Real-time healthcare monitoring system using wireless sensor network

K.M. Al-Aubidy*, A.M. Derbas and
A.W. Al-Mutairi

Intelligent and Embedded Systems Research Group,
Faculty of Engineering,
Philadelphia University, Jordan
Email: alaubidy@gmail.com
Email: aderbas@philadelphia.edu.jo
Email: awm_mutairi@hotmail.com
*Corresponding author

Abstract: This paper presents the design, implementation and evaluation of a wireless portable healthcare monitoring system. It has a set of medical sensors connected to an embedded microcontroller with a wireless communication module. By scanning the medical sensors, the embedded microcontroller checks if the patient health condition is normal or not. In the case of abnormal condition, the embedded unit transmits the measured signals directly to a medical centre through the internet. According to the patient health condition, a doctor will send medical advice to the patient to address the abnormality of the patient. A prototype system has been designed, implemented, and validated by both laboratory test and comparison with recommended medical standards. A detailed analysis and evaluation of the healthcare unit is given in the paper. The obtained results indicate that the proposed healthcare system is accurate in scanning, clear in monitoring, reliable in communication, and can be used as a portable medical kit for outdoor patient monitoring and supervising, or as a medical station at home.

Keywords: embedded healthcare; wireless sensor networks; WSNs; ECG monitoring; biomedical device; outdoor patient monitoring.

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Biographical notes: Kasim M. Al-Aubidy received his BSc and MSc in Control and Computer Engineering from the University of Technology, Iraq in 1979 and 1982, respectively, and PhD in Real-Time Computing from the University of Liverpool, England in 1989. He is currently a Professor and Dean of Engineering Faculty at Philadelphia University, Jordan. His research interests include fuzzy logic, neural networks, genetic algorithm and their real-time applications. He was awarded Philadelphia Award for best researcher in 2000. He is currently the chief editor of two international journals, and a member of editorial board of several scientific journals. He has co-authored four books and published 80 papers on topics related to computer applications.

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1 Introduction

Due to the rapid advances in computer technology (hardware and software) and high speed wireless communications, network environments have changed from office oriented environments to home digital electronics networks (Hwang and Yu, 2012). Real-time applications based on home network are spreading significantly and have become of great importance, especially those dealing with remote monitoring and control areas. Recently, wireless sensor networks (WSNs) have been adopted for real-time monitoring and alarming in healthcare applications. Integrating medical sensors, microcontrollers, and smart phones which offer embedded systems to provide patients, doctors and medical centres with real-time health information to save time, cost, and lifes (Kumar, 2012; Mukherjee et al., 2014; Sarmiento et al., 2010; Pantelopoulos and Bourbakis, 2010).

WSNs are very suitable technology to deal with emergency situations, especially abnormal conditions of patients suffering from diseases during their normal lifes. Many researchers have developed WSNs for healthcare monitoring and disease detection. Chung et al. (2008) proposed a healthcare monitoring system with ECG and blood pressure measurement, where a mobile phone performs continuous data analysis and then transmits data over a wireless sensor network. Kumar et al. (2012) mentioned that WSNs have delivered significant improvements to the healthcare systems in the 21st century and will continue to play a central role in the future of modern healthcare industry. Monitoring health conditions of a human body is a multidisciplinary task, which involves sensing, intelligent computing and wireless networking (Yan et al., 2015). Continuous monitoring of the biomedical signals related to current heart activity is necessary for patients suffering from diseases (Saxena et al., 2003). Such online monitoring systems require software for both uploading patient's health signals through the internet, and allowing medical staff to monitor the patient's state.

Using computers, smart mobiles and wireless technology in healthcare applications will achieve many goals, such as shorter diagnosis time, accuracy, increasing number of monitored patients, and reducing of paper work and many others (Fotiadis et al., 2006). In such applications, doctors can monitor their patients anywhere and at any time without the need for the patient to stay in hospital (Rout et al., 2013; Tomašić and Trobec, 2011). Rajasekaran et al. (2013) demonstrated that WSN technology can offer a wide range of benefits to patients, doctors, medical centres, and society through continuous monitoring, early detection of abnormal conditions, supervised rehabilitation, and potential knowledge discovery through data mining of all gathered information. In fact, smart mobile phones are integrated with wireless network; therefore, it is useful to use these devices for remote medical data sensing, data acquisition, and monitoring. Such technology will help doctors to identify the health problem using online scanned signals and medical history of the patient.

The big challenges of health monitoring systems are the real-time detecting of abnormal health conditions and fast action from the medical centre. In some cases, when the patient is outdoors and feels something wrong, hospital tests show that everything is normal. In fact, it is not easy to detect all kinds of abnormal activities unless real-time monitoring is done by keeping the patient in the intensive-care unit (ICU) in the hospital for few days. Therefore, a wireless real-time portable monitoring device can be developed to help the physician and the medical centre to give proper medical treatment and procedures.

This paper is an extension version of a paper submitted in an international conference (Al-Aubidy et al., 2016). Its objective is to design and implement a real-time healthcare monitoring and guiding system. The proposed system is a portable unit based on a single-chip microcontroller equipped with a set of medical sensors. The embedded microcontroller has a wireless communication tool to transfer real-time medical information between the patient and the medical centre. The organisation of the paper is as follows; Section 2 describes types and characteristics of the selected sensors. Section 3 briefly describes the hardware and software design of the proposed system. Blood pressure calculation and calibration are given in Section 4, while Section 5 discusses calculations of electrocardiography (ECG) parameters. The implemented prototype testing and evaluation are described in Section 6. Finally, a related conclusion and future work suggestions are listed.

