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A Cost-Effective Framework for Remote Patient Monitoring using a Wearable Device and Cloud Computing

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Abstract: Due to elderly aging problems, increased cost of regular screening and continuous patient monitoring, there is a clinical need for practical patient monitoring in or out of hospital, and to continuously provide warning in case of sudden changes in patient status. The aim of this paper is to design a framework for ubiquitous patient monitoring and signal analysis by exploiting a powerful Cloud Application (with high efficiency, wide accessibility and high scalability on the server side), while constructing a cost-effective, ubiquitous and portable system on the consumer side so that a common man can afford it. The portable device can be used to monitor an individual in case of any sudden changes in a person and display the results via a commonly available Smartphone in real-time. The data can also be saved and sent to hospital or the people concerned through SMS, Email, or Cloud to the analysis center (Cloud Application Center), which analyzes the data on the database and classifies patient disease to inform doctors to make further diagnoses and take an action in fast and efficient manner. This study designed and evaluated an integrated software and a wearable device to acquire vital sign data from temperature sensors, heartbeat sensors and Electrocardiogram (ECG). The evaluation results showed the suitability of the wearable device with Cloud data services that increases system performance and accessibility worldwide for ubiquitous monitoring of vital signs.

Keywords: Electrocardiography (ECG), Heartbeat, IOIO-OTG, Cloud Computing, Wearable Device, Android

1. Introduction

Cardiovascular diseases are a major cause of mortality with over 37%of all deaths [1]. The high mortality rate and the high rate of disabilities in survivors are a social and economic burden [1]. Furthermore, the average life expectancy is continuously increasing in many countries [1], for example, the average life expectancy is over 80 in Canada according to Statistics Canada. The cost of health care to sustain the well-being of the elderly population in the west has also increased dramatically [1]. This requires continuous monitoring of patients and the elderly in or out of hospital, as well as an alerting system in the case of sudden changes in the state of the a patient's health or a follow-up of the monitoring of patient vital signs. Early information could improve the care cycles and lower the side effects and timely therapy may prevent or reduce disabilities. These social and health issues can be diminished by developing a real-time ubiquitous patient monitoring system and introducing a smart way of monitoring patients and the elderly.

The third phase of the internet after World Wide Web and the mobile Internet is Internet of things technologies. Internet of things (IoT) is a new paradigm that makes daily object (equipped with sensors) to be low-power, low-cost and fully internet connected via sensors and microprocessor chips. IoT sensors and affordable IoT devices link physical and virtual objects through a newly extended IPv6 architecture in Global Network of Interdisciplinary Internet. Numerous studies have been published by other authors on remote patient monitoring and the design of vital sign monitoring devices [2-5]. A Wireless Body Area Networks (WBAN) system for ambulatory monitoring of physical activity and health status was developed by Jovanov *et al.* [6]. They developed a standard platform using common off-the-shelf wireless sensor platforms including ZigBee-compliant radio interface, an ultra-low-power microcontroller, an accelerometer, an accelerometer circuit and bioamplifier for Electrocardiogram (ECG) monitoring [6]. Anliker *et al.* developed a wearable multi-parameter medical monitoring and alert system. The system was a wrist worn remote monitoring device with a single lead ECG monitoring. Oxygen saturation, temperature and blood pressure were measured using this device. All the measured data was sent to an online medical mission control station using a global system for mobile (GSM) communication protocol [7]. EL-Aty [8] developed a wireless wearable body area network (WWBAN) for elderly people for long-term health monitoring, and used heart rate and blood oxygen sensors to measure heartbeat and blood oxygen saturation. The author used an IOIO board as his microcontroller unit to interface with an Android Smartphone via a Bluetooth connection [8]. However, these devices did not classify cardiac diseases or display proper ECG features that make sense and are suitable for extracting ECG features to perform automated disease classification as required by [18] for the intended patient monitoring outside of hospital.

The aim of this study is to design a cost-effective framework for a wearable device and Cloud computing to monitor patient vital signs remotely without staff supervision and warn designated staff automatically using Cloud Application Services. To achieve this, we built a cost-effective, non-invasive, portable and ubiquitous wearable device and developed software applications to relay patient vital signs continuously to a designated center through a Smartphone and Cloud application.

