Wearable System for Heat Stress Monitoring in Firefighting Applications

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Abstract. The paper proposes a multiparameter sensor platform capable of measuring the rate and thermal stress state which the user (in particular a firefighter) is subject to. For that, three wearable sensors (temperature, humidity and heart rate) send the information via Zigbee low energy wireless protocol, to a remote device (smartphone, wrist watch or PDA) monitoring the status of the worker. Additionally, an activity sensor allows the determination of body fall or immobilization situations. Preliminary tests support the viability of the proposed solution.

Keywords: thermal stress, wearable sensors, firefighting, wireless communication, risk prediction

1 Introduction

Firefighting is one of the most physically demanding occupations with a high risk of exposure to environmental and chemical hazards which require firefighters to wear personal protective equipment (PPE) and sometime self-contained breathing apparatus (SCBA). The physical demands of firefighter activities in various tasks resulting from intrinsic metabolic demands and extrinsic clothing factors force firefighters to work at near and/or maximal heart rate [1]. In particular, the combined weight of both the PPE and SCBA as well as the clothing insulation characteristics (e.g., increased thermal resistance and decreased vapor permeability) play a significant role in determining the physical demands experienced by firefighters performing various tasks can lead to physiological and thermoregulatory strain which can lead to compromised physical capability, impaired cognitive function, reduced work tolerance, and coupled with an increased risk of physical injuries and illness (e.g., heat stroke and falls) [2].

Over the past several decades, laboratory and field-based human heat stress studies, including simulated firefighter activities, have provided valuable information that has helped to identify the thermo-physiological responses to firefighter activities and provide practical safety information for firefighters, when their vital status is continuously monitored .

Wearable physiological monitoring systems uses an array of sensors integrated into the fabric of the wearer to continuously acquire and transmit the physiological data to a remote monitoring station. The data acquired at the remote monitoring station is correlated to study the overall health status of the wearer. The wearable monitoring systems allow an individual to monitor his/her vital signs remotely and receive feedback to maintain a good health status. The aim of this paper is to describe a wearable device to be used in the professional field of firefighters. The system allows to detect the thermal stress that firefighters may suffer in case of fire, to measure vital parameters and to determine a falling down in the middle of the fire or the firefighter immobilization due to blocking of access roads.

Of course, the conventional physiological monitoring systems cannot be used for wearable physiological monitoring applications. More of that, despite recent advances in medical technology, none of the currently available devices provides a combination of wearability, size and functionality that satisfies completely demanding firefighting requirements. The goal of our effort was to design a lightweight, wearable, ergonomic device that not only records and streams a comprehensive set of diagnostic-quality physiologic parameters, but can also record body position and orientation, acceleration in three axes, and can be used to mark events.

2 Previous work

ItA number of wearable physiological monitoring systems have been developed to monitor the health status of the individual wearer. A wearable physiological monitoring system called '*Smart Vest'* to monitor various physiological parameters such as ECG, heart rate, blood pressure, body temperature and GSR, which are transmitted wireless to a remote monitoring station along with the geo-location of the wearer is described in [3]. A wrist worn wearable medical monitoring and alert system (*AMON*) targeting high-risk cardiac/respiratory patients, has been developed to monitor physiological parameters such as ECG, heart rate, blood pressure, skin temperature [4]. The system can be useful also for monitoring people working in hazardous environments. A wearable physiological monitoring system for space and terrestrial applications named '*Life Guard'*[5] was developed to monitor the health status of the astronauts in space. The *WEALTHY* (Wearable Health Care System) involves wearable textile interfaces integrating sensors, electrodes and connections realized with conductive and piezoresistive yarns, enabling the monitoring of respiration, ECG, EMG, body posture and movement [6].

Recently, a number of wearable physiological monitoring systems have been put into practical use for health monitoring of the wearer in real life situations and their performances have been reported [7], [8], [9]. Varying degrees of success have been reported and the percentage failures in the outdoor use are high. The main drawbacks associated with the conventional wearable physiological systems are:

- The wires integrated into fabric act like antennas and can easily pick up the noises from nearby radiating sources.
- The sensors once integrated into the fabric, its location cannot be changed or altered easily.
- Typically these systems consist of a centralized processing unit to digitize, process and transmit the data to a remote monitoring system. The processor is loaded heavily to perform multi-channel data acquisition, processing and transmission of data.
- The cables from the vest interconnecting the sensors can get damaged very easily due to twisting and turning of the cables, while the wearer is performing his routine activity.

