Multi-Functional Safety Jacket for Firefighters

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***Abstract*—One of the riskiest modern jobs is firefighting, which is the process or the action of extinguishing fire. A design of a multi-functional safety jacket for firefighters was attempted. The design includes: 1) a firefighting jacket, 2) various sensors, 3) a communication system, 4) LED bars, 5) a touchscreen, and 6) a battery bank. The safety jacket provides many functionalities to a firefighter at task. The embedded heat sensors measured the skin temperature of the firefighter, the room temperature, and that of all inanimate objects, such as walls, doors, and ceilings. An alert was given if a potential fire was hidden behind these objects. The gas sensor measured the level of carbon monoxide (CO), combustible gases, and smoke in the room. A warning signal would also be generated if the gas level became hazardous. A wireless radio module was attached to the jacket to facilitate team communication. The safety jacket would also alert firefighters of any obstacles ahead to avoid collision. In case a firefighter fell suddenly, a message would be sent to the external base to request for help. Sensitivity tests revealed the accuracy, the complexity, and performance of the prototype.**

Keywords: firefighter's health, hazardous area, wearable device, alarm system, threshold values.

I. INTRODUCTION

The firefighting career is a dangerous and risky profession. Firefighters are trained to extinguish hazardous fires that destroy lives, properties, and the environment. The field of Civil Defense requires cadres willing to sacrifice themselves to save the lives of others, while facing fatal dangers on the job. Thus, serving other people is their top priority. During rescue operations, firefighters deal with various intensities of heat waves [1]. Hence, because of everyday rescue activities, firefighters are continually exposed to toxic and carcinogenic substances, such as benzene, 1,3-butadiene, and formaldehyde.

Numerous experiments investigating the effect of heat strokes, toxic gases, and hidden obstacles on firefighters' health have been conducted in the past [2]–[6]. Since a minor mistake can irreversibly affect the life of fire personnel, finding the exact life threatening danger in an uncontrolled fire scenery can be problematic at times. Hence, a leapfrog technology with all the required degrees of freedom and complexities must be geared with the sole purpose of saving lives. A detailed background on thermal protective clothing for firefighters was given in [7]. In addition, an improved measurement of thermal parameters' impact on firefighters in conjunction with a digital monitoring system was investigated in [4]. A real-time measurement of vital signs for effective firefighting was conducted; data were transmitted by radio to the control station, saved, and then evaluated [6].

In the last couple of years, major hazardous fires have occurred in Dubai. According to the authorities of Dubai's Civil Defense, the highest number of fire blasts in 2017 happened in June, compared to the other months of the year. This was mainly due to the customary summer temperature peaks. Two-hundred thirty-two (232) fires occurred in 2017. It was recorded that about 19%, 21%, and 60% of the fires were categorized as a major, moderate, and minor intensity fire, respectively. Thus, both civilians and firefighters on the various accident sites were reported to either be in danger or reported to be injured [8]. In addition, according to Gulf News, there has been 41% decrease of fire accidents in buildings and establishments during the first half of 2017 across the UAE. Although the aforementioned percent seemed significant, it was well below the fire safety strategy targets set for the period of 2017-2021.

At the international level, the National Fire Protection Association, short-handed as NFPA (USA) conducted a study, which includes overall statistics of on-duty firefighter casualties and non-incidental deaths in the US. The report stated that job-related exposures for firefighters end in chronic illnesses, such as cancer and heart disease, in addition to deaths and injuries that occur while on-duty. It was also reported that 42% of the firefighters died as result of chronic diseases. Another case study done by NFPA, which emphasized on causes of deaths and nature of injury, indicated that 9% of deaths of firefighters were due to asphyxiation (suffocation) or smoke inhalation.

According to [5], the related health concerns with firefighting is tremendous. The firefighters have least chances not to develop various cancers compared to non-firefighters. Therefore, a recurring daily risk in the course of any rescue operation is that after many hours of chemical and/or heat exposure, half of the workers may experience more sweating and intense muscle pains [3].