2. Methodology

2.1 Overview

A cost-effective framework is designed for ubiquitous patient monitoring and analysis. As shown in Fig. 1, a portable wearable device accumulates the patient data (vital signs) acquired from sensors attached to a patient body. These sensors are connected to a specially designed IOIO board, which collects data and transfers them to a Smartphone. The temperature sensor measures patient body temperature and pulse sensor acquires heartbeat data. ECG provides the electrical activity of human heart. The application running on the Smartphone can accumulate the sensor data via a Bluetooth connection from the board. After accumulating the data, it sends them to the Cloud Data Center simultaneously to store the data. After this point, the analysis center (Cloud Application Center) analyzes the data on the database and classifies patient disease to inform clinicians to take an action.

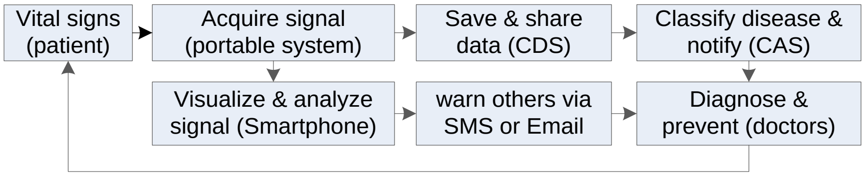


Figure 1. A generic functionality and procedure for Smartphone and Cloud based patient monitoring and signal analysis.

CDS stands for Cloud Data Services, and CAS stands for Cloud Application Services.

2.2 Framework Design

The proposed framework in Fig. 2 consists of (i) a portable wearable device placed on a patient's body including biomedical sensors, a custom design microcontroller and a power unit, (ii) a Smartphone that uses internet or wireless connectivity to collect the patient data, (iii) Cloud Data Service that store patient data, and (iv) Cloud Application Services that analyze patient data and deliver notification on patient vital sign changes to designated (end) users such as doctors, patients or designated staff through Cloud.

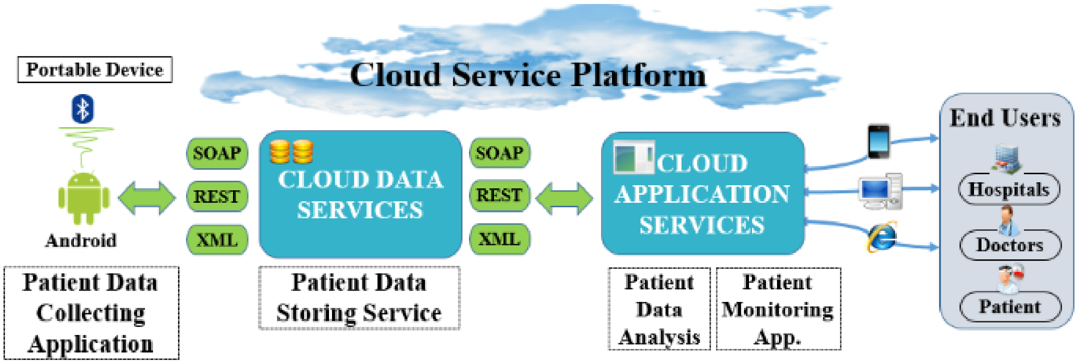


Figure 2. A framework showing the proposed patient monitoring based on portable wearable device, Smartphone and Cloud with their operational principles.

The hardware wearable device includes biomedical sensors, a IOIO board (a PIC micro-controller-based board), a power source and a Bluetooth module. While the software section consists of software programs that operate those sensors, the IOIO board and the Smartphone, as well as the communication between them and software analyzer to extract or mine features of patient vital signals.

An Android based patient application is developed for a Smartphone to collect sensor data from patients located anywhere at the first stage. The collected patient data in Android phone is sent to a custom web server application through any available internet connection (i.e. 4G or Wi-Fi). Then, the data server accumulates the patient data through Cloud and analyzes them with the help of powerful servers to monitor designated (end) users in real-time. These collected data are packaged properly in HTTP standards, with a known IP address of the PC, when the acquired data is sent. The developed special web server application helps to access and store data in the database server on the PC. Cloud offers many different features and pricing opportunities with their powerful APIs. Using a Simple Object Access Protocol (SOAP), APIs store data in Cloud easily in the mobile device.

