A Sensor Fusion Wearable Health-Monitoring System with Haptic Feedback

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***Abstract*—A wearable integrated health-monitoring system is presented in this paper. The system is based on a multi-sensor fusion approach. It consists of a chest-worn device that embeds a controller board, an electrocardiogram (ECG) sensor, a temperature sensor, an accelerometer, a vibration motor, a colour-changing light-emitting diode (LED) and a push-button. This multi-sensor device allows for performing biometric and medical monitoring applications. Distinctive haptic feedback patterns can be actuated by means of the embedded vibration motor according to the user's health state. The embedded colour-changing LED is employed to provide the wearer with an additional intuitive visual feedback of the current health state. The push-button provided can be pushed by the user to report a potential emergency condition. The collected biometric information can be used to monitor the health state of the person involved in real-time or to get sensitive data to be subsequently analysed for medical diagnosis.**

In this preliminary work, the system architecture is presented. As a possible application scenario, the health-monitoring of offshore operators is considered. Related initial simulations and experiments are carried out to validate the efficiency of the proposed technology. In particular, the system reduces risk, taking into consideration assessments based on the individual and on overall potentially-harmful situations.

I. INTRODUCTION

Wearable devices are now at the heart of just about every discussion related to the Internet of Things (IoT), and the full range of new capabilities pervasive connectivity can bring [1]. In this perspective, the design and development of wearable health-monitoring systems (WHMS) has received lots of attention from the scientific community and industry during the last years. These low-cost systems are made up of various small physiological sensors, transmission modules and processors. As a result, they are well-suited to wearable and unobtrusive mental and physical health status monitoring solutions and do not impose limits on time or location [2]. Even though independent sensor information is conducive to revealing the working state of the system to some extent, a comprehensive multi-parameter sensing model is more effective for analysis and evaluation of potential operational risks. To the best of our knowledge, multi-sensor fusion is one of the most suitable technologies to use when dealing with data from disparate sources [3].

In this article, a wearable health sensor monitoring system based on a multi-sensor fusion approach is outlined. It consists of a chest-worn device that embeds a controller board, an electrocardiogram (ECG) sensor, a temperature sensor, an accelerometer, a vibration motor, a colour-changing light-emitting diode (LED) and a push-button. Biometric and medical monitoring applications can be performed by using this multi-sensor device. The embedded vibration motor makes it possible to actuate distinctive haptic feedback patterns according to the wearer's health state. Haptic feedback, also known as *haptics*, is the use of the sense of touch in a user interface designed to provide the user with additional information. In this way, the user can intuitively become self aware of his own health situation. The user is also provided with an additional intuitive visual feedback about the current health state by means of the embedded colour-changing LED. In addition, the provided push-button can be used by the user to report a potential emergency state. By collecting the sensor data, it is possible to monitor the health state of a user or to get sensitive data in real-time. Retrieved data can subsequently be analysed for medical diagnosis. Biometric information gathered can be wirelessly sent using the standard Wi-Fi communication protocol to a medical diagnosis center. Data can be sent to a cloud computing system to perform permanent storage or visualised in real-time by sending the information directly to a laptop or smart phone. Encryption techniques can be used to transfer data securely and to consider privacy concerns. Data mining can be performed with the raw data and could be used in conjunction with methods from the fields of artificial intelligence, machine learning, statistics and

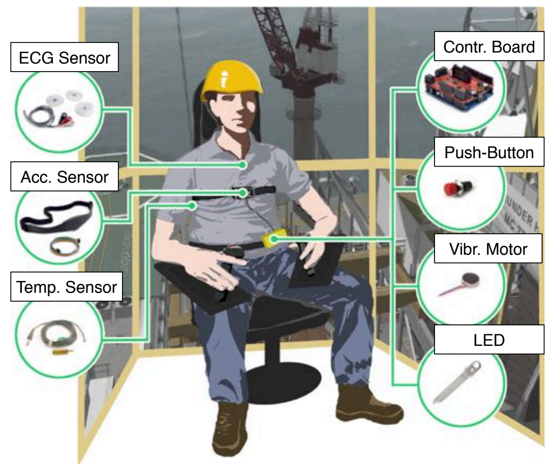

Fig. 1. The concept for a wearable multi-sensor health-monitoring system exemplified for the case of offshore operations.

database systems. The overall goal of the data mining process is to extract information from the data set and transform it into an understandable structure so that it is possible to find previously unknown information to make inferences regarding the user's health state. In this preliminary work, the system architecture is presented.

