Vital Responder – Wearable Sensing Challenges in Uncontrolled Critical Environments

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Abstract. The goal of the Vital Responder research project is to explore the synergies between innovative wearable technologies, scattered sensor networks, intelligent building technology and precise localization services to provide secure, reliable and effective first-response systems in critical emergency scenarios. Critical events, such as natural disaster or other large-scale emergency, induce fatigue and stress in first responders, such as fire fighters, policemen and paramedics. There are distinct fatigue and stress factors (and even pathologies) that were identified among these professionals. Nevertheless, previous work has uncovered a lack of real-time monitoring and decision technologies that can lead to in-depth understanding of the physiological stress processes and to the development of adequate response mechanisms. Our "silver bullet" to address these challenges is a suite of non-intrusive wearable technologies, as inconspicuous as a t-shirt, capable of gathering relevant information about the individual and disseminating this information through a wireless sensor network. In this paper we will describe the objectives, activities and results of the first two years of the Vital Responder project, depicting how it is possible to address wearable sensing challenges even in very uncontrolled environments.

Keywords: Wearable sensing, sensor networks, biomedical signal processing.

1 Introduction

A recent study on firefighters in the United States [1] showed that 45% of the deaths that occur among U.S. firefighters, while they are on duty, are caused by heart disease. This number is twice as high as for police officers and three times as high as the average incidence of heart disease at work. Furthermore the study shows that the risk of death from coronary heart disease during fire suppression is approximately 10 to 100 times as high as that for nonemergency events. These facts clearly show that for a firefighter the most life threatening condition besides factors such as direct contact to fire or chemicals, is the condition of his heart. Factors that have an obvious high impact on the cardiovascular system are stress and fatigue, which might also be triggering factors for its overload.

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The Vital Responder project is an interdisciplinary research project formed by teams from Institute of Electronics and Telematics Engineering of Aveiro (IEETA), Carnegie Mellon University (CMU), Instituto de Telecomunicações (IT) in Porto and Aveiro, and BioDevices, S.A. The goal of the Vital Responder research project is to explore the synergies between innovative wearable technologies, scattered sensor networks, intelligent building technology and precise localization services to provide secure, reliable and effective first-response systems in critical emergency scenarios. For this goal the estimation of stress and fatigue in first responders is a main concern to prevent cardiac failure and is addressed by using a wearable technology (Fig.1) to obtain information on the firefighter's cardiovascular status via electrocardiography (ECG).

Fig. 1. The Vital Jacket is a wearable vital sign monitoring device. Due to its design in form of a light T-shirt it allows to record one lead clinical quality ECG with a sampling frequency of 200 Hz without restricting the freedom to move.

As in other areas of telemedicine, vital signs monitors are an important part of medical equipment market that has been moving from hospitals to the patient's home [2]. In critical situations, the use of these portable vital signs monitors has proved to be valuable [3]. In this domain, intelligent wearable garments are emerging as the most promising technology [4][5][6]. In a prevous study [7] Cunha et al. showed that the market of wearable vital signs monitors presented eight relevant players. We have evaluated their "integration of vital signs" and "user mobility" characteristics, and results showed two main players: Sensatex's "Smart Shirt", and Vivometrics' "LifeShirt". These are but rare examples of wearable technology for vital signs monitoring, and Vital Jacket (Fig.1) is clearly one of the most successful products, being a comfortable high clinical quality medical device compliant with the EU MDD directive 42/93/CE and manufactured through a ISO9001 and ISO13485 certified process. This device is certified for clinical usage in more than 30 countries. Regarding the estimation of stress in real environments using wearable sensors, recent research has been mostly focused on driving scenarios [8,9] or to estimate stress during high performance jet flights [10]. Some interesting results were obtained by analyzing the sympathovagal balance between sympathetic and parasympathetic activity using heart rate variability (HRV) measurements [11].

It is thus quite clear that the Vital Responder project, when compared to current scientific literature, addresses the very demanding challenges of a highly uncontrolled environment, such as firefighters in action. Will our sensors gather all the required signals with enough quality? Can we transmit this information robustly? Is it possible to estimate stress using conventional HRV measures when there is intense physical activity too? In this paper we will describe the successful experience of the Vital Responder project, including not only a generic presentation on its structure (Section 2), as well as some specific topics associated with the difficulties of attempting to monitor vital signs in uncontrolled environments. We will discuss how standard technologies needed to be adapted to forest fire environments (Section 3), how a sophisticated data annotation system had to be designed for contextualizing the gathered vital signs (Section 4) and how current state-of-the-art biomedical signal research results are not easily transferred to uncontrolled environments (Section 5).