2.3 Portable wearable device

The portable wearable device consists of IOIO development board, a Bluetooth adaptor, and three types of biomedical sensors (heart bit, temperature and ECG). These sensors are analog sensors that have a simplicity in writing programs and establishing a communication between the sensor and microcontroller. Analog sensors are also cheaper than digital sensors for our project. These sensors are used to collect raw signals from a human body and send them to the microcontroller unit of the IOIO board. The microcontroller unit transmits the data through a Bluetooth dongle to the Smartphone, which displays the output values graphically and numerically. The data are stored at the Cloud Data Services, but they can be saved to an SD card of the Smartphone.

IOIO-OTG board: IOIO-OTG [9] is a PIC microcontroller-based board designed for Android devices with the capability of interfacing with external hardware (sensors) using various common protocols (i.e. Bluetooth). The IOIO contains a single PIC24FJ256GB210 family microcontroller [9] that acts as a USB host and interprets commands from an Android application [10]. The IOIO board also supports both USB cable and Bluetooth module. In order to acquire sensor readings, I/O capability of sensors and its compatibility with IOIO is required because different sensors have a number of output protocols. The developed Android application runs on a Smartphone, after the program is installed to the IOIO board by connecting it to the Smartphone via a USB cable or Bluetooth dongle.

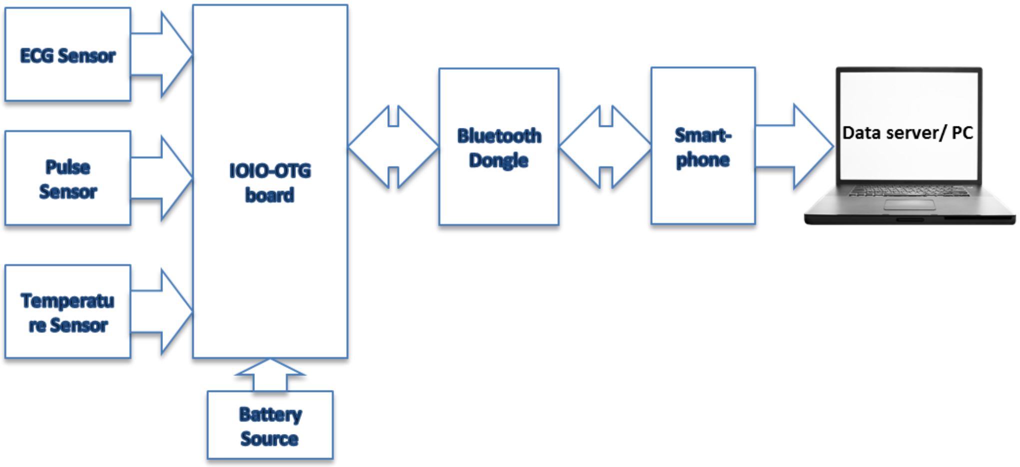


Figure 3. The hardware architecture of the portable device for patient data acquisition, and server communication for data collection and processing via a Smartphone.

Bluetooth adaptor: The Bluetooth adaptor (PL-5824) was used to establish wireless communication between the microcontroller and the Smartphone. The operating range (100 M), frequency band (2.4 GHz), maximum data rate transfer (1 MB) and sensitivity of the Bluetooth were found suitable for this study.

Power source: The power source consists of a lithium battery with a capacity of 300 mAh and a normal voltage of 3.7 V. We connected two of them in series to produce a total of 7.4 V. The IOIO board has input voltage ranges from 5–15 V, and output voltages of 3.3 V and 5 V. The expected battery life is 18 hours. Nokia charge adapters also can be directly connected to the board as an external extra power source during a test analysis, although it is not suitable for a mobile patient.

Electrocardiogram (ECG) sensor: ECG sensors are analog sensors used to monitor the electrical activity of the heart. To measure the electrical activity, we used three electrodes such as a positive, a negative and ground (GND) in order to form an electrical circuit. To produce the most useful information, we followed the optimized lead placements proposed by [11], who showed the points where each lead is arranged and measured. The three-lead ECG system based on three bipolar leads form the Einthoven's Triangle. The three leads consisted of two "active" and one "inactive" (earth). Lead I was used to measure the electrical potential between right arm (-) and left arm (+), while lead II was used measure the electrical potential between right arm (-) and left leg (+) [8]. Lead III was for electrical potential between left arm (-) and left leg (+) [12,13]. The two active leads were connected to in/out pins of 40 and 38 on the IOIO board. The inactive lead can be arranged anywhere suitable on the body [14] and was connected to GND on the IOIO board.

