Design and Implementation of a Wearable Sensor Network System for IoT-Connected Safety and Health Applications

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***Abstract*—This paper presents a wearable sensor network system for Internet of Things (IoT) connected safety and health applications. Safety and health of workers are important for industrial workplace; therefore, an IoT network system which can monitor both environmental and physiological can greatly improve the safety in the workplace. The proposed network system incorporates multiple wearable sensors to monitor environmental and physiological parameters. The wearable sensors on different subjects can communicate with each other and transmit the data to a gateway via a LoRa network which forms a heterogeneous IoT platform with Bluetooth-based medical signal sensing network. Once harmful environments are detected and, the sensor node will provide an effective notification and warning mechanism for the users. A smart IoT gateway is implemented to provide data processing, local web server and cloud connection. After the gateway receives the data from wearable sensors, it will forward the data to an IoT cloud for further data storage, processing and visualization.**

***Index Terms*—Wearable sensors; LoRa; Connected health; Safety; BAN.**

I. Introduction

Internet of things (IoT) has become a promising technological paradigm and attracted many research interests in recent years. It is predicted that there will be 26 to 50 billion Internet connected devices by 2020 and 100 billion by 2030 [1]. IoT can enhance performance of wireless sensor networks (WSNs) especially in environmental monitoring and healthcare applications. With the emergence of IoT, users can easily view the real-time environmental and physiological data from web-browser or mobile applications at anywhere and anytime.

Wearable body area network (WBAN) is a special purpose WSN that is generally used in healthcare environments to monitor physiological signals that can improve the quality of life, and consequently health and wellness [2] [3], for example, a wrist worn wearable system for photoplethysmogram (PPG) monitoring [4], a WBAN with motion and electrocardiogram (ECG) sensors for rehabilitation [5], and an edged-based WBAN healthcare monitoring system with heart rate monitoring [6]. Apart from healthcare applications, WBANs have also been used to monitor environments. For instance, the work [7] monitors temperature, humidity, and ultraviolet (UV) for safety applications. Authors in [8] present a wearable sensor network for indoor environmental monitoring. There is not much work covering both environmental and physiological parameters monitoring. For instance, the work [9] continuously monitor the environment and health of the subject for chronic respiratory disease.

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Safety is very important for industrial workplace, especially for workers constantly switching working environments between indoor and outdoor. In outdoor environments, UV, ozone, carbon monoxide (CO) and particular matter (PM) are harmful to human health. According to [10], solar exposure has been well established as the major cause of skin cancer in Australia. UV radiation is the component of sunlight which is harmful. Long-term exposure to UV index level of 3 or above can lead to skin cancer. UV exposure is also a cause of eye diseases [11] [10] .

In addition to UV, carbon dioxide (CO_2), smoke, CO, and Volatile organic compounds (VOC) are some commonly indoor pollutants [12]. Symptoms of CO_2 poisoning, such as hearing loss, headache and rapid pulse rate, may happen to some occupants when the CO_2 level is above 600 ppm [13]. Therefore, it is essential to have a WSN system to monitor both UV and CO_2 for industrial workplace.

To prevent workers from being exposed to any risky and hazardous situations, some physiological parameters of workers should also be monitored. Body temperature and heart rate are the most studied parameters in WBAN-based medical monitoring works. Among different wearable environmental monitoring applications, temperature and humidity are the

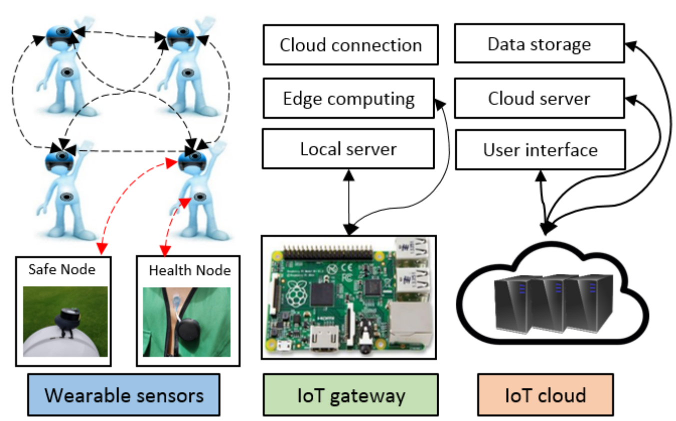

Fig. 1: The architecture of the proposed WBAN.