To overcome the above issues related to wearable physiological monitoring, the individual sensors integrated into the vest can be housed with electronics and wireless communication system to acquire and transmit the physiological data. A number of tiny wireless sensors, strategically placed on the human body create a wireless body area network that can monitor various vital signs, providing real-time feedback to the user and medical personnel.

3 Wearable devices requirements

AThe risk for workers' health and safety, originate by working exposed to extreme heat conditions, are caused by an extreme heat accumulation in the body. This phenomenon is called thermal stress, which can be defined as the heat load received, resulting from the interaction between environmental conditions of the workplace, the physical activity and the clothes that workers wear.

When a person works under conditions of thermal stress, the body is altered and the person suffers physiological overload as a result of an increase of the body temperature. Certain physiological mechanisms (such as sweating and peripheral vasodilatation) make the body leave the heat excess and if even thought, the body temperature exceeds 38 º C, serious health problems and even death may occur. This phenomenon is a major cause of death among firefighters and it can also happen to professionals working with high heat sources such as foundries and metal or glass industry.

When there is an emergency situation like a fire, the firefighters are exposed to a high heat conditions that could affect their performance. In these cases, a solution could be to wear a wearable device that could warn the firefighter when there is the thermal stress risk and the firefighter.

The main objective of our work was to create a smart shirt capable of measuring the rate and thermal stress state which the user is subject to. The system monitors the different required parameters and then sends wirelessly the information to a unique central system with wireless technologies to inform the user about his state and warns him in case of danger. Three variables are crucial to determine if a person is in risk of having thermal stress: relative humidity, temperature and heart rate.

The humidity and temperature sensors should not be in direct contact with the skin but must measure the microclima between the textile and the skin. For the acquisition of those variables, we are using a sensor from Sensirion SHT7x family [10] (including SHT71 and SHT75) sensors of relative humidity and temperature, since this sensor integrated both acquisitions in a single device that easies the integration. The sensors integrate sensor elements plus signal processing in compact format and provide a fully calibrated digital output. A unique capacitive sensor element is used for measuring relative humidity while temperature is measured by a band-gap sensor. The applied CMOS technology guarantees excellent reliability and long term stability. Both sensors are seamlessly coupled to a 14bit analog to digital converter and a serial interface circuit.

With humidity and temperature, we can obtain the heat index through the following expression:

$$HI=-42.379+2.0490(Tf)+10.143(RH)-0.22476(Tf)(RH)-(6.8378\times10^{-3})(Tf^{2})-(5.4817\times10^{-2})RH^{2}+(1.2287\times10^{-3})(Tf^{2})RH+(8.5282\times10^{-4})(RH^{2})(Tf)-(1.99\times10^{-6})(Tf^{2})(RH^{2})$$

where HI = heat index in degrees Fahrenheit; Tf = temperature in degrees Fahrenheit;

RH = relative humidity in percent form [11].

The heat index (HI) is an index that combines air temperature and relative humidity in an attempt to determine the human-perceived equivalent temperature. The result is also known as the "apparent temperature". For example, when the temperature is 90 °F (32 °C) with very high humidity, the heat index can be about 105 °F (41 °C). The human body normally cools itself by perspiration, or sweating. Heat is removed from the body by evaporation of that sweat. However, relative humidity reduces the evaporation rate because the higher vapor content of the surrounding air does not allow the maximum amount of evaporation from the body to occur. This results in a lower rate of heat removal from the body, hence the sensation of being overheated. This effect is subjective; its measurement has been based on subjective descriptions of how hot subjects feel for a given temperature and humidity. This results in a heat index that relates one combination of temperature and humidity to another one at higher temperature and lower humidity.

