An Intelligent IoT-Based Wearable Health Monitoring System

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Abstract. Due to the increasing usage of wireless technologies and the miniaturization of electronic sensors, progress in wearable health monitoring technologies has been improved drastically. With strong potential to alter the future of healthcare services by using Internet of Things (IoT) active health monitoring sensors for omnipresent monitoring of patients and athletes through their regular daily routines. Medical applications such as remote monitoring, biofeedback and telemedicine create an entirely new base of medical quality and cost management. The objective of this work is to develop a low cost, high quality multipurpose wearable smart system for healthcare monitoring of heart diseases patients, and fitness athletes. In this paper, we discuss the three phases of our proposed system. In the first phase, we use the Raspberry-Pi as an open source microcontroller with a HealthyPi hat acting as a medium between the Raspberry-Pi and the biomedical sensors connected to HealthyPi hat, with various parameters such as temperature, ECG, heartbeat, oximetry etc. We began our experiment using 15 test subjects with different genders age and fitness level. We, placed the proposed wearable device and collected the readings data for each test subject while resting, walking and running. The second phase is connecting our system to an open source IoT platform to represent the data through a graphical IoT dashboard to be viewed by doctors remotely, as well as implementing action rules that send alarms to patient and doctor in case of problem detection. In the third phase, we designed and tested a Fuzzy Logic system that inputs the accelerometer, gyroscope, heart rate and blood oxygen level data collected from the experiments, and provides the physical state (resting, walking or running) as output, which helps in determining the health status of the patient/athlete. The obtained results of the proposed method show a successful remote health status monitoring of test subjects through the IoT dashboard in real-time, and detection of abnormalities in their health status, as well as efficient detecting the physical motion mode using the proposed fuzzy logic system design.

Keywords: Raspberry-Pi, Internet of Things, Fuzzy, ECG, Telemedicine, Biofeedback, Accelerometer, Gyroscope, Wireless.
1 Introduction

A great aim is to provide a multipurpose system that not only can be used to monitor heart disease patients or fitness athletes’ performance but also used in rural areas and countries with low healthcare capabilities and budgets.

The areas of IoT, telemedicine and biomedical sensors were researched to reach the design and method of implementing a multipurpose wireless monitoring system for patients and athletes. [1-2].

The importance of a wireless monitoring system for patients and athletes is outlined in identifying the patient’s essential health parameters and activities remotely with the assistance of sensors situated on the human body.

This paper proposes a real-time multipurpose system based on IoT that can share real-time medical data between the patients and doctors. This proposed system has an extensive application area, which includes but not limited to the management of disease like heart disease, where the patient needs to be continuously monitored, or the monitoring of athlete health status and fitness level.

Now, we are highlighting some of the many benefits of the proposed system

- Cost effective: the patient or athlete can be monitored remotely from any location. This minimizes the travelling cost, hospital bill and time wastage for multiple visits.
- Fast services: the system enables immediate assistance to the patient by the healthcare takers and doctors.
- Management on real-time basis: this enables the patient to get necessary treatment immediately, which helps in preventing further complications.
- Improvement of life quality: the proposed method can also help ageing people, as well as chronically ill people to improve their life quality with the assistance of health experts who will be monitoring the patient’s health status and receive notifications of any abnormalities.

Further data analysis is performed by designing a fuzzy logic system using the Mamdani method, to detect the type of physical motion taking place, enabling doctors to fully understand all aspects of the patient’s health status. This is in addition to provide fitness athletes assurance over their health status and enable them to strive for improvement in their fitness levels [3-6].

2 Proposed Method

Figure 1 shows the block diagram of our proposed system which is divided into three phases.
Fig. 1. Multipurpose IoT ready health monitoring proposed system block diagram.

In the first phase, the ECG sensor, the temperature sensor and the SPO2 sensor begin data collection and transmit it to the HealthyPi controller. The controller performs the configured digital signal processing in its programming code on the raw input data and provides a clear, understandable output that is transmitted to the Raspberry Pi. [7-8]. In the second phase, the Raspberry Pi immediately begins transmission of the output data to the selected IoT dashboard using the MQTT protocol. In the third phase, we use the provided output data to perform further analysis and enable detection of physical and health states of the patient/athlete. The output data are used as inputs in our Fuzzy Logic system which we designed using the Mamdani Fuzzy Inference method. Five inputs are added to the system: Accelerometer in x-direction, Accelerometer in y-direction, Gyroscope in y-direction, Heart Rate (HR) and Oxygen Saturation.