This paper attempts to design a lifesaving jacket with several embedded sensors, which facilitates the duty of firefighters by providing them with safety alternatives. The device is easy to wear, light, and highly protective. It raises the fighters' awareness to their surroundings, thus making them respond faster to plausible dangers. The jacket was designed to decrease risks faced by firefighters by helping them escape dangerous situations and by sending vital messages to the control station.

The unique attributes of this design compared to other jackets are many-fold. First, it had a two-ways communication device, which includes a wireless data transmission and GSM cellular connection with the operation center. Second, three temperature sensors were embedded on the jacket, where sensor *A* (MLX-90614) was for a close-range measurement of both ambient and room temperatures, sensor *B* (MCP-9808) was used for body temperature, and sensor *C* (MLX-90621), a 16 by 4 array, was meant for a far-range infrared object's temperature measurement. Third, the novel design had a Laser detector to sense distant objects. Fourth, it had a RGB colored screen for instant data display. Fifth, the jacket was designed with a touch-activated call features using touch-screen schemes. Lastly, the abovementioned sensors and a microcontroller were sewn onto the jacket instead of an undergarment to provide more comfort to the firefighter.

II. METHODOLOGY

Primarily, the design of the proposed jacket would not have been possible without the sound knowledge of the firefighting career, on one hand. On the other hand, the design might have not been complete without the keen understanding of the diverse, complex, and hazardous work-place environments. Therefore, an identification followed by a comprehensive understanding of the key components turned out to be decisive criteria in designing the jacket. Hence, Table 1 summarizes the major key elements.

Table 1. Key design components

Variables/Devices	Quantity	Types
Temperature sensors	3	MCP9808, MLX90614, and MLX90621
Gas sensors	2	MQ2 and MQ7
Display screen	1	TFT HXD8357
Text to speech alarm	1	eMic
Distance sensors	2	Ultrasonic and Laser Lidar
Communication module	1	Fona Lora
Accelerometer	1	Adafruit 9-DOF (L3GD20H)
Visibility sensor	2	LED bar
Heart-rate sensor	1	Polar wireless

The listed devices were paramount in fixing the bearable temperature, acceptable inhaled gases, and other smoke levels that a firefighter can tolerate while on duty. These components helped not only to design the jacket, but also to make it an integral design that could satisfy most of the modern lifesaving standards. Hence, a strategic project plan was formulated in line with the top-down methodology as explained below. For simplicity purposes, some of the most critical devices from the abovementioned table were selected and thoroughly explained in the analysis section.

A. Data preparation and analysis

The whole design started with a thorough analysis of the obtained information. Also, a number of existing problems (already mentioned) that needed solutions and the requirements necessary to resolve the safety issues were adequately listed. Based on the adopted procedure, a list of possible components was written with their respective contributions to re-inforce the functionalities of the safety jacket under scrutiny.

B. Testing of components

The components were first categorized into groups based on their functions, such as temperature, fluid, distance, communication instruments. Afterward, the instruments were separately tested and then integrated into one another in line with their categorization. These holistic assemblies enabled them to share strategic data with ease and convenience deemed to save firefighters' lives. Additionally, other minor components were simply built from scratch. Altogether, the components were mounted on a circuit board in order to check their compatibility, accuracy, and efficiency.

C. Device implementation

After the careful selection of the various components based on their accuracy, durability, and integrability, each one of them was assigned a physical location on the jacket. The determination of the locations may seemed easy at the first attempt, but was actually finalized through many trials and errors as the devices needed to be sewed on a critical spot in order to fully function. As stated above, the nature of the firefighters' work, the rough terrains, and their movements at the fire sites were all taken into account. In doing so, the jacket would be more effective in protecting the firefighters.