2 Medical sensors

Integrating medical sensors with wireless communication technology to fellow up the patient's health conditions during his/her normal life has great advantages for both the patient and the doctor. In this case, each patient is considered as a node in a WSN connected to a central node located at a medical centre through an internet connection. The node is a portable healthcare unit with an embedded microcontroller connected to a set of medical sensors as shown in Figure 1.

Figure 1 Layout of the system architecture

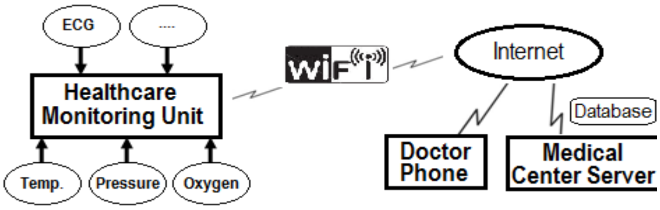


Table 1 Characteristics of medical sensors

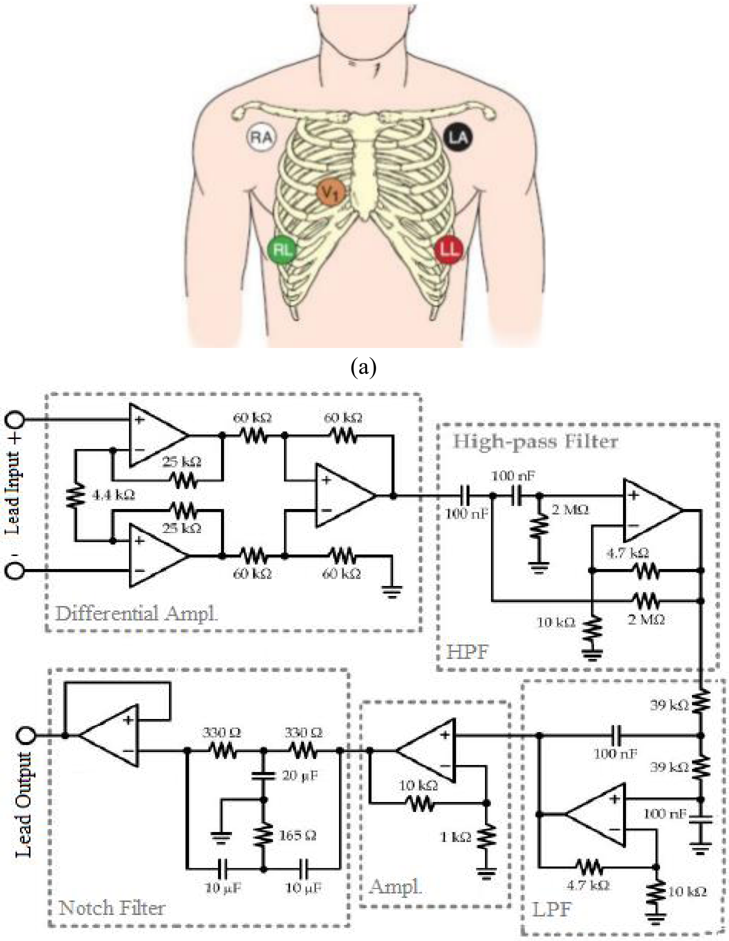
Medical sensor	*Signal range*	*Sampling frequency*
Electrocardiograph (ECG)	0.01–5.0 mV	100 sample/sec
Finger pulse oximeter (SpO_2)	45–200 beats/min 12–40 breaths/min	100 sample/sec
Blood pressure	40–300 mmHg	1 sample/sec
Temperature	20–50 Celsius	1 sample/sec

Real-time measurement of health parameters depends on the medical case of the patient and sensors required for health monitoring. For the proposed healthcare system design, a set of reliable, small and low power medical sensors were considered. Table 1 illustrates the general characteristics of the selected sensors. Four sensors were used to measure five variables; heart rate, oxygen level, blood pressure, human temperature, and ECG signals.

2.1 ECG sensing

ECG is the process of recording electrical and muscular functions of the heart during a period of time. The implemented ECG unit uses only five electrodes (RA, RL, LA, LL and V1) attached to the human body. Each ECG sensor detects the signal and converts it to an electrical signal with amplitude varies from 1 mV to 5 mV. The analogue signals generated from the ECG electrodes are filtered and amplified using a signal conditioning circuit given in Figure 2. It consists of an instrumentation amplifier, high pass filter, low pass filter (with cut-off frequency of 150 Hz), gain amplifier, and notch filter.