Pulse sensor: Pulse (heartbeat) sensor was used to measure heart rate in a simplistic way by monitoring the flow of blood through the earlobe or a fingertip. The acquired signal is amplified, inverted and filtered using a designated circuit on this sensor. The connections to the IOIO board are as follows: red wire to 3.3 Vin, black wire to GND and purple wire to pin 36.

Temperature sensor: The temperature sensor is an integrated circuit sensor that can be used to measure temperature with an electrical output proportional to the temperature. It is a low voltage precision centigrade temperature sensor [9]. TMP36 has 3 pins. The left pin (V_{in}) is the input voltage connected to 5 V pin on the IOIO board. The middle pin (V_{out}) is the analog output voltage that is connected to pin 36 of the IOIO board. The right pin (GND) is the ground pin of the IOIO board. The process of converting the voltage to temperature is based in the formula: $T\ (℃) = (V_{out} - 500)/10$, where voltage is in mV.

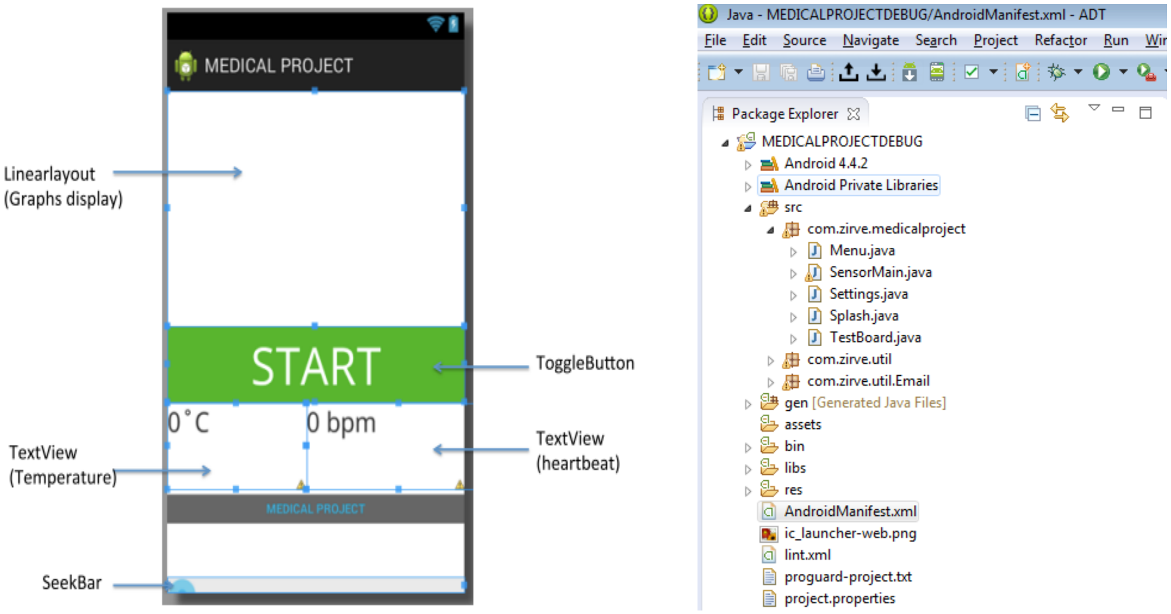
Customized Package design: a portable package was designed according to ergonomic design principles and guidelines to practically monitor elderly people and patient status periodically without impeding their normal activities. The customized package that contains the hardware device was made from special hard plastics that are placed on the upper arm (biceps) with an adjustable belt that looks like a blood pressure monitor, as shown in Fig. 4. The upper arm is close to all sensors connecting interested points on the body so patients can lay down, walk, stand or sit without their movement affected by the wearable device. The customized package has an aesthetic style that resists hand shaking and is comfortable and adjustable.

Figure 4. A customized package and the interface between the wearable device and a patient body.

2.4 Android Software Design

Android APIs provide powerful functionality on application development and support *Java* language features. Thus, we exploited the capabilities of the Android platform software [15]. An AndroidManifest.xml file provides information for the device to run the application in Android as shown in Fig. 5B with an example of activity and configurations. Fig. 5B shows the GUI of the Android application that patient data are collected from sensors using the developed Android based patient application. The software tools are Android Developer Tools (ADT) Bundle with Eclipse IDE [15] on a computer and Git server (Gitlab.com) to deploy the project which provides a collaborative working environment on the project and stores the history of changes in the project. The ADT Bundle includes Eclipse (plus ADT plugin) Android SDK Tools, Android Platform tools, the latest Android platform and the latest Android system image for the emulator.