Consequently, the components were divided into five main groups dependent on three best criteria: 1) the distribution pattern, 2) the most even weight-to-gadget ratio, and 3) the ideal visual attractiveness that ensured the optimal comfortability and guaranteed highest accuracy as shown in Figure 1. The first group was placed on the left sleeve (A); it included a 1) display screen for an easy check by the firefighter, 2) compatible LoRa radio that sends any displayed data to a control room, and 3) skin temperature sensor, which was placed in contact with the body. The second group included two gas sensors (MQ-7 and MQ-2), and one heart-rate sensor positioned at lower left (B). The third group, comprised of a Fona communication device and an eMic speech alert, was located on the upper-right pocket (C). Both the Fona and the eMic were connected to a single headphone. The fourth group, consisted of an accelerometer and ambient temperature sensor, was placed on the upper-right side of the jacket (D). The fifth group contained a long-range temperature sensor and a LASER-LIDAR (LL) for distance measurement purposes (E). The LIDAR was coupled to a servomotor; this scheme potentially increased the precision of the measurements. Finally, to make the firefighters more visible to one another in fuggy weathers, one LED bar was sewn around the upper part of each sleeve.

Figure 1. Prototype design: where A is the Touchscreen display, Lora radio, and Skin temp sensor; B is the Flammable/Poisonous gas sensors and Heart rate monitor belt; C is the GSM Text-Speech module; D is the Ambient temp sensor and Accelerometer; E is the Object temp sensor, LL, and Servo motor.

III. RESULTS AND DISCUSSIONS

The prototype was subjected to a sensitivity test in order to know the real performance of all the major components. The best components representing each feature were then chosen to reproduce the final model. These tests showed the degree of accuracy, level of responsivity, and prototype's performance.

A. Temperature sensors

For model validation intents and purposes, Table 2 portrays a comparative measurement of the selected temperature sensors versus the real approximation values. The measured skin temperature was very close to the real skin temperature value, which was found in [9] to be 30ºC. Moreover, the ambient/room temperature sensor was utilized to measure the exact room temperature. The measured temperature was slightly higher than the normal because of a power outage in the workshop the day of the test. In addition, the far-range object's temperature sensor provided the layout for different temperatures. Since it is a well-known fact that it is not practical to initiate a real and huge fire, the precision of the far-range sensor was tested on candle flames as done in [10]. Since it was capable of detecting flames as small as that of a candle, then it certainly can detect larger fires.

Table 2. Temperature sensor results

Sensors	Measured (ºC)	Real approximation (ºC)
Skin temperature	29.87	30
Room temperature	26.85	25

B. Gas Sensors

One of the most difficult tests was that of the gases due to their inherently invisible, volatile, and/or odorless nature. Therefore, the carbon monoxide (CO) and flammable-gas sensors' readings were not very accurate. These measurements were difficult to get because of their sensitivity to other types of gasses, such as CO_2, N_2, and O_2. Hence, the first method utilized to measure the concentrations of CO was by flaming a covered candle with a larger jar to limit the supply of oxygen. As a result, in few seconds the flame was extinct due to the lack of oxygen, thus producing sufficient amount of CO for the test. Albeit the CO being in a small amount, the reading was good enough. It can be conjectured that the aforementioned readings were slightly affected by smoke, but were decent enough to deduce scientific conclusions. Afterward, an averaging experiment was implemented through a filter. The gas sensors' readings were recorded 50 times in clean air and then averaged to attain a threshold value. This value, for all practical intents and purposes, represented an acceptable particle level. Thus, any increase above this threshold means the detected gas level was increasing. Therefore, any increase above this average reading means the detected gas level was increasing. Table 3 presents the results obtained in a clean environment using butane. It can be seen that MQ7 has a higher sensitivity on CO, but has the potential to detect simultaneously methane and other combustibles [11].

Table 3. Gas sensor results

Sensors	Averaged Measurement (above reference)
MQ7 (CO/ Methane)	287
MQ2 (LPG/Methane/Smoke)	210

In addition, Figure 2 depicts a graphical comparison between the MQ7 and MQ2 sensors in measuring butane flames. This graph shows that the MQ7 has, once more, a better sensitivity than MQ2, thus making the MQ7 suitable for this design.