Figure 2 ECG Sensing unit, (a) ECG leads placement (b) signal conditioning unit (see online version for colours)



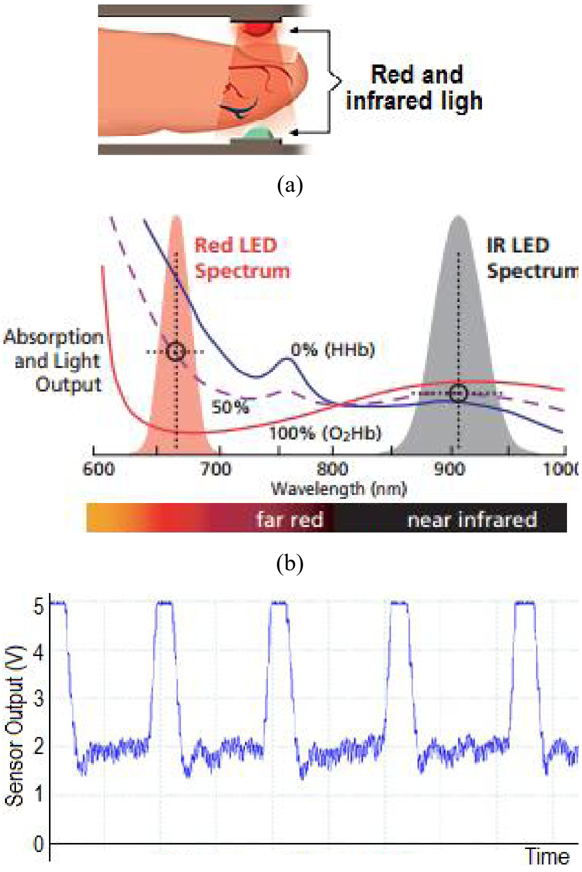
(a)

(b)

2.2 Heart rate and oxygen level detection

A finger pulse oximeter is used to measure both the level of Oxygen saturation (SpO_2) and the heart beat rate. It consists of red or infrared LEDs and a photodetector that receives light from the site being measured. The pulse oximeter principle works by using this red or infrared light to measure the light absorption characteristics of hemoglobin in the blood. As illustrated in Figure 3, the hemoglobin groups can absorb energy of various wavelengths of light, depending on whether the hemoglobin is oxygenated (absorbs more infrared light) or deoxygenated (absorbs more red light). This help to measure the relative transmittances of the IR and red light, convert these transmittances into absorbances, and then compare these values to approximate blood oxygenation (Pulse Oximetry, 2016). The output pulses generated from the pulse oximeter sensor are used by the microcontroller to calculate the heart rate of the patient.

Figure 3 Principles of finger pulse oximeter sensor, (a) finger pulse oximeter sensor (b) absorption and light output (c) sensor output pulses (see online version for colours)



(a)

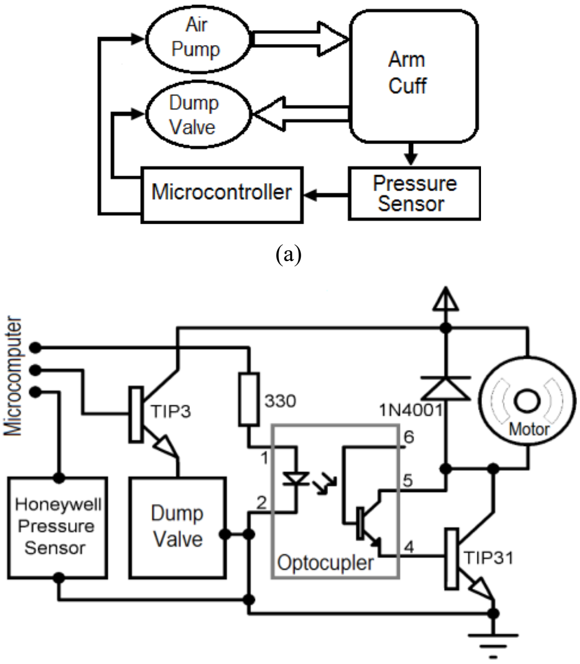
(b)

(c)

2.3 Blood pressure sensing

A Silicon pressure sensor type (ASDX 015PDAA5) has been used to measure the blood pressure. It offers digital interface with the embedded microcontroller, as illustrated in Figure 4. The pressure sensor is connected to a dump valve and a DC motor through an air pipe. The embedded microcontroller is used to manage the sequence and operation of the DC motor and the dump valve to obtain the blood presser readings. The measurement method is based on the detection of the pressure variations in the arm cuff detected by the pressure sensor. This sensor offers high voltage output (4.0 Vdc span) with ±2.0% accuracy over the specified full scale pressure span.

Figure 4 Blood pressure sensing, (a) measurement method (b) interfacing circuit



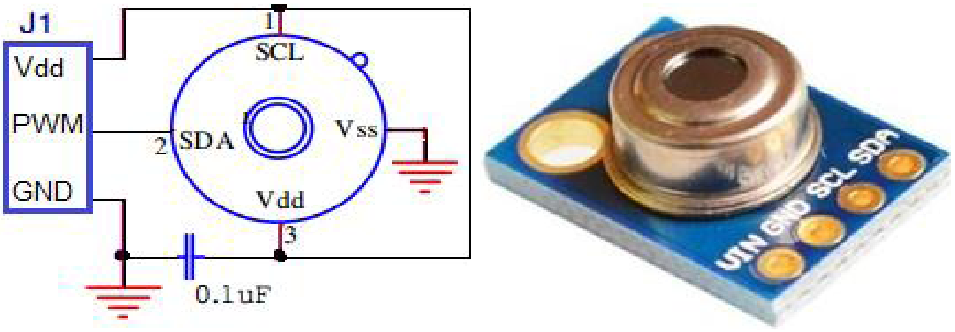
(a)

(b)

2.4 Temperature sensing

The MLX90614 is a small size, low cost, non-contact Infra-Red temperature sensor built from two chips: the infra-red thermopile detector, and a signal conditioning. It offers 10-bit PWM output signal for continuous temperature measurement with an output resolution of 0.14°C. It can be connected directly to the microcomputer input, as shown in Figure 5.

