Warning System for Firefighters Using E-Textile

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***Abstract*—This paper presents a research focused on an e-textile based warning system for firefighters which is intended to bring more safety to firefighters on-the-job. The system is designed so that it is integrated into an undergarment shirt worn underneath a firefighter's protective jacket/suit. It is able to monitor heart rate, detect a firefighter's position relative to his posture, detect CO gas concentrations in the environment and measure ambient temperature. The warning system, as a whole, consists of the sensors and a microcontroller integrated into the undergarment through e-textile technology, and a wireless monitoring device. Measured data are wirelessly transmitted and received by the monitoring device capable of data visualization and are intended to be used by an operation chief to monitor a firefighter. When monitored data exceed a certain threshold value the firefighter will be notified by means of a light and sound alarm. The system performed well when tested against specific digital sensors and withstood moisture exposure tests. Wireless communication was consistently established to the monitoring device.**

Keywords-e-textile; firefighter; warning system; monitoring device; lilypad

I. Introduction

Firefighting is considered as a dangerous profession. Direct contact to fire, extreme heat stress, and even heart attack are possible cause of fatal injury. Extreme physical exertion during fire-fighting is unavoidable [1]. In 2013 alone, based on the World Fire Statistics, of which 31 countries acted as participants, by the International Association of Fire and Rescue Services there were a total of 130 firefighter deaths and more than 69,000 firefighters were injured on the job [2].

Wearable technology has been paving the way in creating systems for monitoring physiological and environmental conditions. Fabrics integrated with electronic devices such as sensors are what is referred to as electronic textiles (or e-textiles) [3]. E-textiles have multiple applications in health monitoring, specifically the monitoring of various vital signs such as heart rate, breathing rate, and temperature; sports training and exercise muscle exertion detection; and driver fatigue monitoring [4]. Multiple items of clothing, such as a t-shirt, an outer garment, and a pair boots, were used as the locations of the various sensors. Data collection is handled by a wearable electronic device that transmits these data into a remote monitoring software [5]. A wireless garment with embedded textile, sensor integrated vest and comfortable wearable fabric are some example of this technology [6]. Detection of problems for respiration, ECG and EMG study, fitness and physical activity and cardio-vascular diseases are examples of what this technology can provide [7].

According to Extreme Physiology and Medicine, sudden cardiac death and other cardiovascular disease occur during emergency duty of fire [8]. It is necessary to keep track of the target heart rate since it can affect person's performance [9]. High exposure to carbon monoxide can lead to loss of consciousness and a decrease in the ability of blood to carry oxygen. It can lead to significant toxicity that affects the nervous system and heart and even causes death. Depression, confusion, and memory loss can arise if low level exposure to carbon monoxide is prolonged [10]. There is a proposed system that monitors heart rate, detects movement, measures temperature and humidity, and detects toxic and combustible gases using a firefighter's outer garment as the medium for attaching the necessary electronics. It used various sensor modules and several control units that wirelessly sent the gathered information via a wide area network to a firefighter operation chief that monitored the condition of a firefighter [11]. For a person that works in a high risk environment, protective clothing is necessary to protect themselves from exposure to extreme heat and other life threatening hazards [12].

Monitoring room temperature can be a great help in maintaining electrical devices or components in good condition. Humidity and moisture can exist everywhere due to the water vapor surrounding us. Moisture can bring damage and cause failure in the system. On the other hand, having too low humidity level can result to short circuit and can generate static electricity [13].

The general objective of this study is to develop a warning system for firefighters through the use of e-textile technology. The specific objectives of this study are as follows: (1) to develop an undergarment that acquire vital signals for firefighters during operation with the use of e-textiles; (2) to develop a software program that analyzes the acquired signals to monitor the physiological and environmental state of firefighters; (3) to wirelessly transmit data from the undergarment's control unit to a monitoring device; and (4) to calibrate and test the system in providing information to firefighter and chief of operation.