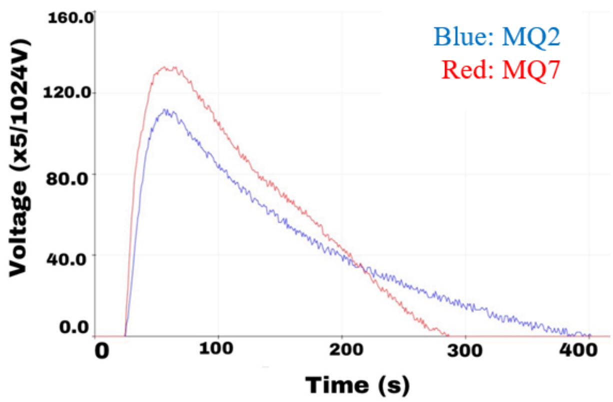

Figure 2. MQ2 and MQ7 response to Butane flames

C. Distance sensors

The Laser-Lidar (LL) and an ultrasonic (UC) device, both sensors attached to the jacket, were tested by placing a box at a distance of 1m. The measured distances are displayed in Table 4. Results, as can be seen from the table, revealed that the LL sensor proved to be more accurate and reliable than the ultrasonic one. The former showed a precision range of +/-2.5 cm, while the latter sensed the box too closer than it really was. Another important issue with the ultrasonic sensor was that it failed to detect the presence of grey-colored objects. Therefore, the LL was chosen to fulfil the needs of this study as it had proved to detect obstacles in the near and far-range distances.

Table 4. Measured distances in cm over time

Sensor	Measured distance over time (cm)
LL	97, 98, 98, 99, 100, 102, 101,100,100,101,101,100 100,100
UC	82, 85, 83, 83, 76, 77, 78, 78, 78, 77, 73, 75, 86, 82

D. Alert methods

To warn the firefighters of any danger at a fire site, either of the following methods was utilized: 1) visual and/or 2) sound. On the one hand, the visual method was achieved through the use of a TFT screen. Hence, the TFT screen was successfully tested. As a result, the fighter's skin temperature, the room temperature, gas levels, and distance to hot obstacles were displayed as seen in Figure 3. Consequently, if any of the abovementioned parameters exceeds a certain set threshold value, a "red" message appeared on the TFT screen as shown in the same figure. This screen, located on the left sleeve of the jacket, has some extra features, such as touchscreen and GSM call option. A demerit worth pointing is that the screen, not only showed low resolution issues, but also exhibited a relatively longer clearance time. Nonetheless, the low time performance can be controlled by inserting a speed function in the Arduino codes.

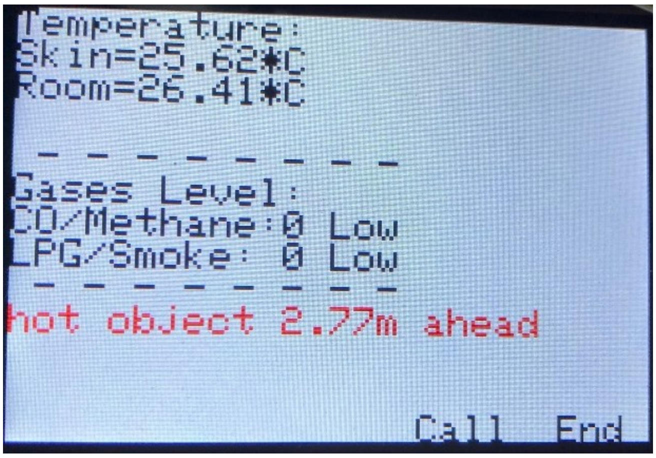

Figure 3. Measurements displayed on touchscreen.