Figure 5 Temperature sensor (see online version for colours)



(a) (b)

Source: Melexis Co (2013)

3 Healthcare system design

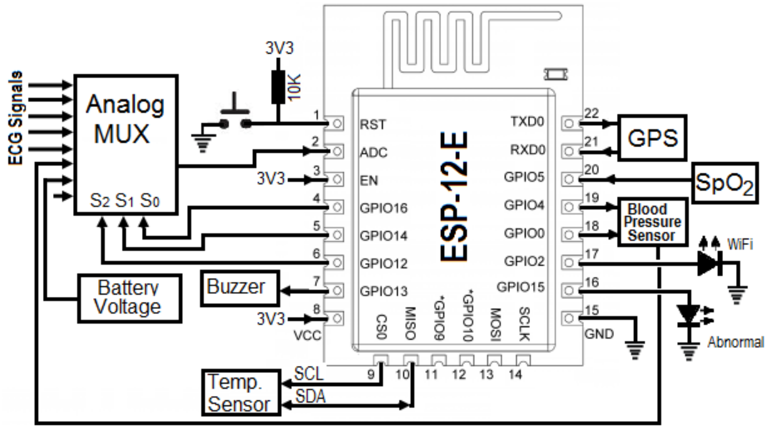
The proposed monitoring system is composed of two sections; the patient embedded unit, and the medical centre unit (server), as illustrated in Figure 1. This paper will consider design and implementation of the first section. A microcontroller with wireless communication tool is interfaced with set of medical sensors. Wireless communication can be achieved between the patient and the authorised medical centre. The doctor can communicate with the patient medical case either using his smart phone or a computer with internet access. The embedded healthcare unit represents the core of the monitoring system. It performs the following:

- setting initial parameters for the system, and the patient
- collecting raw data from the medical sensors
- processing measured signals to calculate and detect abnormal conditions
- transmitting scanned data and related health parameters to the medical centre's server if there is any abnormal condition
- receiving online recommendation from the doctor
- offering real-time display for biomedical measurements and medical guidance sent from the doctor.

3.1 Hardware design

The ESP-12E module is a single chip microcontroller designed based on the ultra-low power consumption UART-WiFi ESP8266 processor. It has integrated low power 32-bit processor, 10-bit ADC, 2.4 GHz WiFi, TCP/IP protocol stack, internal antenna, around 36 kB RAM and 4 MB external flash memory to store user programs. It is recommended for mobile devices and WSN applications. For these features it is used in the proposed prototype of the healthcare system.

Figure 6 Hardware design of the embedded sensing unit



Four sensors are interfaced to the microprocessor module which has a single analogue input. An analogue multiplexer is used to interface the analogue output signals from the ECG electrodes, blood pressure sensor, and the battery voltage level sensor. The PWM signal generated from the temperature sensor, and the generated pulses from the Oxygen level (SpO_2) sensor are connected directly to the microprocessor module. Figure 6 illustrates the hardware design of the embedded unit which offers wireless communication with medical centre through the internet. It is clear that real-time scanning, monitoring, processing of medical parameters, accessing real time global positioning system (GPS) location, and send everything via 3G/4G connection to internet, will consume a lot of energy. Therefore, a portable battery is required to provide enough energy for portable system besides charging mobile phone for ten hours continuous.

3.2 Software design

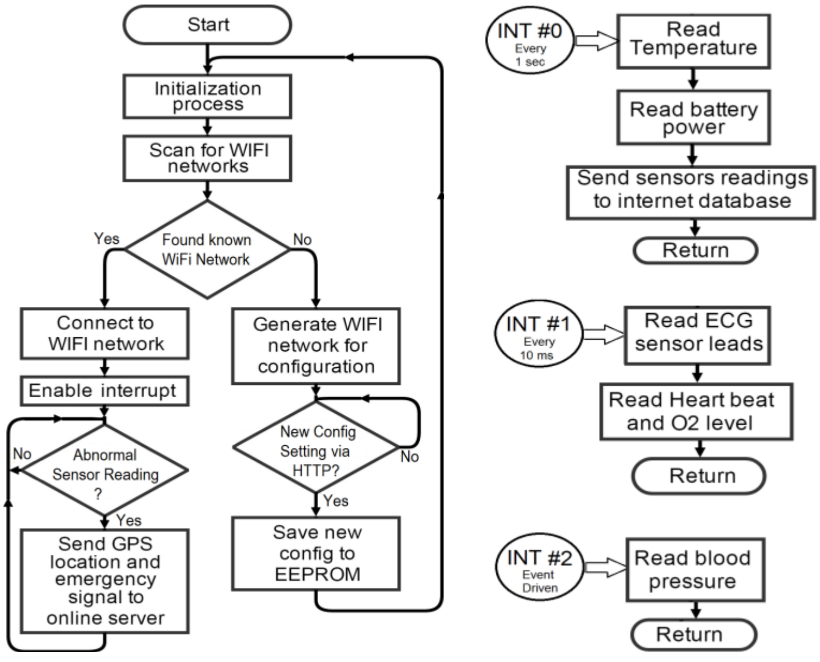
The software is divided into two main parts; the embedded microcontroller software, and the medical centre server online database.