Membership functions are determined for each sensor and each motion type output. Then, we populated the inference engine with our if-then rules to relate the inputs to outputs using the data readings from the experiments. The inference engine obtains the degree of fulfillment for each input and infers the membership degree of each output from the fuzzy rules. The most probable output is then obtained from the membership degrees of each output through defuzzification.
2.1 Hardware Components Used in Proposed System

2.1.1 Raspberry Pi 3 B+
The Raspberry Pi is a series of small single-board computers developed by the Raspberry Pi Foundation to promote the teaching of basic computer science in schools and developing countries.

The Raspberry Pi 3 Model B+ is one of the latest products in the Raspberry Pi 3 range, boasting a 64-bit quad core processor running at 1.4 GHz, dual-band 2.4 GHz and 5 GHz wireless LAN, Bluetooth 4.2/BLE, faster Ethernet [9]. This is illustrated in Fig. 2.

![Raspberry Pi 3 B+ specs](image)

Fig. 2. Raspberry Pi 3 B+ specs [9].

2.1.2 HealthyPi 3 Hat
The HealthyPi, Fig. 3, is the first fully open-source, full-featured vital sign monitor. Using the Raspberry Pi as its computing and display platform, the HealthyPi add-on HAT turns the Raspberry Pi into a vital sign monitoring system. It includes the following sensors: ECG and respiration: TI ADS1292R, Pulse oximetry: TI AFE4400, Temperature: Maxim MAX30205, Microcontroller: Atmel ATSAMD21, Programmability: Arduino Zero Bootloader.
2.1.3 Electrocardiogram (ECG) Sensor
The ADS1292R, Fig. 4, is a multichannel, simultaneous sampling, 24-bit, delta-sigma (ΔΣ) analog-to-digital converters (ADCs) with a built-in programmable gain amplifier (PGA), internal reference, and an onboard oscillator. The ADS1292R incorporates all features commonly required in portable, low-power medical electrocardiogram (ECG), sports, and fitness applications, with high levels of integration and exceptional performance. The ADS1292R enables the creation of scalable medical instrumentation systems at significantly reduced size, power, and overall cost.

2.1.4 Pulse Oximeter Sensor
The AFE4400, Fig. 5, is a fully-integrated analog front-end (AFE) ideally suited for pulse Oximeter applications. It consists of a low-noise receiver channel with an integrated analog-to-digital converter (ADC), an LED transmit section, and diagnostics for sensor and LED fault detection. The device is a very configurable timing controller. This flexibility enables the user to have complete control of the device timing characteristics. To ease clocking requirements and provide a low-jitter clock to the
AFE4400, an oscillator is also integrated that functions from an external crystal. The AFE4400 communicates to an external microcontroller or host processor using an SPI™ interface.

![AFE4400 pulse Oximeter layout and cable](image)

**Fig. 5.** AFE4400 pulse Oximeter layout and cable [12].

### 2.1.5 Body Temperature Sensor

The MAX30205, Fig. 6, temperature sensor accurately measures temperature and converts the temperature measurements to a digital form using a high-resolution, sigma-delta, analog-to-digital converter (ADC). The clinical thermometry accuracy specification is met when the sensor is soldered directly to the HealthyPi. The communication is performed through an I2C-compatible 2-wire serial interface, which accepts standard write, read, send, and receive byte commands to read the temperature data.

The sensor has a 2.7V to 3.3V supply voltage range, low 600µA supply current, and a lockup-protected I2C-compatible interface that make them ideal for wearable fitness and medical applications.

![MAX30205 body temperature layout](image)

**Fig. 6.** MAX30205 body temperature layout [13].

### 2.2 Software Components Used in the Proposed System

#### 2.2.1 IoT Dashboard
The IoT dashboards monitor and control boards and sensors. While many familiar data sources are purely digital; the IoT dashboards filled with graphs, charts, and many other widgets, are the digital tools we use to visualize and organize data coming from the physical system to our computers. They are cloud-based and global. The IoT adoption is in part, thanks to the expansion of cloud computing and its proficient data collection, processing, and analysis capabilities. With the global accessibility of cloud data-storage platforms, no longer do businesses or private users need server rooms to store data nor the on-hand IT engineer to run it. With the global architecture of most cloud or IoT service providers, the IoT dashboards can be accessed simply with a URL and any standard browser or mobile application, anywhere in the world. In our work, we used an open source IoT dashboard io.adafruit.com.