The proposed system opens up to a variety of application possibilities. As a possible application scenario, the health-monitoring of offshore operators is considered in this preliminary work. The operation of an offshore installation is associated with a high level of uncertainty because it usually operates in a dynamic environment in which technical, human and organisational difficulties may lead to malfunctions capable of causing accidents. This kind of working environment is generally associated with a considerable amount of stress for the workers. Apart from receiving stressors that are common to most workplaces, they are also exposed to stressors that are specific to the offshore setting [4]. Physical stressors include noise, vibration, poor lighting and ventilation, confined living and working space, adverse offshore weather conditions, long working hours and shift work. Mandatory health and safety monitoring of all crew members was put in place by the offshore health and safety law to minimise human error and potential resulting hazards. It is also mandatory to keep records pertinent to such monitoring. Until now, these procedures require the operators to periodically take routines checks and often to travel to a hospital or facility to complete tasks and fill out questionnaires. As such, there is an urgent need to develop more efficient methods and tools that will allow for a greater accuracy and therefore more reliable modelling and simulation of risk assessment. To meet these requirements, the proposed system can be employed for monitoring different body parts and health indicators of the operator, where fatigue, loss of concentration and stress factors are easily manifested. The underlying idea is shown in Fig. 1.

The paper is organised as follows. A review of the related research work is given in Section II. In Section III, we focus on the description of the system architecture and on the presentation of the main components. In Section IV, related simulations and experiments of a possible application scenario are carried out to validate the efficiency of the proposed technology. Conclusions and future work are outlined in Section V.

II. RELATED RESEARCH WORKS

In the last decade there have been numerous research efforts and products that can be classified as WHMS [2]. For instance, the *Advanced Care and Alert Portable Telemedical Monitor* (AMON) was introduced in [5]. The system consists of a wrist-worn device, which is capable of measuring blood pressure, skin temperature, blood oxygen saturation, and a one-lead ECG. In addition, a two-axis accelerometer is incorporated for correlating user activity with measured vital signs. All the received data from the wrist-worn device can be remotely analysed by physicians.

A relatively new approach consists of developing systems based on smart textiles. For instance, in the Wearable Health Care System (WEALTHY) project [6], different sensor elements were integrated in fabric form (using conductive and piezoresistive materials) on a textile structure. The system is able to monitor a three-lead ECG, electromyogram (EMG) placed on the arms, thoracic and abdominal respiration rate, body position and movement, skin temperature, and core temperature. The wearable system incorporates an analogue and digital signal-processing module with GPRS or Bluetooth wireless transmission capabilities. Another example of using smart textiles is, the MagIC [7], a washable sensorised vest including fully woven textile sensors for ECG and respiration rate monitoring and a portable electronic board, which evaluates the wearer's motion level and is responsible for signal preprocessing and data transmission from Bluetooth to a local PC or PDA. Skin temperature sensors are also present and the system is designed for the home monitoring of elderly people or cardiac patients. However, health monitoring during daily ambulatory life is also possible.

Nonetheless, to the best of our knowledge, an health sensor monitoring system that features a multi-sensor fusion approach and also provides an integrated haptic feedback for the user has not yet been deeply investigated. The lack for such a system is even more evident in the maritime field because of the particularly challenging operation scenario.

III. SYSTEM ARCHITECTURE

In this section, the proposed system architecture is presented. The framework is based on a multi-sensor fusion approach. In particular, a client-server pattern is adopted. A chest-worn device operates as a client and remotely communicates with a server where the logic of the presented architecture is implemented. In the following, the key elements of the system are presented. The reader is referred to Fig. 2.

A. Client (Chest-Worn Device)

A wearable device is designed to work as a client and to gather different biometric data. In particular, it is a chest-worn device that consists of a controller box attached to a belt. The device is worn by the user and it is powered by means of a polymer lithium ion battery. In the following, the components that are housed in the controller box are listed:

- an *Arduino Uno* board [8] based on the *ATmega328* micro-controller is used as a client. *Arduino* is an open-source electronics prototyping platform based on flexible, easy-to-use hardware and software. Using *Arduino* boards simplifies the amount of hardware and software development needed to get a system running. The choice of using *Arduino* boards makes the system framework easy to maintain and makes it possible to easily add new features in the future;
- to give communication capabilities to the proposed wearable device, an *Arduino WiFi Shield* [8] is stacked on top of the adopted controller board. In detail, the *Arduino WiFi Shield* allows the client to communicate with the server by using the 802.11 wireless specification (WiFi). The *Arduino WiFi Shield* connects to an *Arduino Uno* board using long wire-wrap headers that extend through the shield. This keeps the pin layout intact and allows another shield to be stacked on top;
- to gather the wearer's biometric data, an *e-Health Sensor Shield* [9] is stacked on top of the adopted