3.2.1 Embedded unit software

The software of the embedded unit consists of two parts; the main program and the interrupt service routines, as shown in Figure 7. The main program starts by initialising assigned sensors to physical I/O ports, providing baud rates and reading EEPROM memory for saved WiFi networks passwords. Then, it starts up built in WiFi and starts searching surroundings for a known WiFi network. If EEPROM is empty or no known WiFi is found, the program calls a function to broadcast a WiFi network. This allows the user to connect to device IP address and configure the microcontroller chip (ESP-12E).

Configuration includes adding new WiFi settings, deleting a WIFI network from list, changing sensors settings or calibrating them. All data are saved on EEPROM, and the microcontroller initiates a reset command to apply new settings. If the microcontroller starts and finds a known WIFI network after reset, it connects to it and activates interrupts besides trying to ping online database then starts blinking WiFi LED every two seconds to indicate a stable connection to internet.

Figure 7 Software design flowchart, (a) main program (b) interrupt service routines



(a) (b)

When an interrupt happens, one of the interrupt service routines will be executed. The first interrupt (interrupt #0) is assigned to timer (TMR1) and set to frequency of 1 Hz. The second interrupt (interrupt #1) is assigned to timer (TMR2) and is set to frequency of 100 Hz. The third interrupt is a hardware driven type caused by the WiFi to receive blood pressure reading command. When first interrupt occurs, it reads both temperature sensor and battery remaining voltage (V). The percentage of battery voltage (V_{bat}) is given by;

$$V_{bat} = \frac{(V - V_{\min})}{(V_{\max} - V_{\min})} \tag{1}$$

where

V	current voltage measured from sensor at any time
$V_{\min}$	minimum voltage of battery at empty state
$V_{\max}$	maximum voltage of battery at full state.

The values of $V_{\max}$ and $V_{\min}$ are preloaded to the EEPROM depending on battery type and calibration test results. Then all sensors readings are sent to online database as records.

When the second interrupt occurs, the microcontroller reads ECG sensors, heartbeat and oxygen level. When Event driven interrupt occurs, the microcontroller calls blood pressure measuring procedures.

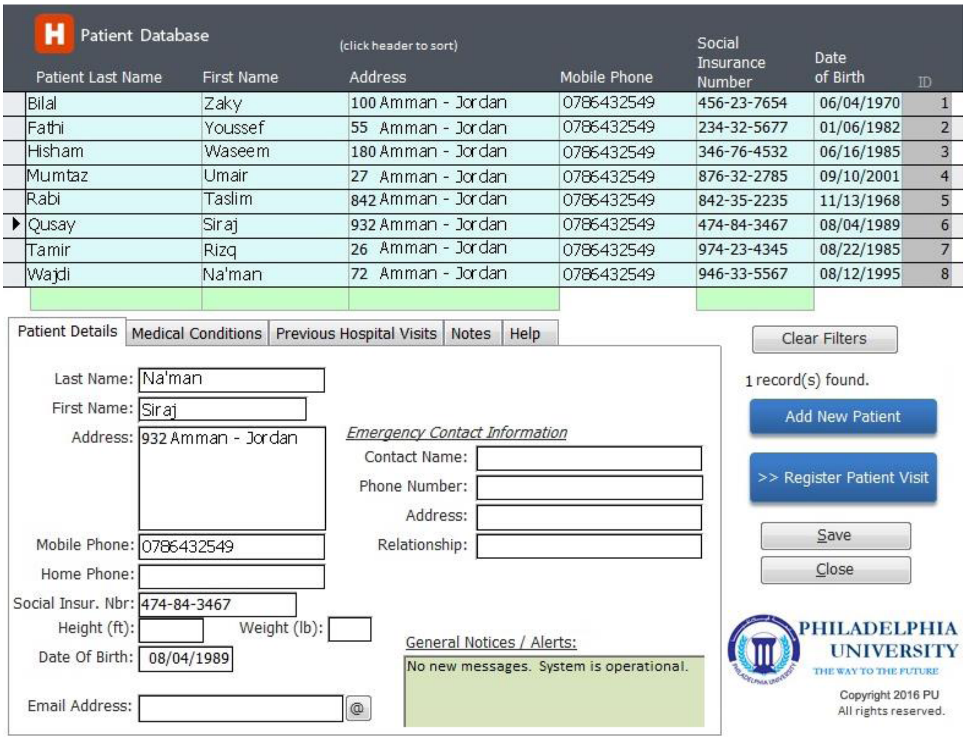
All readings are compared with pre-saved accepted values for patient, if the comparison returns an abnormal value, the microcontroller reads GPS and sends current location with emergency signal to online database, it also uses online service to send

SMS and perform multiple missed calls to both the medical centre and the physician numbers. The SMS contains a direct link to patient profile in online database to view his readings and GPS location in real time.