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most commonly monitored parameters.

In this paper, we present a heterogeneous wearable IoT sensor network system for connected safety and health applications, which is suitable for industrial workplace. The system architecture is shown in Fig. 1. The wearable network consists of multiple wearable sensor nodes which are capable of communicating with each other. Each person is equipped with two nodes: the first node is named Safe Node for environmental condition monitoring including ambient temperature, relative humidity, UV, and CO_2; the second node named Health Node is for physiological signals monitoring including body temperature and heart rate. Two wireless technologies are utilized in our work including BLE for short range data transmission and LoRa for long range data transmission.

Heterogeneous devices including LoRa-based long-range Safe Node and BLE-based short-range Health Node enable the short-range IoT data to be transmitted at longer distance and connected to the Internet. Unlike [14], wearable sensors on different subjects are designed to communicate with each other for an effective connectivity. In addition, a smart IoT gateway is designed and implemented to process, store and pass the data to cloud infrastructure. Monitored data can be displayed from a local web server located in the gateway and a website in the cloud server. If any emergency condition is detected, the system can notify users by pushing notifications to the their smartphone.

The remainder of this paper is organized as follows: Hardware and software implementation are provided in Section II and III; Section IV presents some experimental results; finally, the conclusion and future works are summarized in Section v.

II. Hardware Implementation

A. Safe Node Implementation

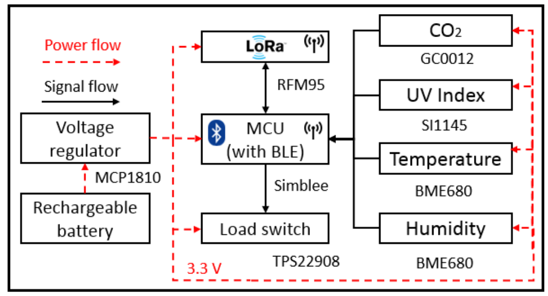
The block diagram of the Safe Node is shown in Fig. 2 (a). Each Safe Node has a power management unit, one MCU, a LoRa module, and four environmental sensors. The Safe Node is powered by a rechargeable battery and a voltage regulate (MCP1810) will regulate the battery voltage to a constant voltage (3.3 V). The MCU is Simblee with built-in BLE function.

The LoRa module is RFM95 from HoperRF Electronics. This is a low-power (0.2 µA in sleep mode) and Long-Range (LoRa) transceiver. The LoRa is responsible for transmission long range data from the BAN to the remote gateway. The BLE receives the data from the Health Node that is attached to the chest.

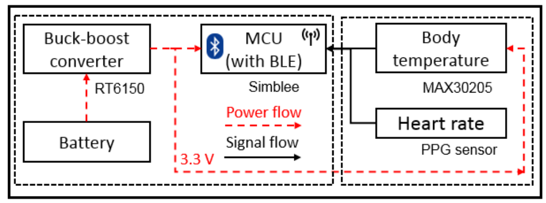
Four environmental sensors selected are temperature (BME680), relative humidity (SI1145), UV (SI1145) and carbon dioxide (CO_2, GC0012). These sensors are selected due to their high performance, high accuracy, and low power consumption.

B. Health Node Implementation

Fig. 2 (b) presents the block diagram of the Health Node. The Health Node comprises a power management unit, an MCU with BLE (Simblee), and two physiological sensors.



(a) Safe Node



(b) Health Node

Fig. 2: Block diagram of the wearable sensor node.

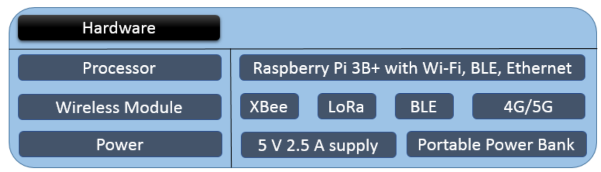


Fig. 3: Hardware architecture of the gateway.

A low-power buck-boost converter (RT6150) is adopted to regulate the battery voltage at 3.3 V for the rest of the circuit. Body temperature sensor (MAX30205) and heart rate sensor (PPG) are connected to the MCU by flexible wires. Both of the health parameters will be transmitted to the Safe Node via the BLE network (WBAN).