2.2.2 MQTT Protocol
The MQTT, Fig. 7, stands for MQ Telemetry Transport. It is a publish/subscribe, simple and lightweight messaging protocol, designed for small devices, low-bandwidth, high-latency or unreliable networks. The design principles are minimizing network bandwidth and device resource requirements, while also attempting to ensure reliability and a degree of assurance of delivery. These principles help in making the protocol ideal to the emerging “machine-to-machine” (M2M) or “Internet of Things” (IoT) world of connected devices, where bandwidth and battery power are at a premium.

Andy Stanford-Clark of IBM and Arlen Nipper of Arcom invented the MQTT. The standard ports for MQTT are TCP/IP port 1883 which is reserved with IANA for use with MQTT. The TCP/IP port 8883 is also registered for using MQTT over SSL [14-15].

![MQTT block diagram](image)

2.2.3 Android Application
The IoTool, Fig. 8, is a multi-award-winning smartphone gateway and the API allows the IoT researching and fast prototyping with minimal costs in domains: IoT, eHealth, sports and wellness.

Currently, the IoTool supports more than 100 different sensors with more than 258 sensor readings, 50 actuators and different types of triggers connected to an ordinary smartphone through a very flexible extensions system. The IoTool works on Android devices. The IoTool on a smartphone can process, collect, encrypt, store, show values and diagrams, sync to cloud.
3 Fuzzy Logic Algorithm

The Fuzzy logic is a many-valued logic, where fuzzy variables value ranges from 0 to 1. It tries to model human reasoning and relativity of opinion. The membership function is a curve that defines how each input space is mapped to a degree of membership between 0 and 1. The Fuzzy input parameters, such as the numerical value of heart rate, is represented by a fuzzy membership function. There are many types of membership functions: triangle, trapezoidal, bell-shaped, etc... [17]. The Fuzzy inference system tries to define the fuzzy membership functions to feature vector variables and classes and deduce fuzzy rules to relate feature vector inputs to classes.

The steps of fuzzy classification are shown below in Fig. 9.

- Input/output variable definition: the set of sensors is defined to be the inputs, and the set of motion modes are defined to be the outputs.
- Membership function determination: for each sensor input and each motion mode output, a set of membership functions are defined to associate an input feature value to sets such as “High”, “Medium” and “Low”.
- Fuzzy rules generation: the fuzzy IF-THEN rules are defined to relate inputs to outputs using statistical data readings obtained from the test experiments.
- Infer Output: the degree of fulfillment (DOF) is obtained for each input and then, the membership degree of each output is inferred from the fuzzy rules.
- Defuzzification: the most probable output is obtained from the membership degrees of each output [18].
4 Experimental Work

We started our implementation by collecting readings using the ECG, temperature and Oximeter sensors connected to the HealthyPi hat which is connected to the Raspberry Pi. These readings were collected from 15 different test subjects with varying age, gender and fitness levels. Subjects were tested in 3 physical motion types: resting, walking and running, which provided 45 unique readings to use in our system [19-21].

![Real-time data on screen.](image)

The readings (results) were collected leading to construct Tables 1-4.

**Table 1. Resting mode readings**

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Ax</th>
<th>Ay</th>
<th>HR</th>
<th>O2</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min</td>
<td>-0.01</td>
<td>-0.14</td>
<td>68 BPM</td>
<td>96</td>
<td>36.2°C</td>
</tr>
<tr>
<td>Max</td>
<td>0.35</td>
<td>0.58</td>
<td>80 BPM</td>
<td>100</td>
<td>37.0°C</td>
</tr>
</tbody>
</table>
Table 2. Walking mode readings.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Ax</th>
<th>Ay</th>
<th>HR</th>
<th>O2</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min</td>
<td>-0.4</td>
<td>-0.45</td>
<td>84 BPM</td>
<td>97</td>
<td>36.4°C</td>
</tr>
<tr>
<td>Max</td>
<td>0.66</td>
<td>0.58</td>
<td>100 BPM</td>
<td>100</td>
<td>37.1°C</td>
</tr>
</tbody>
</table>