3.2.2 Medical centre software

To achieve real-time communication between patient embedded unit and the medical centre, a server is required to create and access online database. Measured signals from medical sensors will be sent to internet database via WiFi connection. For the implemented prototype, a domain on a host has been used for testing purposes, and a database has been created using PHPMyAdmin that is accessible through http://host/phpmyadmin.

Figure 8 GUI on medical centre's server (see online version for colours)



Patient Last Name	First Name	Address	Mobile Phone	Social Insurance Number	Date of Birth	ID
Bilal	Zaky	100 Amman - Jordan	0786432549	456-23-7654	06/04/1970	1
Fathi	Youssef	55 Amman - Jordan	0786432549	234-32-5677	01/06/1982	2
Hisham	Waseem	180 Amman - Jordan	0786432549	346-76-4532	06/16/1985	3
Mumtaz	Umair	27 Amman - Jordan	0786432549	876-32-2785	09/10/2001	4
Rabi	Taslim	842 Amman - Jordan	0786432549	842-35-2235	11/13/1968	5
▶ Qusay	Siraj	932 Amman - Jordan	0786432549	474-84-3467	08/04/1989	6
Tamir	Rizq	26 Amman - Jordan	0786432549	974-23-4345	08/22/1985	7
Wajdi	Na'man	72 Amman - Jordan	0786432549	946-33-5567	08/12/1995	8

1 record(s) found.

Last Name: Na'man
First Name: Siraj
Address: 932 Amman - Jordan
Mobile Phone: 0786432549
Home Phone:
Social Insur. Nbr: 474-84-3467
Height (ft):
Weight (lb):
Date Of Birth: 08/04/1989
Email Address:

Emergency Contact Information
Contact Name:
Phone Number:
Address:
Relationship:

General Notices / Alerts:
No new messages. System is operational.

The database has a good GUI built on PHP and can be queried via MySQL, as illustrated in Figure 8. The online database consists of patient list that shows personal information about patients with a search by name/mobile phone options. When a patient is selected, his/her information can be modified, and if there is any abnormal case in last 24 hours, it will appear as a note besides providing the date and time of last update from the biomedical system. Medical conditions tab shows database entries for specified patient, such as all normal and abnormal readings uploaded into database.

The communication protocol between online database and patient's healthcare unit happens as https requests sent from patient device to online database. The request consists of a package with seven records, as shown in Table 2.

Table 2 Format of the request package

Header	*Patient ID*	*Password*	*BP reading*	*ECG reading*	*SpO_2 reading*	*Heart rate reading*	*Checksum*	*Tail*
1 byte	5 bytes	12 bytes	2 bytes	4 bytes	1 byte	1 byte	4 bytes	1 byte

The header is a single byte fixed value to tell server that there is an update, the header used is 0xCE. The ID represents the patient's ID in hospital, and is preloaded with every device and consists of 5 bytes numbers. The <Password> is a special preloaded password for data upload, it consists of 12 random generated bytes from computer application, and installed in both patient device and online database. In case of password mismatch, the online server will ignore received packet. The blood pressure reading <BP-reading> consists of two values (high and low), each is represented by 2 bytes. The <ECG-reading> is five lead average reading numbers, where one of them is considered as a reference. There are four average reading numbers received during a predefined time (T), each reading is sent as 1 byte packet. The <SpO_2 reading> is a percentage value and requires single byte. The <heart-rate-reading> is a single byte number determines how many pulses per minute are detected. The <checksum> is 4 bytes number to check if data is received correctly or not? Actually, it is not needed in TCP connection because they are automatically added, however, the checksum is added as a security step because it would be harder to send a fake package and determine both checksum and password in it. The <tail> is a single byte number that determines end of packet, here 0xDC is used.

The packet length is 31 bytes, and does not need a lot of traffic to be sent. In order to receive packets from server such as calibration packets or BP requests, then wait until next update and reply with a simple HTML page that contains all needed requests. The microcontroller will read the reply, check password and checksum parameters then start performing commands.

Commands sent from server side can include set/clear for patient ID, password beside setting sampling time (T), timeout to send requests and calibration signals for sensors beside ability to add offsets on sensors readings.

In case of abnormal condition, the microcontroller changes all sampling times to minimum and performs higher traffic to push more data to the server, and packet size changes from 31 bytes to 40 bytes, since the GPS location will be added before the checksum at the end of packet.

In case of connection loss, the microcontroller will store readings on EEPROM memory, which is around 4 MB, and can store up to 524,288 reading streams because each reading stream is 8 bytes of data, this is enough offline sampling for two months at sampling rate (T) of ten seconds.