C. Edge Gateway

The hardware architecture of the gateway is presented in Fig. 3. It consists of one Raspberry Pi Model 3, wireless modules, and power supply unit. The Raspberry Pi is running on Raspbian system which is an open source Linux operating system. It supports several different languages including Java, Node.js, Python, C and C++. It is low-power consumption that requires only 2.5 A and 5 V power supply, which can be directly powered by portable power bank. As a result, the gateway can be easily relocated without being permanently attached to a main power supply. A LoRa module is additionally attached to the Raspberry Pi and communicate with the Pi to receive the wireless data from the Safe Nodes. If other wireless module such as XBee is utilized, additional XBee can be plugged into the Pi.

III. Software Implementation

A. Long Range Wireless Communication

The wearable network is based on LoRa network. Each Safe Node is able to communicate with each other via LoRa. LoRa network is based on a star network topology, which means data is transmitted from point to point. If the data is not addressed and encrypted, it can be received and seen by all the LoRa node in the same region with same specifications. To improve the security and privacy of the network, data encryption is embedded before each packet transmission.

1) Mode of Operation: There are three modes of operation for the wearable sensor node (Safe Node) as shown in Fig. 4:

- Idle mode: the Safe Node listens to the RF channel and receives the RF data;
- Transmit mode: the Safe Node transmits the RF data to the gateway and its surrounded Safe Nodes;
- Low-power mode: the Safe Node enters a low-power sleep mode, which will turn off all the sensors and RF module and only leave the MCU in a low-power mode.

2) Wearable Communication: The goal of wearable communication is to provide prompt safety warning messages to all workers on site so that they can respond to emergency circumstances as early as possible without getting notifications from the gateway.

Each Safe Node can transmit two types of RF packet: class 1 packet and class 2 packet. Class 1 packet is general environmental data that is transmitted when no harmful environments are detected. The targeting destination of this message is the IoT gateway. Class 2 packet is transmitted when harmful environments are detected. This packet is transmitted to other wearable devices as well as the gateway node.

The software algorithm of the Safe Node is presented in Fig. 5. In continues monitoring mode, the sensor node keeps monitoring environmental data without entering low-power mode. The Safe Node will enter idle mode after initialization and listen to the RF channel for incoming messages. If RF data is received, an RF data differentiation function will check whether the RF data is a warning message with harmful environmental data from other Safe Nodes. If it is harmful data, it will notify the user via a smartphone application. Otherwise, the software algorithm will ignore the message and go back to Idle mode.

If no RF data is received, the Safe Node will measure and record sensors' data according to a pre-defined period. If any harmful environments is detected, it will form a class 2 packet and transmit the RF packet to all other Safe Nodes including the IoT gateway. If no harmful environment is detected, class 1 packet will be formed and transmitted to the IoT gateway.

B. Gateway Software Implementation

The software architecture of the gateway supporting wearable sensor networks for IoT connected safety and health applications is presented in Fig. 6. The architecture includes

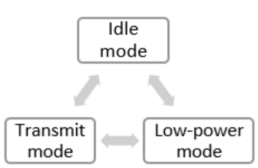


Fig. 4: Modes of operation.

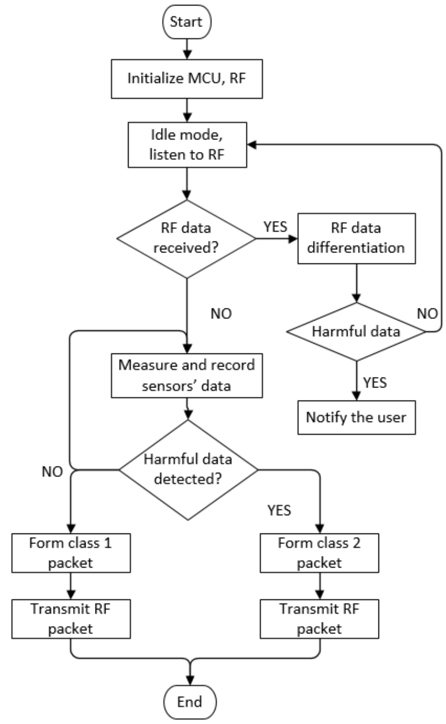


Fig. 5: Safe Node software diagram.

five components: 1) WSN data manager (WDM), 2) Data process manager (DPM), 3) Database manager (DBM), 4) Local web server, and 5) Cloud connection.