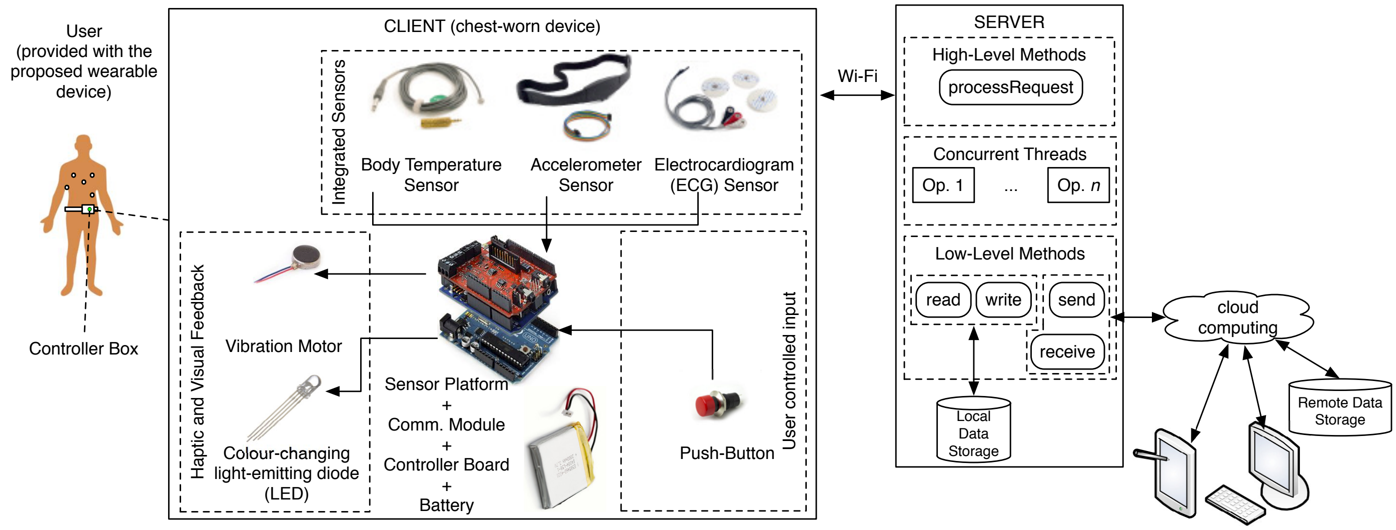

Fig. 2. The proposed system architecture of the wearable multi-sensor fusion health-monitoring system.

communication module. The *e-Health Sensor Shield* allows *Arduino* boards to easily gather information from different sensors. An open-source software library is provided with the *e-Health Sensor Shield*, allowing for easy access to the sensor data.

Different biometric sensors can be connected to the *e-Health Sensor Shield* according to various needs. Specifically, the following sensors are employed in our implementation:

- an ECG sensor kit, which consists of three leads (positive, negative and neutral) to be attached to the user's body. This sensor input can be used as a diagnostic tool to assess the electrical and muscular functions of the user's heart. The ECG has grown to be one of the most commonly used tests in modern medicine. In particular, this sensor has proven to be useful in the diagnosis of several cardiac pathologies ranging from myocardial ischemia and infarction to syncope and palpitations. However, the accuracy of the ECG depends on the condition being tested. A heart problem may not always show up on the ECG. Some heart conditions never produce any specific ECG changes [10];

- an accelerometer sensor, which can be placed on the user's body with a comfortable elastic band. This sensor can be used to monitor five different wearer positions (standing/sitting, supine, prone, left and right). In many cases, it is necessary to monitor the user's body positions and movements because of their connection to particular diseases (i.e., restless legs syndrome). For the particular case of offshore operators, analysing movements during on-board operations also helps in determining work quality and irregular pattern behaviours. The accelerometer sensor could also help to detect fainting or falling of the operator while working;

- a temperature sensor, which can be placed under the user's axilla. Body temperature is an important health state indicator and accurate measurements can provide medical insight into the wearer's response to different situations. The reason is that a number of diseases are accompanied by characteristic changes in body temperature. Likewise, the course of certain diseases can be monitored by measuring body temperature, and the efficiency of a treatment can be evaluated by the physician.