On the other hand, the sound alert was achieved through an embedded eMic as stated above. The eMic device was programmed to produce a sound if either/or one of the following events occur: 1) the firefighter's skin temperature goes above normal; 2) the room temperature goes above 50^{o}C; and 3) the CO, smoke, and flammable gas levels are high. Additionally, the sound alarm would turn on when the device was near any matter, such as metals and cement in contact with fire or ember on the opposite side. This feature helps the firefighters to stay on alert and act rapidly to circumvent any upcoming dangers.

E. Communication

For an operator to monitor the condition of firefighters, the Lora communication device was used on both transmitting and receiving terminals. The device was able to communicate all the measurements of the transmitting device placed the jacket to the receiving module tuned at 915MHz. Figure 4 shows the receiving screen connected to Lora. Results revealed: 1) the skin and room temperatures were normal; 2) the CO and smoke levels were low, thus acceptable; 3) the distance to obstacles was safe; 4) the heart-rate was low, but normal; and 5) finally the firefighter status (moving or immobile). The latter vital scheme was achieved through a built-in accelerometer, which enables an operator to monitor whether the jacket bearer was standing, moving, stationary, or lying down. The best performance range in terms of distance was found to be around 2 km between the transmitter and receiver. This allows crewmembers to take the necessary actions based on one of the abovementioned five outcomes to save the firefighter.

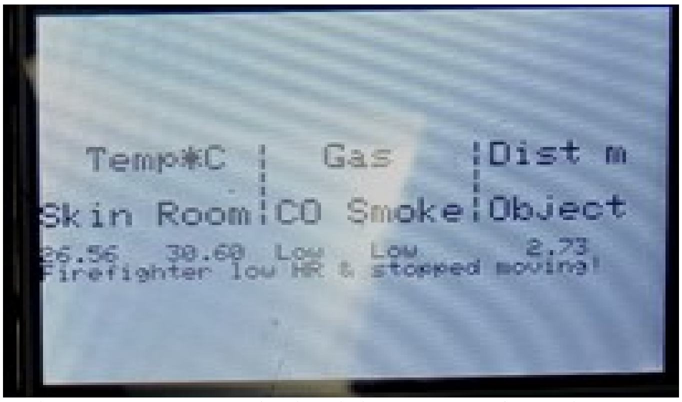

Figure 4. Operator screen showing vital measurements from main screen.

To communicate vocally between dispatches, Fona GSM was utilized. The disadvantage with Fona goes back to the inherent limitations of the GSM technology. Fona devices are dependent on available cellular coverage, thus contingent to repeaters inside shielded buildings. If the repeaters were down during a fire in a building, this method of communication would be doomed.

F. Light signals

The two LED bars attached to the upper arms, one on each sleeve of the prototype, proved to shine brightly in dark rooms. The emitted lights were noticed from tens of meters. This not only makes the firefighter visible in dark areas, but also facilitates the monitoring of his movements to nearby crewmembers.

Lastly, it is worthy of note to point out that, some minor components were eliminated from the final design. Such components were, but not limited to the following: 1) Light sensor, eliminated because adding it was not a major part that affects the decision-making process and 2) UV light sensor, removed because it turned out to be irrelevant. It is an established fact that normal fire emits heat, visible light, infrared, and ultra violet radiation. Fortunately, the amount of radiated UV is a very small amount and regarded as negligible, thus reading from this sensor might be imprecise.

IV. CONCLUSION

Throughout their missions, firefighters across the world have been working in the scariest and most dangerous environments. This research helped to concisely circumvent some of the most encountered challenges of firefighting tasks. The problems of fire hazards, sporadic communication losses between crewmembers, and instant explosions faced by firefighters on duty were addressed and solved through this novel design. The multi-functional safety jacket is useful, not only to the UAE's Civil Defense, but also to the other fire units in the region at large. The jacket was designed to raise the awareness of firefighters concerning their surroundings, in terms of temperature overshoots, possible leaking of lethal gases, and the dangers of hidden obstacles. The device has proved to facilitate communication means, even in the harshest conditions, between crewmembers by enabling the execution of both safety and emergency procedures in an unpredictable environment.

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