A program written in Python is used to interface with different wireless module, such as LoRa, XBee, and BLE. In this work, the program reads data from LoRa network wearable and passes the RF data to DPM. After receiving the data from WDM, DPM will do a preliminary data processing including filtering the data and transforming the data to useful environmental data. To improve the data security and privacy, DPM will encrypt the data before store the data into MySQL. The data stored in the local MySQL database can be retrieved in the future for further analysis. A website running at the local server which is based on Node.js, HTML, CSS and JavaScript is developed to visualize the sensors' data in real-time. Data from the gateway can be transferred to the cloud via Wi-Fi, Ethernet, and cellular network.

C. Cloud Implementation

The cloud server is hosted in DigitalOcean that is an American cloud service provider. The server is running with

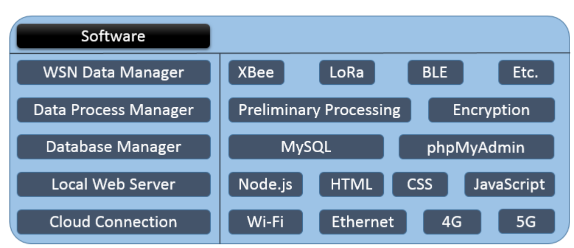


Fig. 6: Software architecture of the gateway.

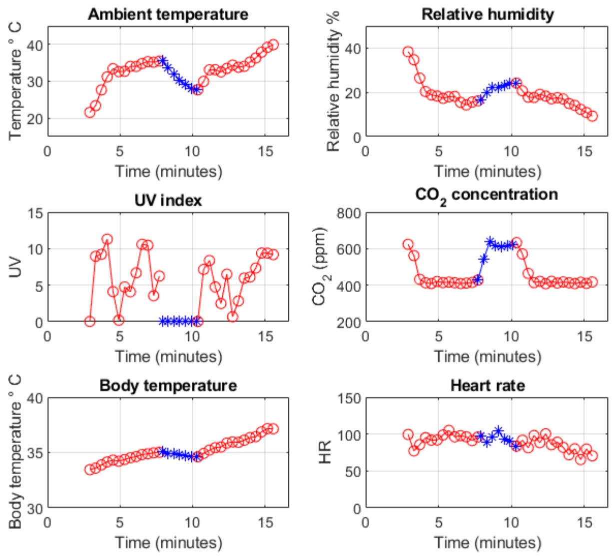


Fig. 7: Real-time measurements for different sensors.

Ubuntu 16.04.5 with 2GB RAM and 25GB Disk space. Similar to the gateway website implementation, a cloud-based website is written on Node.js and Node-RED. A Mosquitto broker is also installed on the cloud server and it is configured as a bridge that will connect the MQTT broker in the gateway and cloud. MySQL database is also installed in the server for data storage. To best protect and ensure data security, credentials will be required if any user wants to access the data on the server. The server is configured to do an automatic backup of the Ubuntu image once a week to ensure the data will not be lost.

IV. Experimental Results and Discussion

A. *Sensors' performance*

Some real-time measurements from different sensors worn by one subject is presented in Fig. 7. The Safe Node is attached to the helmet while the Health Node is attached to the subject's chest. The red curve indicates that the subject is outdoors and the blue line represents indoors. It can be clearly seen that, when the subject is outdoors, the ambient temperature and UV are higher than indoors. Because warmer temperature can absorb more moisture, relative humidity is lower when the subject is indoors. For CO_2 concentration, it is higher in indoors as compared to outdoors. There are some fluctuations of UV index reading, which is due to the tree shades when the subject is walking around. Body temperature and heart rate data is also presented in the figure. Body temperature keeps increasing except when the subject is indoors from just below 34 °C to approximately 37 °C. This is because when the subject is outdoors, the body temperature sensor is heated by the direct sunlight. The subject's heart rate reading is fluctuated around 100 bpm.

V. Conclusion

In this paper, we present an IoT network system for connected health and safety applications for industrial outdoor workplace. The system is able to monitor both physiological and environmental data forming a network from wearable sensors attached to workers' body and provide invaluable information to the system operator and workers for safety and health monitoring. Aspects such as sensor node hardware and software design, gateway and cloud implementation are discussed. In our future works, different environmental and physiological sensors can be integrated to the system to suit different workplaces. A smartphone-based IoT gateway can be developed to reduce the dependency of the fixed location gateway.

Acknowledgment

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