Once calculated the HI, if above certain level, we must check the heart rate beats. Depending on the above parameters HI (above a threshold) and heart beats rate, we can obtain the risk of the person in four levels: Precaution, Extreme Precaution, Danger and Extreme Danger (see Table 1). As Heart Beat Rate (HBR) indicator we have chosed Age-Adjusted Maximum Heart Rate (AAMHR), which is the highest safe heart rate at each age for extended periods, which is calculated using the formula: 220-(age)= AAMHR. If the pulse exceeds 75% of the AAMHR, the responder worked too long and his next work cycle should be decreased by one third (from 30 minutes to twenty minutes in our example). If the AAMHR is impractical to use, a value of 110 beats-per-minute may be substituted.

Table 1. Thermal stress risk levels

HI	BHR(%)	Notes
27–32 °C	> 75%	Caution: fatigue is possible with prolonged exposure and activity. Continuing activity could result in heat cramps.
32–41 °C	>80%	Extreme caution: heat cramps and heat exhaustion are possible. Continuing activity could result in heat stroke.
41–54 °C	>75%	Danger: heat cramps and heat exhaustion are likely; heat stroke is probable with continued activity.
> 54°C	>80%	Extreme danger: heat stroke is imminent.

The hear rate beat is acquired through textiles electrodes integrated on the T-shirt fists . A good electrode placement is a key issue since we work with very low power signals and the movements of the user can produce bad contacts and distort the signal. Given this, those electrodes can be easily integrated in the elastic band in the cuffs that contact the skin since the wrists are a good electrocardiography (ECG) acquisition point. For a good acquisition of cardiac signal is crucial to increase the conductivity between the electrodes and the skin. Most systems use conductive gels which eventually end up drying and disabling the electrode. Our electrodes leverage the same sweat the user to reduce the resistivity. Therefore, to make the system work, it is necessary that the person is sweating, which is implicit in the risk of heat stress. Finally, the experiments were developed using an especial Nomex [12] t-shirt with three integrated sensors (relative humidity, temperature and heart rate) to capture the physical measures and evaluate the risk of thermal stress. This e-textile product was provided by courtesy of

Estambril company that is a partner of our team in the project ITEA2_LifeWear entitled Mobilized Lifestyle with Wearables [13].
Our target application is characterized by infrequent, non-constant transfer of small amounts of information between the sensor nodes, to a central device, a wrist-watch, smartphone or PDA. In the set of possible protocols, Bluetooth Low Energy (BLE) and Zigbee provide a low consumption, but with a low data rate. Because a low energy consumption is a key issue to maximize battery duration and the data rate needed to transmit is low, we discarted WiFi and WiMAX technologies and focus on Zigbee technologies. The full system will be charged through an induction system using a commercial flexible and flat battery.

4 System architecture

The architecture of the monitoring platform is shown in fig.1. The wearable physiological monitoring platform consists of three sub-systems namely: 1) vest (shirt) with the sensors integrated and an ankle mounted sensor; 2) wearable data acquisition and processing hardware and 3) remote monitoring device. In the vest sensors for acquiring the physiological parameters which determine the thermal stress are integrated. The sensors outputs and power cables are interconnected to the data acquisition and processing hardware by means of wires routed through the wires woven in the vest. In the wearable data acquisition and processing hardware are housed the circuits for amplification, filtering and digitization. The digitized and processed data is transmitted wireless to a remote monitoring device (a wrist watch, a smartphone or a PDA) warning about the danger of thermal stress so the firefighter knows that he should leave that situation to avoid falling down. Additionally, the ankle sensor allows controlling the movement of the firefighter and notifies any deadlock situation, including worker's fall.
As activity sensor we intend to use the ActiS sensor, first developed by Jovanov *et al*. [14], but in the dedicated version for protection suits proposed by Kemp [15]. The ActiS sensor incorporates two accelerometers and a one-channel bio amplifier. The device monitors both heart activity and the position of the upper trunk, and also alternately be used to monitor the position and activity of the arms and legs.

