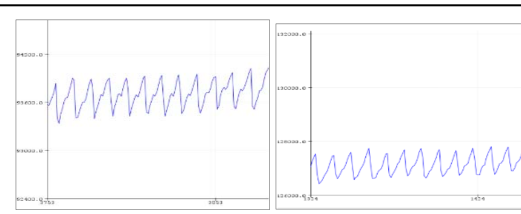
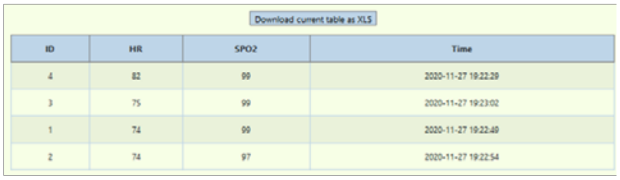


Figure 4. Left: IR PPG Waveform, Right: Red PPG Waveform

HR and SpO_2 are then calculated using the algorithms mentioned and sent to the application wirelessly. The Serial Monitor of Arduino IDE depicts the published results of a measurement to the broker, with the device's id included.

At the same time the value appears in the table with the real time measurements of the Web App. Now the measurements of the device with id = 3 have been updated to HR = 75 and SpO_2 = 99 as shown in Figure 6. This table can be downloaded as an Excel file from the Download XLS button.



Download current table as XLS

ID	HR	SPO2	Time
4	82	99	2020-11-27 19:22:29
3	75	99	2020-11-27 19:23:02
1	74	99	2020-11-27 19:22:49
2	74	97	2020-11-27 19:22:54

Figure 6. Real time measurements from patients in the GUI

Concurrently the previous measurements of the patients are shown in charts, separate for each one, including the variation of HR and SpO_2 along the procedure as shown in Figure 7.

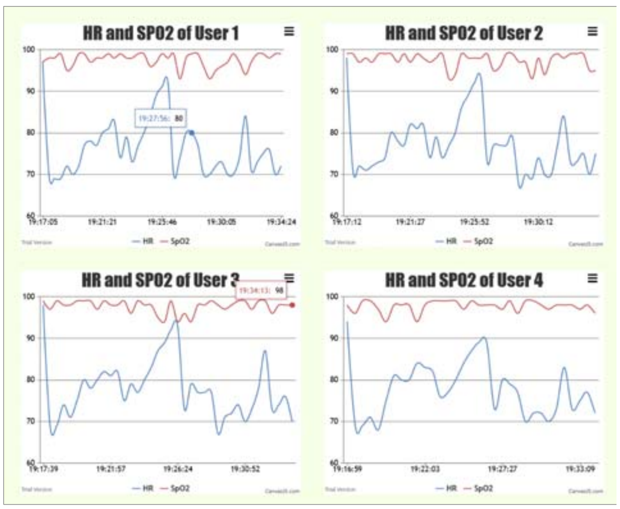


Figure 7. Charts being recorded along the procedure

Patient history is obtained in two ways, either in chart form or in detailed list. Each chart can be downloaded through the options listed in the upper right corner as depicted in Figure 8.

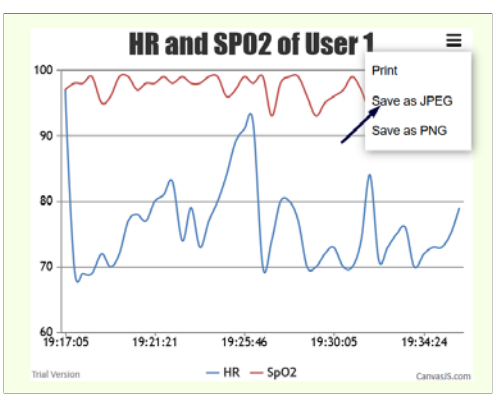
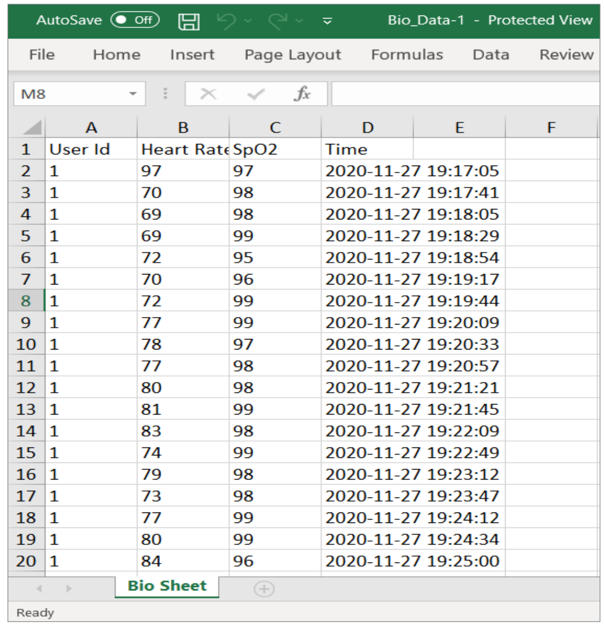


Figure 8. Patient history to image file



AutoSave Off Bio_Data-1 - Protected View

File Home Insert Page Layout Formulas Data Review

M8

	A	B	C	D
1	User Id	Heart Rate	SpO2	Time
2	1	97	97	2020-11-27 19:17:05
3	1	70	98	2020-11-27 19:17:41
4	1	69	98	2020-11-27 19:18:05
5	1	69	99	2020-11-27 19:18:29
6	1	72	95	2020-11-27 19:18:54
7	1	70	96	2020-11-27 19:19:17
8	1	72	99	2020-11-27 19:19:44
9	1	77	99	2020-11-27 19:20:09
10	1	78	97	2020-11-27 19:20:33
11	1	77	98	2020-11-27 19:20:57
12	1	80	98	2020-11-27 19:21:21
13	1	81	99	2020-11-27 19:21:45
14	1	83	98	2020-11-27 19:22:09
15	1	74	99	2020-11-27 19:22:49
16	1	79	98	2020-11-27 19:23:12
17	1	73	98	2020-11-27 19:23:47
18	1	77	99	2020-11-27 19:24:12
19	1	80	99	2020-11-27 19:24:34
20	1	84	96	2020-11-27 19:25:00

Bio Sheet

Ready

Figure 5. Patient image to Excel file

The second option is to download the history to an Excel file by pressing *Download Medical History* after selecting the device id from the list. Then, a detailed list of measurements for device with id = 1 shall appear as shown in Figure 5.

After the history is downloaded, the device's data must be deleted in order to be given to another patient. In case no patient is in the Emergency Department, all devices must be cleared.

V. Conclusion

The integrated system presented in this paper, is a comprehensive solution for collecting, processing and displaying medical data so as to be able to constantly monitor patients' health. It can be easily integrated into the EDs, ameliorating the health care services provided from physicians. The device built as part of this integrated system for collecting and processing vital parameters from patients is a handy, user-friendly, and cost-effective solution. Two very critical parameters for the patients' welfare, namely heart rate and blood oxygen saturation are extracted from the sensor signals. The device's ability to wirelessly transmit these data, combined with its compact size, make it really easy to utilize. Moreover, the developed web application provides a holistic view of patients' health status and enables the medical staff towards early diagnoses and efficient treatments.

Acknowledgment

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