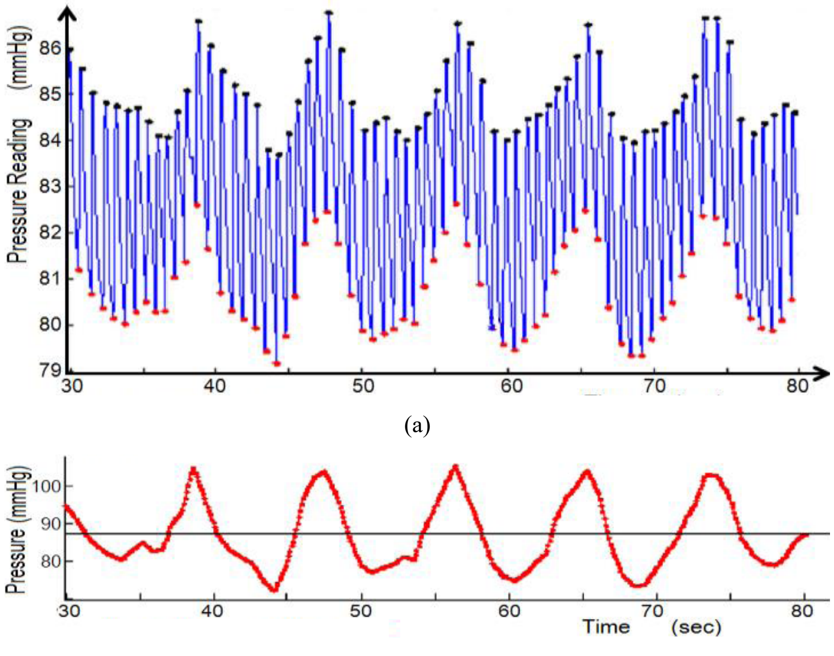
4 Blood pressure measurement

The embedded microcontroller of the healthcare unit scans the pressure sensor and calculates blood pressure by using the following sequences:

- Read pressure sensor.
- Start listening to ADC.
- Completely deflate cuff by opening corresponding valve.

- Start inflating cuff until it reaches 180 mmHg.
- Measure and process ADC value and start looking for systolic pressure value where signal oscillation is detected and starts to grow. If the program counts more than four pulses, the reading is accepted and current pressure is recorded.
- Deflate cuff by 5 mmHg and process ADC signal again, and repeat until signal oscillation stops, where this reading is also recorded.

Figure 9 Signals from the blood pressure sensor, (a) raw data (b) filtered data (see online version for colours)

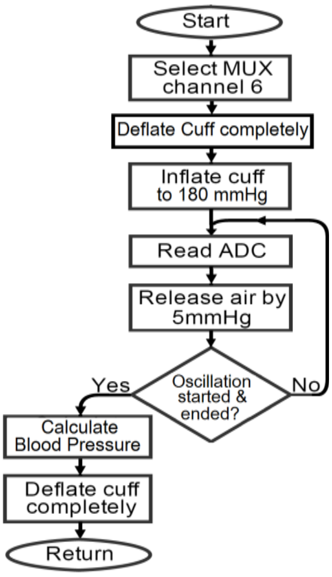


(a)

(b)

The detected oscillation in pressure signal is the heart rate, thus the systolic limit of blood pressure indicates the maximum pressure that allows blood to pass, and minimum limit indicates minimum pressure that allows us to measure oscillation. As shown in Figure 9, the blue line indicates raw data received from pressure sensor after physical filtering, while the red line shows heart rate oscillation after software filtration process. As illustrated in Figure 10, the controller makes sure that cuff has been inflated completely, and then it enables ADC interrupt to take samples when needed. Then, the motor starts and flats cuff to 180 mmHg (as default set), and bump starts to inflate cuff by 50 mmHg each time. When oscillation is detected and four pulses are counted, the value is recorded as systolic blood pressure, after that the microcontroller keeps measuring oscillation while cuff is being deflated until oscillation falls down under accepted threshold. This value is recorded as diastolic blood pressure value.

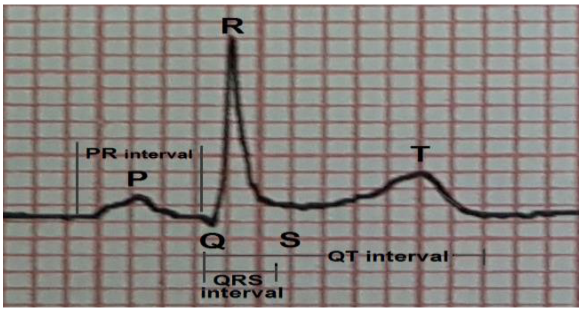
Figure 10 Blood pressure measurement flowchart



5 ECG parameters measurements

Several authors (Chugh and Gupta, 2013; Kumari et al., 2015; Gradl et al., 2012), have mentioned that a typical ECG signal is characterised by five points (P, Q, R, S, and T). It consists of three main waves; PR interval, QRS duration, and QT interval, as given in Figure 11. Table 3 lists the main features of a normal ECG signal for a healthy person (Islam et al., 2015).

Figure 11 Main components in ECG signal (see online version for colours)



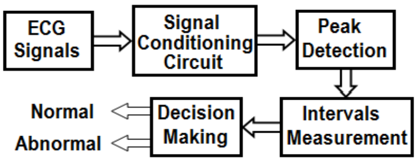
In fact, the original signals detected from ECG sensors are noisy signals, and the peaks of the ECG signal cannot be detected easily. Therefore, a signal conditioning circuit together with an algorithm implemented by the embedded microcontroller are required to cancel any noise and detect peaks, as illustrated in Figure 12. The initial step for ECG parameters extraction is to detect P, Q, R, S and T peaks, then measure the intervals PR, QRS and QT. A rule-based decision maker has been used to detect if the

ECG diagnosis is normal or abnormal. It is based on real-time measurements of the extracted ECG features. In this paper, several cardiologists have been consulted to find relationships between ECG intervals and final decision.