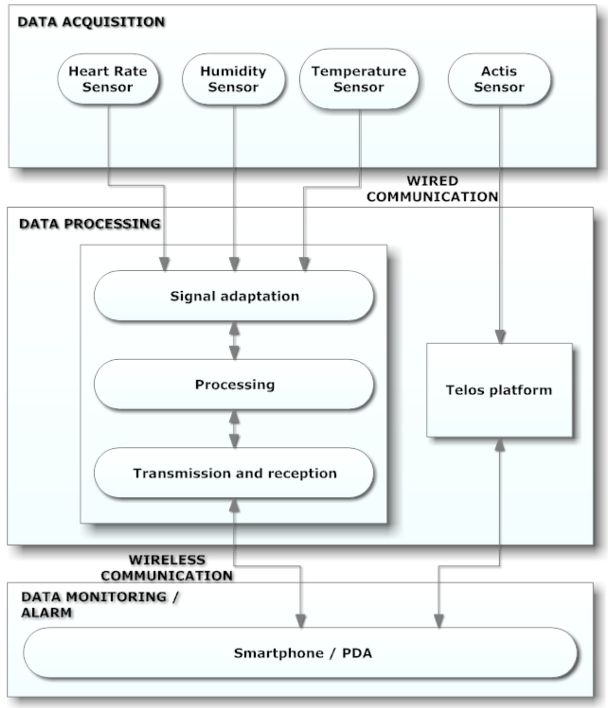

Fig.1.The block scheme of the monitoring system

The prototype presented by Jovanov et al. used a ZigBee protocol stack which is based on the IEEE 802.15.4 standard. Further, the platform was moved to the Telos mote, which supports a ZigBee radio stack. The ActiS sensor itself consists of a Telos mote by Moteiv [16] , along with a custom module named the ISPM (Intelligent Signal Processing Module). The ISPM incorporates two dual-axis accelerometers (Analog Digital ADXL202s) to cover all 3 axes and a one-channel bio amplifier along with a low-power microcontroller (the Texas Instruments MSP430F1232). The microcontroller provides signal conditioning and other low-level processing before the readings are transmitted to the Telos mote via a hardware UART. The Telos mote was chosen due to its size and software support in addition to its built-in sensors which may be used for detecting ambient conditions. It also includes a ZigBee compliant radio and antenna.

5 Data processing objectives

In this phase of the research experiments were limited to testing and validation of the solution for determining the heat stress and of the procedures for wireless data transmission to the monitoring and alarm device. Besides confirming the validity of the data processing methods, currently performed in an nonspecific environment, we tried to develop a predictive model for the assessment of hazards a firefighter in action may face. Additionnaly were developed two types of scenarios for the use of the monitoring system: for the training of firefighters and for their actions in emergency situations.

The heat stress prediction algorithm is based around a Dynamic Bayesian Network (DBN) model incorporating the subject's current activity, the cooling applied to the subject, and the subject's mean skin apparent temperature (heat index HI) as a proxy for core temperature. In this model, it is assumed that activity A_τ, cooling level C_τ, and heat index HI_τ meaured at time τ are sufficient to allow prediction of future mean skin temperature and that the triplet (A, C, HI) has the Markov property (knowing the past history would not improve the prediction). There are two parameters that must be determined prior to training and using the predictor: i) A unit of time defining how far into the future the prediction is needed. In our work, one minute prediction is used and so $\tau+1$ is taken to mean "the current time plus one minute", so prediction can be performed on the computationally constrained platform in real-time as required by the application. ii) The mean skin apparent temperature (heat index) to be used as a "danger" threshold d. The model allows us to predict the probability of heat stress by finding the probability of the threshold temperature being reached or exceeded $P(d| A_\tau, C_\tau, HI_\tau)$.

The prediction model will be used in both firefighting scenarios:

Training: it's necessary to monitor data on vital signs of the firefighter, engaged in trials consisted of four identical back-to-back cycles of: walking on a treadmill (3 mins), kneeling while moving weights (2 mins), crawling (2 mins), ergometer based arm exercise (4 mins), cognitive tests while sitting (3 mins) and standing (1 min).