Another relevant feature of the proposed wearable device is that it provides the wearer with an intuitive haptic and visual feedback. To realise this feature, the following components are adopted:

- a vibration motor is embedded in the proposed chest-worn device. The motor is placed on the back side of the controller box and it allows for actuating distinctive haptic feedback patterns according to the wearer's health state. This feature is fundamental for improving the user's risk perception. This is important information for all users, and in particular it is highly relevant when working heavy duty equipment, driving or doing other demanding work as exemplified by offshore operators. Currently, offshore installations put the onus on the operators to identify the major hazards [11]. For this reason, the way in which people think, feel and behave in response to risk is receiving increasing attention, both among academics and those who are involved in promoting and regulating safety. Risk is perceived differently by different people. In this optic, the use of haptics can significantly improve the user experience. Touch is one of the most reliable and robust senses: it is fundamental to our memory and for discerning. When the wearer's health state is normal, the motor does not produce any vibrations. If instead, the wearer's health state is not normal, two different vibration patterns are actuated to symbolise a potentially abnormal condition (low frequency vibrations) or a rather dangerous state of health (high frequency vibrations);

- a colour-changing LED is embedded in the proposed chest-worn device and placed on the visible side of the controller box. This LED provides the user with an additional intuitive visual feedback of the current

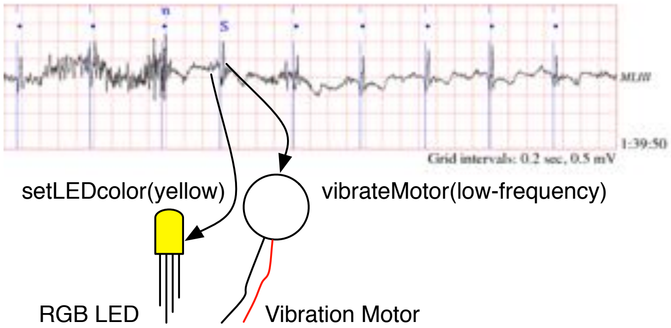

Fig. 3. An occurrence of supraventricular premature or ectopic beat (atrial or nodal), which is labeled as "S".

health state. In particular, three different colours are used: green to indicate a normal health state, yellow to symbolise a potentially abnormal condition and red to point out a dangerous health state.

In addition, a push-button is embedded in the proposed wearable device, allowing the user to report a potential emergency condition or accident.

B. Multi-Threading and Multi-Level Hierarchical Server

The server implements a multi-threading and multi-level control program. Strict real-time criteria are adopted. This allows to simultaneously and efficiently collect data from different users. Moreover, the chosen architectural pattern offers several advantages including improved performance and scalability. Three different logical levels are defined to process the client requests:

- the *High-Level methods* layer includes the high-level and distributed control function, *processRequest*, which handles each client request;
- the *Concurrent Threads* level is the layer where each client request is treated as a concurrent process. In detail, the health state of each user is continuously monitored by a separate thread. This level can access both the lower *Low-Level methods* layer as well as the higher *High-Level methods* layer. Each monitoring thread continuously sends the current information status back to the corresponding client so that the vibration motor and the LED can be accordingly actuated;
- the *Low-Level methods* layer includes the low-level functions that are used to write the acquired data to a local database (*write*), to read previously acquired data from a local database (*read*), to send the acquired data to the cloud (*send*), and to receive previously acquired data from the cloud (*receive*).

From an implementation point of view, the server is implemented by using the *Java* programming language and the corresponding standard tools for multithreaded programming.

IV. Simulation Results

The main focus of this work is building the system architecture and validating the communication pattern. Therefore, preliminary simulation experiments are performed with simulated data rather than real sensor data. In particular, different sample data from different open access databases are considered. Portions of these data are fed to the client to simulate real sensor measurements.

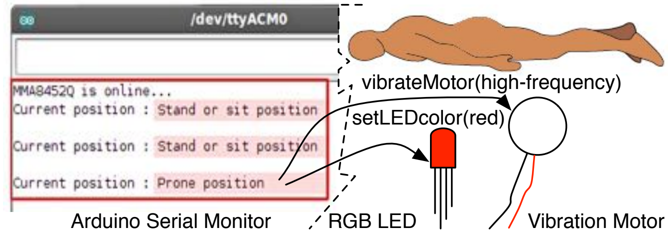

Fig. 4. An occurrence of prone position detection for the user.