This study covered the creation of an Arduino-based e-textile warning system capable of measuring the heart rate, ambient temperature, carbon monoxide levels in the air, and

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posture of a firefighter. It also included the creation of a monitoring software wirelessly connected to a control unit attached to a firefighter's undergarment. Furthermore, the wireless communication of the undergarment and the external control unit is limited only to the allowable range of the transmitter.

II. Creation of a Firefighter's Undergarment Integrated with Sensors using E-textile

A. Methodology

A constructive research process was applied in this study. This process aims to solve a practical problem and involves the following: (1) identifying the problem, (2) formulation of objectives, (3) obtaining related researches of the study area, (4) designing the best solution, (5) testing of the solution, (6) examination and interpretation of results.

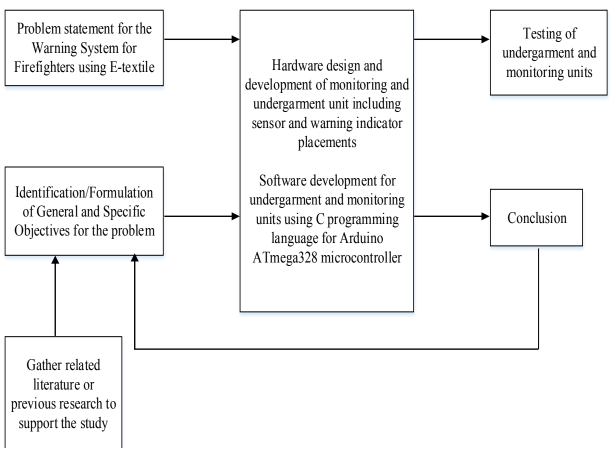

Figure 1. Block diagram of methodology process

Figure 1 outlines the research process flow followed throughout this research study. The review of related literature is the gathered data from research materials such as IEEE journals, articles, books and internet regarding the thesis topic defining the objectives. This chapter, now, discusses the hardware, software design processes as well as the experimentation and discussion of results.

The system is composed of individual sensors connected to the microcontroller. The system is wirelessly communicating to the monitoring device through a transmitter. The undergarment system processes the data and provide the firefighter a warning through indicators while the monitoring system displays acquired data from the sensors numerically.

Software is developed which collects and analyzes data from the sensors and the accelerometer. It is responsible for activating the warning indicators and enabling the wireless transfer of data to another software (running on a monitoring device) that displays the condition of the firefighter according to the data gathered from the undergarment sensors. Arduino software is used in interfacing with the hardware device using C programming language.

The system is designed to work for firefighters during operation. Figure 2 shows the conceptual framework which begins by reading the data gathered by different sensors attached on the undergarment such as the heart rate, ambient temperature, posture and carbon monoxide concentration. This serves as the input of the system. The Arduino attached in the garment processes the obtained information received by the sensors. It will gather and identify whether the obtained vital signals were considered as critical working conditions. For the output part, the result of the process is displayed and served as a warning indicator for the firefighter (user) and the operation chief (observer).

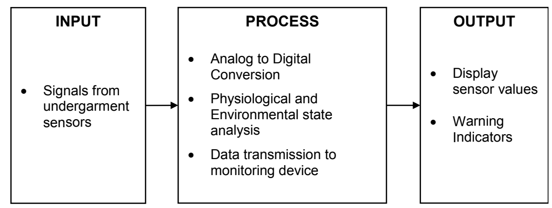

Figure 2. Conceptual framework

B. Design of Undergarment

Figure 3 shows the proposed system hardware. It is composed of the firefighter's undergarment integrated with sensors. Conductive threads are woven in the garment to facilitate the connection. Data are processed through Arduino and a wireless module enables wireless data transfer for real time monitoring of the operation chief. Placement of sensors are considered to acquire precise results and to reduce discomfort of the firefighter during operation with the existence of the module. Carbon Monoxide sensor is placed at the neckline of the undergarment which is near the nose airway. This is to provide CO concentration that can be possibly inhaled by firefighter. Pulse rate sensor is placed in the chest or in the wrist that offers high pulse signals. Accelerometer is placed at the point where it can get the user's posture and not be easily changed in inclination.