Table 3. Running mode readings.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Ax</th>
<th>Ay</th>
<th>HR</th>
<th>O2</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min</td>
<td>-0.6</td>
<td>-0.5</td>
<td>110 BPM</td>
<td>96</td>
<td>36.5°C</td>
</tr>
<tr>
<td>Max</td>
<td>0.81</td>
<td>0.95</td>
<td>190 BPM</td>
<td>100</td>
<td>37.3°C</td>
</tr>
</tbody>
</table>

Table 4. All motion modes readings combined.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Ax</th>
<th>Ay</th>
<th>HR</th>
<th>O2</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min</td>
<td>-0.01</td>
<td>-0.14</td>
<td>68 BPM</td>
<td>96</td>
<td>36.2°C</td>
</tr>
<tr>
<td>Max</td>
<td>0.81</td>
<td>0.95</td>
<td>190 BPM</td>
<td>100</td>
<td>37.3°C</td>
</tr>
</tbody>
</table>

Then, we were able to transmit this data to our IoT dashboard using the MQTT protocol and a built-in MQTT client. This enabled us to monitor and view a live stream of the test subject’s health status including ECG graph, heart rate, body temperature and blood oxygen level. This is explained in Fig. 11. We configured our IoT dashboard to perform further processing on the received data and send alerts to the patient and doctor if a sensor reading level decreases or increases beyond a single point.
Finally, we created a fuzzy logic system designed using the Mamdani method with triangle membership functions. We used five inputs to our system, Accelerometer in x-direction, Accelerometer in y-direction, Gyroscope in y-direction, Heart Rate, and Blood Oxygen Level.

Figures 12-16 show the input membership functions, while Fig. 17 below shows the output membership function.
5 Results and Discussion

A successful implementation of our system enabled us to monitor the test subjects in real-time, to detect any abnormalities in their health status as well as to perform further analysis on their collected readings data with our designed fuzzy logic system and detect the type of physical motion occurring.

Figures 18-23 show the output detection of different motion modes.
Fig. 18. Output result inferred from rules showing resting mode.

Fig. 19. Predicted output surface between Ax, HR: Rest State.

Fig. 20. Output result inferred from rules showing: Walking Mode.
Fig. 21. Predicted output surface between Ax, HR: Walking State.

Fig. 22. Output result inferred from rules showing: Running Mode
Fig. 23. Predicted output surface between Ax, HR: Running State.

We were also able to provide immediate notification to test subjects and their doctors once any issue or abnormality in their health status readings was detected using the IoT dashboard io.adafruit.com.

An observation was made that body temperature within normal ranges does not differ in the detection of physical motion type, as the body temperature difference is minute and is considered negligible in our experiment.

Table 5 shows the count of successful detection on motion type and unsuccessful detection as well as the error percentage after performing 45 test cases.

Table 5. Detection results and error percentage.

<table>
<thead>
<tr>
<th>Detection</th>
<th>Resting</th>
<th>Walking</th>
<th>Running</th>
</tr>
</thead>
<tbody>
<tr>
<td>Successful</td>
<td>14</td>
<td>13</td>
<td>14</td>
</tr>
<tr>
<td>Unsuccessful</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Accuracy</td>
<td></td>
<td></td>
<td>92%</td>
</tr>
</tbody>
</table>

6 Conclusion

The importance of having a multipurpose IoT ready health monitoring system is declared in the areas of healthcare and fitness sports, as well as highlighting the many benefits of such system in providing a balance between cost, quality and manageability for patients, athletes, healthcare centers and doctors.

We were able to accurately collect the health status readings using 3 smart wearable sensors and a smartphone. Remote monitoring of the health vital signs of patients
and transmitting the readings in real-time to the IoT dashboard to be viewed by doctors was achieved successfully.

The proposed fuzzy logic system is able to detect the correct physical motion mode with high accuracy. Using the 45 test cases from our experiments, the proposed fuzzy logic system was able to successfully detect the resting motion mode 14 times out of 15, the walking motion mode 13 times out of 15, and the running motion mode 14 times out of 15. Giving the system an accuracy of 92% in successful motion mode detection.

References