Table 3 Features of a normal ECG signal

Parameter	*Range*
Heartbeat rate	60–100 bpm
PR interval	120–200 msec
QRS interval	40–100 msec
QT interval	Less than 400 msec (male) Less than 450 msec (female)
P wave duration	Less than 100 msec
P wave amplitude	Less than 0.25 mV

Figure 12 ECG parameters measurements



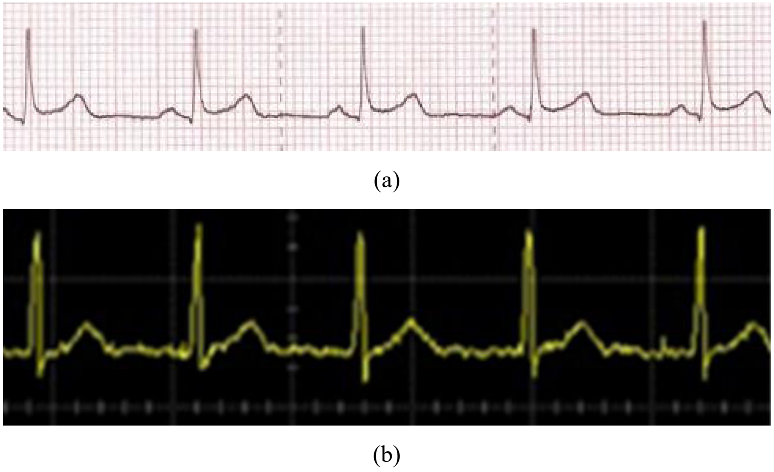
6 System evaluation and discussion

The healthcare monitoring prototype has been tested to make sure that all hardware and software components work properly. The embedded microcontroller has WiFi module for wireless communication between patient side and the medical centre through the internet. The implemented database involves the medical history of every patient including collection of laboratory results, and assessment of a patient's health status. In addition, the implemented database involves the online data received from the patient's healthcare unit including heartbeat rate, ECG signal, and blood pressure. A graphical user interface, shown in Figure 13, has been designed to allow both patients and doctors to monitor the extracted medical signals and parameters in real-time mode.

Figure 13 The GUI monitoring screen (see online version for colours)

The implemented healthcare prototype has been tested to check its functionality, reliability and performance. It is compared with reliable, standard and calibrated medical devices in the medical centre of Philadelphia University-Jordan. Figure 14 shows normal ECG waveforms recorded from both the implemented healthcare monitoring unit (device A) and a recommended device at the medical centre (device B). It is obvious that both waveforms are identical in shape and giving similar measured parameters. In fact, blood pressure readings, oxygen level, temperature, the heartbeat waveform, selected ECG waveform, and other medical parameters generated from the implemented prototype are almost identical to what obtained from the recommended devices at the medical centre, as given in Table 4. It is clear, that the obtained results and graphs are accurate in scanning, clear in monitoring, and reliable in communication.

Figure 14 Normal ECG waveforms, (a) recorded from a medical centre (b) recorded from the healthcare prototype (see online version for colours)



(a)

(b)

Table 4 Validation results of the proposed work

Device	*Temperature °C*		*Oxygen level*		*Heart rate (bpm)*		*Blood pressure (H/L) mmHg*	
	A	*B*	*A*	*B*	*A*	*B*	*A*	*B*
Patient 1	37.1	37.1	97%	96%	79	79	125/92	127/89
Patient 2	37.0	37.0	97%	97%	80	80	120/80	123/80
Patient 3	37.8	37.8	92%	93%	84	84	123/89	122/88
Patient 4	38.1	38.0	92%	92%	85	86	130/91	130/90
Patient 5	37.3	37.3	94%	95%	78	79	135/90	130/90
Patient 6	37.6	37.6	99%	99%	79	79	110/80	109/82
Patient 7	37.3	37.2	92%	92%	82	81	108/83	108/85
Patient 8	37.2	37.2	95%	95%	75	77	122/91	121/90
Patient 9	38.0	38.0	95%	96%	86	87	136/95	133/95
Patient 10	37.4	37.4	94%	94%	89	88	109/83	108/81

7 Conclusions

A wireless healthcare monitoring and guiding system has been discussed in this paper. A low-cost prototype system has been fabricated, assembled and validated in both laboratory test and in medical centres. In addition, embedded software has been designed for real-time scanning, calculating, monitoring and communication with medical centre's server.

The collected data from medical sensors are used by the embedded microcontroller to detect any abnormal health condition in a patient. Accordingly, doctors can use the scanned data to advise the patient online through the internet. Such a system has good ability to process real-time signals generated from biosensors and transmit the measured signals to the medical centre's server through the internet. The functionality and readings of the implemented prototype has been tested and compared with reliable, standard and calibrated medical devices in the medical centre of Philadelphia University. The electronic board size of the implemented prototype is 8 cm × 5 cm and the weight is less than 120 g. The total power consumption is about 300 mW that covers at least 37 working hours. Therefore, the proposed system is suitable for healthcare monitoring. Its functionality is almost similar to the normal monitoring systems used in the ICUs at hospitals. The proposed system can be modified as a home device connected to the internet, by adding extra test units such as Glucose, Uric Acid, Cholesterol, and others.

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