The SensorMain.java in Fig. 5B includes the main sensor activity window (Fig. 5A) that collect all the sensor data, show graphs and texts, and set a time interval for sensor data collection. The Android application code was written in java language to collect and monitor sensor data. The developed application monitors and controls all the components and peripherals (sensors) connected within the portable wearable system. The patient data are collected with the help of some third party libraries including *IOIOLibBT* [19], which is an official library for the IOIO board to communicate and transfer data from the IOIO board to the Android device. To acquire sensor data from any analog input, *analoginput.getVoltage()* function [19] was used that returns a float number between 0-5.5 V. This library was used to develop functionality on the IOIO board via a Bluetooth protocol. The Android application was also designed to have additional email functionality.



(A) (B)

Figure 5. (A) A graphical user interface (GUI) of the Android application and various functionalities used for patient data acquisition and monitoring.

Figure 5. (B) AndroidManifest.xml file that provides information for a device to run the application in Android - an example of activity and configurations.

2.5 Storing and Analyzing patient data through Cloud

The fundamental principles of Cloud idea and one objective of this study are maximizing effectiveness, minimizing the cost, and accessibility. The growing Cloud industry can provide many services (i.e. database, web server, machine learning) on different service models (i.e. Software as a Service, Platform as a Service). Therefore, Cloud was chosen as a solution for storing and analyzing various data because of cost-effectiveness, worldwide accessibility, high computing capabilities and scalability against increasing number of patients. Cloud service providers present different web service APIs via Simple Object Access Protocol (SOAP), which is designed to exchange structured information. It relies on XML message format and Hypertext Transfer Protocol (HTTP) for message transmission [16].

In this system, the collected biomedical sensor data in each android device are sent to Cloud data services periodically (1-10 min) to store in a suitable data structure. The stored data is then used by big Cloud computing services for analyzing disease features or abnormalities with the help of developed analysis application. On the other hand, another web application on Cloud uses the analyzed results of patients to present them to end users.

3. Results

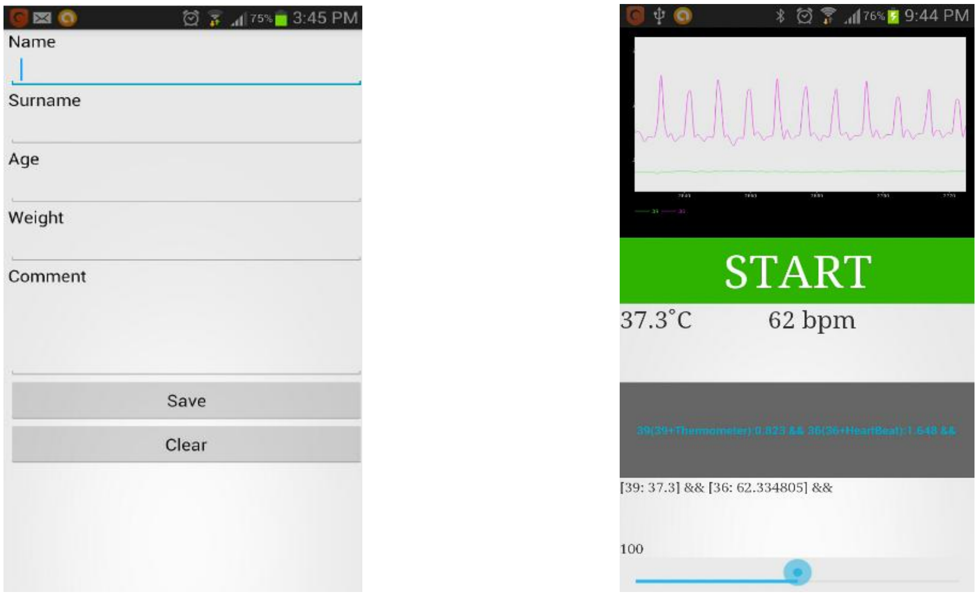
To evaluate the first prototype of the system and measure the vital signs continuously, five healthy male volunteers (instead of actual patients) were asked to perform different activities as listed in Table 1.

Table 1. The recorded details of healthy male volunteers.