Figure 3. Design of firefighter's undergarment using e-textile

In order for the firefighter to assess physiological and environmental conditions, an alarm from a buzzer is activated once critical working condition has been detected. LED indicates basic information such as heart rate, ambient temperature, and CO concentration. These warning indicators are placed at the upper chest area to avoid inconvenience for the firefighter and to appear more conspicuous (i.e. easier to notice).

Figure 4 shows the display which is designed for the monitoring chief. The monitoring device shows heart rate (H.Rate) in beats per minute, ambient temperature (A.Temp) in celsius, carbon monoxide (CO) in parts per minute and posture (POS) as Up or Down depending to firefighters position. All data measured by the sensors are transmitted to the monitoring device. If critical working condition has been detected, alarm would be activated in the form of buzzer.

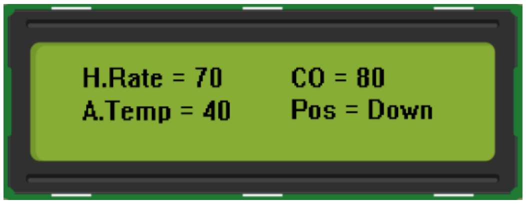

Figure 4. Output of monitoring device

C. *Software Design*

Software development for this research includes the creation of two software programs, the undergarment and monitoring system software. The undergarment system uses a Lilypad Arduino 328 Main board with an ATmega328 microcontroller and is programmed using the Arduino IDE. Similarly, the monitoring system uses an Arduino Uno microcontroller and is also programmed using the Arduino IDE.

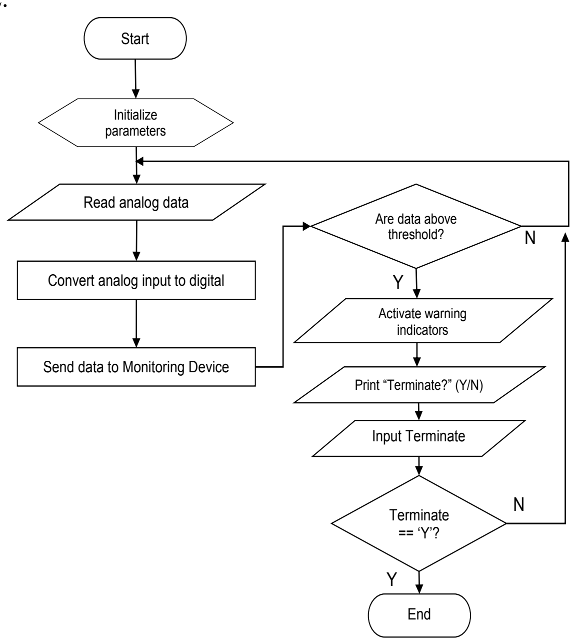

Figure 5. Undergarment system flowchart

Fig. 5 shows the flow of the system. Once the undergarment system is turned on, the system loads necessary modules then the parameters and variables are loaded. The system starts to collect the analog data to convert it to digital. Analysis of the collected data is handled by the Arduino-based control unit, which wirelessly sends the data to monitoring device that is used to display the vitals of a firefighter. The alarm indicator (buzzer and LED) is expected to activate in response to (1) heart rate, for values less than 60 bpm and greater than 120 bpm [14], (2) ambient temperature, for values greater than 40°C [15] and (3) CO concentration, for values greater than 200 ppm [16].