Emergency situation: it is necessary to detect a thermal stress situation to prevent the fireman from falling down in the middle of a fire situation avoiding his death. For this situation the vital signs determinated with wearable sensors will be sent to the data processing board that will calculate the thermal stress level. The result of these calculation will be sent to a remote device (watch or phone). The firefighter could check his own status and if the value given it starts to be dangerous, the device will warn the user through a sound or vibration sign. These values will be also send to the team manager to check from outside the status of each fireman and if some of them is in a thermal stress situation, give the order to leave the service.

6 Experimental results

The experiments for determining heart rate were made with a thin band which is mounted on the chest with electrodes woven into the back of the strap material. The device provides heart rate readings wirelessly to the host system. This type of device is relatively unobtrusive and easy to mount on a subject, though it is required to be mounted beneath clothing in direct contact with the skin. Fig.2 represents the heart rate recording for a person following a training exercise as shown in the previous section. Fig.3 represents the apparent temperature measured during a similar exercise.

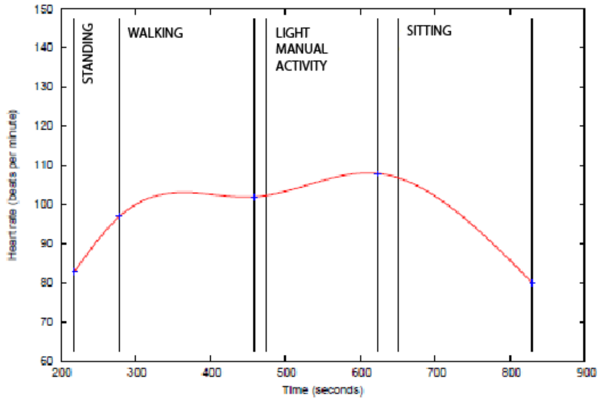

Fig.2. Heart rate during a trial exercise

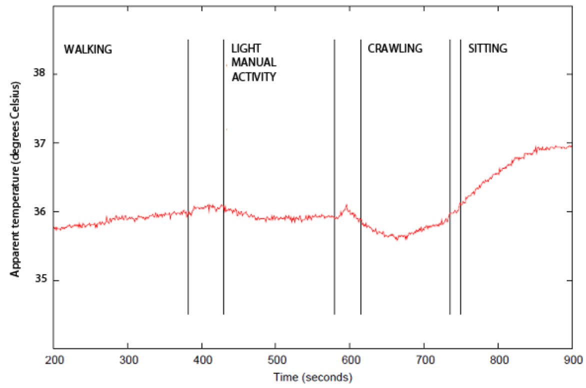

Fig.3. Apparent temperature during a trial exercise

Table 2 presents the probability of exceeding the danger threshold d measured in a training trial with 6 participants, while wearing a protection suit at 40 °C ambient temperature and two different work conditions: no cooling (NC) and body cooling (BC).The meaning of the abbreviations is: Wal-Walking; Kne-Kneeling; Cra-Crawling; Wor-Working; Sit-Sitting

Table 2. Probability of exceeding the threshold d

	Wal	Kne	Cra	Wor	Sit
NC	0.65	0.25	0.40	0.90	0.85
BC	0.80	0.75	0.70	0.70	0.80

Another problem that has been subject of experiments was the wireless communication with the remote monitoring and alarm device. Finally we have decided to utilise IEEE 802.15.4/Zigbee in order to optimize energy consumption and decrease the size of the batteries and therefore the size of the wearable devices, folowing the same procedure as described in [17], but we intend to analyze also other solutions using the excellent guidance of Custodio *et al.* paper [18].

7 Conclusions

In this paper we have presented our ongoing work on a project that aims at creating a wearable shirt with integrated e-textiles technology to prevent thermal stress in emergency activity of firefighters. The project is still under development, but the preliminary experiments proved the validity of the proposed platform, having low power consumption, low complexity, high compatibility, and high extendibility, which was conceived to create also a training device. The experimental study was conducted on wearable training patterns and resultant thermal stress. The results in all of the experiments suggested that this wearable biofeedback system allows monitoring the thermal stress and the hazards in firefighters activity.

Acknowledgements. This work has been partly founded by the Romanian project 326E/12.08.2013 as component of the Eureka project ITEA 2 LifeWear: Mobilized Lifestyle with Wearables.

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