	Age (years)	Weight (Kg)	Height (m)
Volunteer 1	30	83	1.74
Volunteer 2	26	84	1.8
Volunteer 3	32	61	1.72
Volunteer 4	32	70	1.71
Volunteer 5	28	69	1.68

To ensure if the device is functioning as required, four different test scenarios (Table 2) were carried out on these volunteers based on sitting (resting), standing (firm), lying-down (relaxing) and after running (3 minutes).

Secure authentication was required in order to ensure privacy of the individuals, so a password is required by the Android application to login when the application is started from the Smartphone before taking vital sign data from these volunteers. The patient data is securely registered and stored in this application (Fig. 6A), so only designated users can access them. Due to the common HTTP/S based Cloud, user communication is secure from any internet connected data server and android device. The pulse sensor for heartbeat measurement was placed at the fingertip. The temperature sensor was placed in the armpit. Then the application was open on the Smartphone after powering the device. The Bluetooth of the Smartphone was switched on so that the connection is established wirelessly between the two devices. The Bluetooth asked for the IOIO connection password and the connection is established after the password is entered. Fig. 6B shows measurement data graphically and numerically acquired from the patient monitoring device based on body temperature heartbeat.



37.3˚C 62 bpm

39(39+Thermometer):0.823 && 36(36+HeartBeat):1.648 &&

[39: 37.3] && [36: 62.334805] &&

(A) (B)

Figure 6. Screen short while testing temperature and heartbeat on the Android phone: (A) patient registration; (B) Android application GUI for data acquisition and monitoring.

It can be observed from Table 2 that the heart rate varies depending on the volunteers' activity. Each scenario provided its own information to indicate the system response to patient displacement scene. The normal heart rate for an adult is 60 - 100 bpm. From the results, the test measurements that we obtained from both ECG and heartbeat sensors fall within the normal ranges. For all those tests, we conducted data recording and sent them to the data server via Cloud.

Table 2. Heart rate values (bpm-bit per minute) obtained from the pulse sensor.

Scenarios	Sitting	Standing	Lying-down	After run
Volunteer 1	88	93	78	104
Volunteer 2	84	87	80	98
Volunteer 3	73	81	62	84
Volunteer 4	79	80	77	102
Volunteer 5	68	71	61	90

The results of the temperature measurement obtained from the test clearly vary with different scenarios within the normal body temperature range (0.6℃ either above or below 37℃). However, the average normal temperature also changes within the day depending on the activity of that person.

During the experiments, the data was stored in the volunteer's Smartphone. We send HTTP post request from the device to the data server, which worked on 192.168.42.176 and port number 140000 on this example to send the data from the device. The output data from biomedical sensors are *float* data type which is 4 bytes in a device memory. ECG and pulse sensors were evaluated at shorter time intervals with data points acquired continuously from each sensor at 100 milliseconds intervals, while thermometer data was collected in longer time intervals (every minute). Thus, total transferred data was approximately 30-35 Megabytes per day. However, transfer speed is mainly related to the connection bandwidth of an Android device. When this device is connected to a wireless with 3 MB of upload and 10 MB of download capacity, the total time for data transfer is about 2-5 minutes per day depending on data acquisition intervals.

For a scenario where a mobile device may not be able to find a fast internet connection like 3G or Wi-Fi, the transferring mechanism on the Android application was adapted to wired connection (USB cable to connect IOIO board to USB-wired internet) which also has a higher bandwidth that can adjust the uploading period of data accordingly.

4. Discussion and Conclusion

Internet of Things is a promising approach for remote patient monitoring in a healthcare system. This technology uses the ability of connectivity with low-power and low-cost modern sensor chips. Commonly used Smartphones can be well-suited to accumulate sensor data and transfer the acquired data with several interfaces like Bluetooth and 4G. The patient data can be centralized in the cloud for general operations so that a designated physician can access them, which makes data collection and processing cost-effective, and can meet the needs of the elderly and patients.

To provide a platform for integrative and ubiquitous patient monitoring, we proposed a cost-effective framework and designed a prototype of a wearable monitoring system that continuously measures body vital signs (temperature, heartbeat and ECG). The developed Android application running on the Smartphone can accumulate vital sign data via the Bluetooth connection on the IOIO board. The Android Smartphone sends the accumulated data to a designated data server, which saves the data on the server database and monitors sensor data on the patients' Smartphone.