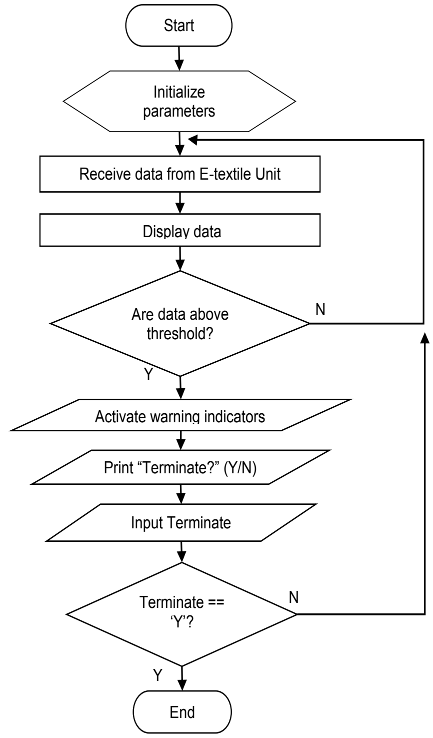

Figure 6. Monitoring unit flowchart

Fig. 6 above illustrates the main routine of the monitoring system. After loading the parameters, it starts to receive data from the undergarment. Once data pass the threshold, or critical levels set in the device, it sends a notification to both the undergarment and the monitoring device. Data collection starts once the device is turned on and continue to collect, analyze and send these data to the monitoring device so long as the device is running. Once the undergarment system has turned off, the device collection, as well as, transmission of data stops.

D. *Results and Discussion*

TABLE I. CALIBRATION FOR HEART RATE AND AMBIENT TEMPERATURE SENSOR

Trial	**Heart Rate (bpm)**			**Ambient Temperature (°C)**		
	Sensor	Digital	% Differ -ence	Sensor	Digital	% Differ- Ence
1	72	70	2.8169	31.19	31.2	0.0320
2	84	83	1.1976	30.51	30.7	0.6208
3	82	81	1.2269	29.48	28.9	1.9869
4	83	81	2.4390	29.14	29.7	1.9034
5	81	80	1.2422	29.14	29.6	1.5662

Table I shows the first ten trials that are conducted individually for each parameter that the system aims to measure using several trials to ensure accuracy. Each sensor reading from the system is compared to the data gathered from standalone sensors (i.e. commercially available sensors that separately measure values for heart rate and temperature). These tests gauge how the system's collected data compares to those of standalone sensors. For temperature, it compares the temperature obtained from the firefighter's undergarment and the temperature obtained by a digital thermometer.

TABLE II. CALIBRATION FOR POSTURE

Trial	Posture	
	Detected on sensor (Up/Down)	Actual Posture (Up/Down)
1	Up	Up
2	Down	Down
3	Down	Down
4	Down	Down
5	Down	Down

For posture, Table II shows the comparison between the data gathered from the accelerometer integrated into the undergarment and the actual posture of the firefighter. This test was conducted to determine user's current posture. Up indicates that the person is in standing position to the ground. Down indicates that the person is lying on the ground.

TABLE III. TRIAL FOR ALARM ACTIVATION OF WARNING SYSTEM

Trial	Heart Rate (bpm)	Posture (Up/ Down)	Ambient Tempe-rature (°C)	CO Con-Centra tion (ppm)	Alarm Activated? (Yes / No)	
					User	Obse-rver
1	90	Down	46.9	500	Y	Y
2	82	Down	31.19	350	Y	Y
3	66	Up	29.14	120	N	N
4	72	Up	30.51	150	N	N
5	76	Up	30.85	185	N	N

Both the undergarment and monitoring unit is programmed to alarm when a threshold is reached as shown in Table III. The test for alarm activation involves the confirmation of the correct function of the alarm system and did not take into consideration activation delay. There are 5 trials performed using a setup where the undergarment and monitoring devices were within an unobstructed 100m distance. Each of trial was recorded in terms of heart rate, posture, ambient temperature, CO concentration and if the alarm would respond correctly. The alarm is expected to be activated when (1) heart rate, for values less than 60 bpm and greater than 120 bpm, (2) ambient temperature, for values greater than 40°C and (3) CO concentration, for values greater than 200 ppm.