Concerning ECG monitoring, we use data from the *Physiobank* archive [12]. Within this archive, the *MIT-BIH Arrhythmia Database* [13] is considered. This database consists of 48 half-hour excerpts of two-channel ambulatory ECG recordings, obtained from 47 subjects. By using this dataset, the possibility of detecting supraventricular premature or ectopic beats (atrial or nodal) [10] is considered. While the sinoatrial node typically regulates the heartbeat during normal sinus rhythm, ectopic beats occur when another region of the atria depolarises before the sinoatrial node and thus triggers a premature heartbeat. Hence, a simply way to detect this event has been developed which consists of comparing the current beat time interval with the average time interval of the previous beats. If the current beat time interval is shorter than the average beat time interval, then the system detects a potential ectopic beat. For instance, this occurrence is highlighted in Fig. 3, where a ECG segment plot is shown. This arrhythmia is a quite common occurrence in all ages and usually is not serious, therefore the system considers this case as a potentially abnormal condition but not as an extremely dangerous state. When this happens, the corresponding server-side monitoring thread sends a status update to the client so that the vibration motor can vibrate with low frequency and the colour of the LED can be changed to yellow.

With regard to the accelerometer sensor, the possibility of detecting five different user positions is considered. By using the software library provided with the *e-Health Sensor Shield*, the proposed system is able to distinguish between the following positions: standing/sitting, supine, prone, left and right. A particularly dangerous situation that can happen is fainting, which for the special case of offshore operations may cause the operator to fall while working. For instance, this occurrence is highlighted in Fig. 4, where the system detects a prone position for the wearer. This situation is quite dangerous for the case where the user is an offshore operator and therefore the system considers this case the most critical state. When this happens, the corresponding server-side monitoring thread sends a status update to the client so that the vibration motor can vibrate with high frequency and the colour of the LED can be changed to red.

Regarding the temperature monitoring, the possibility of detecting states of fever and hyperpyrexia for the user has been considered. Particularly, axillary body temperature measurements are taken at 10-minutes intervals. For the sake of illustration, the case of hyperthermia is considered as an

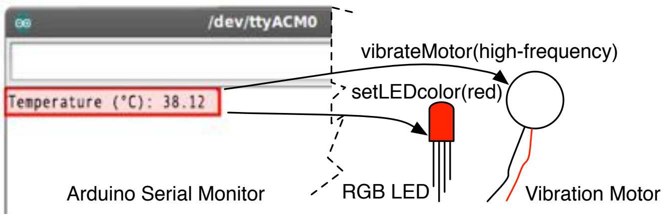

Fig. 5. An occurrence of hyperthermia is detected for the user.

example. This occurrence is highlighted in Fig. 5, where a temperature of 38.12° C is measured. This is quite dangerous for the operator, therefore the system considers this case as a critical state and makes the motor to vibrate with high frequency, while the colour of the LED is changed to red.

V. Conclusions and Future Work

In this paper, a preliminary working prototype of an integrated wearable health sensor monitoring system was presented. A multi-sensor fusion approach was adopted. The system has the following components embedded in a chest-worn device: a controller board, an accelerometer, a vibration motor, a light-emitting diode (LED) capable of changing colours, a push-button, an ECG sensor and a temperature sensor. This device makes it possible to perform biometric and medical monitoring. It is possible to actuate distinctive haptic feedback patterns in accordance with the wearer's health state thanks to the embedded vibration motor. The embedded colour changing LED provides additional intuitive feedback and the user can report a potential emergency condition by using the push-button. It is possible to use the collected biometric information in real-time for monitoring the health state of the user, or subsequently analyse the data to facilitate a medical diagnosis. The information can be sent wirelessly to a cloud computing system for permanent cloud-based data storage or it can be visualised in real time if sent to a laptop or a smart phone. In this work, the health-monitoring of offshore operators was considered as a possible application scenario. Initial simulation experiments were performed to validate the proposed system.

In the future, the use of experimental data will make it possible to certify system performance in a real application scenario. To do this, an extensive field test is necessary involving a large number of users. A comprehensive experimental test would also make it possible to assess the proposed system from a human factor point of view. For the special case of offshore operators, the compliance of the proposed system with the current regulation in the field of maritime operations needs to be investigated. Ethical considerations may also need to be addressed. One more possibility that we are considering as future work is the integration of the proposed system with a positioning system for offshore operations that we recently developed [14]. This integration will make it possible to localise each operator on board the vessel and immediately provide first aid when accidents occur. Another challenge that could be explored in the future is the use of advanced techniques for data mining that draw from the fields of artificial intelligence, machine learning, statistics and database systems. Optimisation methods similar to the ones proposed in [15] may be adopted.

In the near future, we expect wearable technology to deliver a key interface and input into the industrial IoT. The proposed system contribute towards the fulfillment of this idea.

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