The prototype design of the wearable device was tested to monitor vital signs of healthy individuals including heart rate, temperature, and ECG, ubiquitously. In our experiment, we tested connection and data transmission between the Smartphone and the standard PC (data server) in the same network. On the other hand, the monitoring was achieved by adding monitoring functionality to the server application. Due to the common HTTP/S based Cloud, user communication is secure from any internet connected data server or Android device, while a password is required by the Android application to login when the application is started from the Smartphone. The patient data is securely registered and stored in this application, so only designated users can have access to them.

This work is mainly about a feasibility study, so we only monitored the vital signs of healthy individuals including heart rate, temperature, and ECG remotely and ubiquitously, although we intended to use it on patients and the elderly population. Overall, the user experience on this wearable device is satisfactory and it did not affect the volunteers' activities. In terms of power consumption**,** since the wearable device has low power consumption, it provided a long battery life. However, the use of the device is also restricted by power consumption of the Smartphone. Overall success in test evaluation in terms of connectivity and speed shows that Cloud data services increase system performance and worldwide accessibility, making patient follow-up easy with immediate data access.

The system is cost-effective, portable, easy to use, and ubiquitous, since the main component of the system is a commonly used Smartphone (or tablet). Since the wearable device is expandable and maintainable, it can be upgraded with different IOIO compatible sensors including Airflow sensor for breathing, SpO2 sensor for blood oxygenation, Accelerometer to measure patient position. Those sensors can be added without changing the structure of the software or hardware.

Although testing of the ECG produced similar heartbeat in our study, the ECG signal feature was not good enough as it contained too much noise (baseline wander/low frequency noise, power line interference, noise due to muscle movement and other interference from other equipment), so it did not produce a proper ECG feature required by [18] even after post-processing. The automatic classification of myocardial infarction (MI) was not integrated in this study, but automatic cardiac disease classification was continued as a separate project using publically available off-line clinical ECG data [17]. An automatic classification of heart diseases on Cloud Application Services is one of the interesting and the most beneficial aspects of remote patient monitoring. However, according to our observation/survey on the ECG signal features, majority of the published papers did not show a proper ECG feature that meets this requirement for disease classification [18].

To classify cardiac diseases (MI), ECG features are selected from pre-determined time and scale intervals that correspond to Q-pattern, ST elevation / depletion, T inversion which carry the features / characteristics for the MI. The other examples of contiguous leads in 12-lead ECG are as follows, where the ST-T changes on those leads reflect Myocardial Infraction (heart attack) on certain parts of the heart [18]. For example, I, avL, V5 and V6 represent lateral wall of the left ventricle; II, III and avF are for inferior wall of the left ventricle; V1 and V2 are for septal part of the left ventricle; V3 and V4 are for anterior wall of the left ventricle; V1, V2, V3 and V4 are for anterolateral wall. Future developers should consider those facts and the urgent clinical need for automatic detection and classification of cardiac disease. The acquired ECG signals from wearable patient monitoring devices should conform to proper ECG features as required from [18] to perform cardiac disease classification automatically for intended patients or the elderly outside of hospital. Based on the properly acquired ECG signals, doctors can decide the cardiac status of patients to take an action during an emergency situation.

The cost of the wearable device (including the IOIO board, 3 sensors and battery) was about $100 dollars, which is cheaper than other existing products (i.e. QardioCore ECG Monitor: $449, AliveCor Kardia Mobile ECG). IoT also has been used in many areas in both academia and industry in a short period of time [20]. In recent years, the latest improvements in e-Health with this new paradigm makes patient monitoring feasible. The combination of cheap IOT sensors like Bluetooth and WiFi will allow successfully transferring patient data. Thus, patient monitoring is becoming a main interest of several global medical companies (i.e. Philips Medical, Apple, AliveCor) and they are actively working in this area as it is the need of society especially due to elderly aging problems and increased cost to monitor patient health in many countries. A faster detection of these life threatening events and an earlier start of therapy could help clinicians better diagnosis and treat their patients to save many lives and reduce successive disabilities eventually.

In the future, we will apply the disease classification algorithm [17] to ECG signals from the patient monitoring system after we meet the requirement of [18,12] for ECG disease detection and classification. We will also increase the reliability of the patient monitoring software as well runtime registration and deletion of users to deliver notification or warning, quickly and automatically to the hospital patient monitoring system when vital signs of a patient change adversely.

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