TABLE IV. TRIAL FOR EFFECT OF MOISTURE ON WARNING SYSTEM

Trial	Status	Readings			
		Heart Rate Sensor	Tempe-rature Sensor	Accele-rometer	CO Sensor
1	OK	71 bpm	29.01 °C	Up	15 ppm
2	OK	83 bpm	29.90 °C	Up	10 ppm
3	OK	86 bpm	31.63 °C	Down	11 ppm
4	OK	114 bpm	32.78 °C	Up	14 ppm
5	OK	98 bpm	31.42 °C	Down	12 ppm

Table IV detailed the effect of moisture towards the operability of the system. Trials were conducted to determine the effect of moisture (perspiration/water) on the overall functionality and operability of the system. Data gathered from the system while under the effect of moisture determines if the system's operability is (significantly) affected. The test required a brine solution sprayed on the system. After an amount of time (i.e. a few minutes), the system is turned on and undergo continuity test to check for possible problems with the circuit. This process counts as a single trial and succeeding trials are done by repeating this set-up. Data gathered from these trials indicates that the e-textile undergarment system is able to function even when exposed to moisture.

TABLE V. SUMMARY OF ACCURACY

Test	Mean % Difference
Heart Rate	1.7845
Temperature	1.2219
Posture	0

Table V shows the summary of the tests conducted on the accuracy of the data readings collected from the undergarment system and received by the monitoring device. Data from heart rate and temperature sensors both show mean percentage differences below 2% and posture readings shows 100% accuracy.

E. Statistical Analysis

Two-tailed t-test is used in this study to make a comparative analysis on how far apart the means of the vital signs such as heart rate and ambient temperature obtained from the system and by conventional methods of measurement. Heart rate acquired by the system is compared to digital heart rate monitor and temperature is compared to commercially available digital thermometer. This will validate that the system is functioning properly. The significance level (α) is set to 0.05.

Hypothesis 1:

Null Hypothesis (H0): The difference in means of Undergarment pulse rate sensor and digital heart rate monitor is zero.

$$Ho\colon \mu 0 = \mu 1$$

Alternative Hypothesis (H1): The difference in means is not zero

$$H1\colon \mu 0 \neq \mu 1$$

Claim is proven true that there is no significant difference between the mean of two sample data if the calculated t-value is greater than negative critical value and less than positive critical value, - (t Critical two-tail) < t Stat < t Critical two-tail and when p-value is greater than 0.05.

With the degree of freedom value of 18 and significance level (alpha) of 0.05, a value of 2.1009 from the table of critical values, t-value was obtained. Since the calculated t value, which is 0.2751, is greater than -2.1009 and less than 2.1009, and p-value of 0.7863 which is greater than 0.05, it can be said that we do not reject null hypothesis.

Hypothesis 2:

Null Hypothesis (H_0): The difference in means of Undergarment temperature sensor and digital thermometer is zero.

$$Ho: \mu_0 = \mu_1$$

Alternative Hypothesis (H_1): The difference in means is not zero

$$H_1: \mu_0 \neq \mu_1$$

Since the calculated t value, which is -0.2751, is greater than -2.1009 and less than 2.1009, and p-value of 0.9901 which is greater than 0.05, it can be said that the researchers did not reject null hypothesis.

With this outcome, it can be said with 95% confidence that the system's heart rate and temperature sensors are not significantly different to the digital sensors used.

III. Conclusion

Within the scope of the research, the parts of the e-textile based warning system for firefighters that were developed included the following: wireless monitoring device, CO, heartrate, posture detection and temperature sensors. The sensors together with the main control unit (microcontroller) were integrated into an undergarment shirt intended to be worn under the firefighter's protective suit. These sensors are connected to the microcontroller and the transmitter through conductive thread, imbedded into the fabric of the undergarment and together make up the undergarment system. This system is able to communicate with the monitoring device wirelessly through a transmitter operating within the ISM 2.4 GHz frequency. The monitoring device allows data visualization for sensor values and warning alarm for the firefighter when sensor readings reach a certain threshold.

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