2 The Vital Responder Project

In order to address the demanding challenge of monitoring vital signs of first responders in action, a multi-disciplinary approach was required, resulting in the project structure depicted in Fig.2. This includes designing novel wearable technologies (Task 2), robust wireless signal transmission (Task 3), middleware integration (Task 4) and data annotation and analysis (Task 5).

The Vital Responder project is an international cooperation between Portuguese and North American partners funded by Fundação para a Ciência e Tecnologia (CMU-PT/CPS/0046/2008). Its budget totals 519.456€ and it will end in September 2012 after a 3 year duration. Besides academia and industry partners, the project includes two end-user firefighter corporations, namely Bombeiros Voluntários de Amarante and Bombeiros Sapadores de Vila Nova de Gaia, both in Portugal. Some relevant achievements after only two years include 7 MSc thesis (4 finished, 3 ongoing), 7 PhD thesis (1 submitted, 6 ongoing), 4 journal papers (1 published, 3 submitted), 15 conference papers published, more than 25 public presentations, over 1300 hours of recorded vital signs, 10 new VR Vital Jackets deployed and 2 patents (1 accepted, 1 submitted).

More information about the Vital Responder project can be obtained in the following website: www.vitalresponder.org.

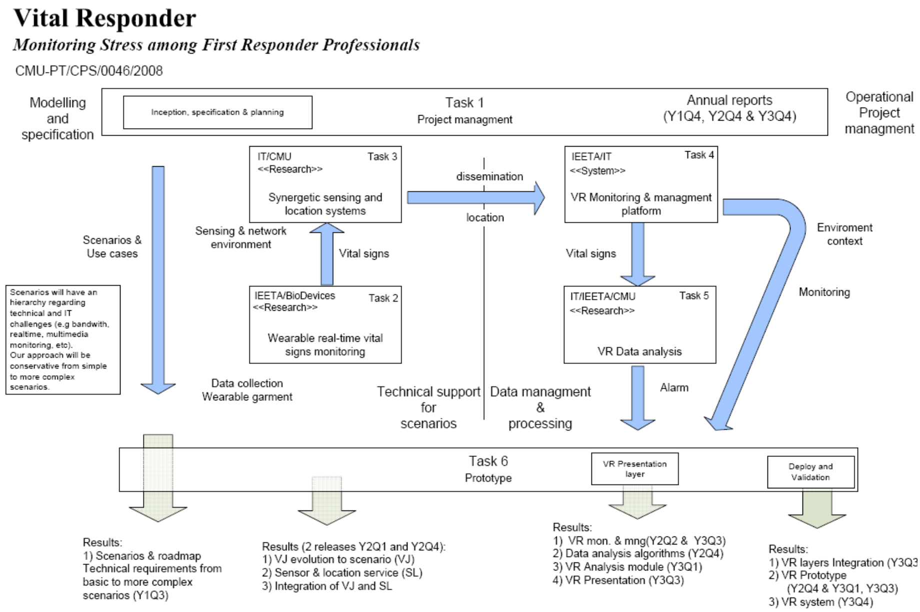

Fig. 2. Diagram of the structure of the Vital Responder project, highlighting its multi-disciplinary nature with tasks ranging from sensor technology, networks, signal processing, machine learning and human-computer interaction.

3 Wearable Sensing

The main objective of Vital Responder regarding wearable sensing is to devise the next generation of wearable intelligent garments for vital signs and other body information suitable for the demanding requirements of first responder professionals. This includes not only the sensing equipment but also its multimedia integration that can support the transmission, recording, annotation, processing and delivery to the final user. Although the Vital Responder project addresses many other challenges (ad-hoc networks for forest fires, building evacuation systems, indoor location systems, arrhythmia detection, fatigue estimation using accelerometers, etc.), we will focus on three specific ones, given their relevance for uncontrolled environments:

- The new **VR Vital Jacket wearable shirt**, adequate for the specific requirements of a firefighter's working conditions. (Section 3.1)
- Novel sensing technologies besides Vital Jacket including, a **real-time blood pressure estimation system,** a **helmet that can record CO, barometric pressure and temperature**, and a new **dry electrode** that is adequate for high temperatures. (Section 3.2)
- The **iVital multimedia integrator** that can be used by a firefighter team leader for viewing the position and vital signs of his team members in real time in an outdoor environment. (Section 3.3)

3.1 Vital Jacket for First Responders

According to the needs identified during our user studies of firefighters in action, a new generation of Vital Jackets has already been produced, tested and deployed in the field. The main problem we had to solve was that our previous process used textile fabrics with a mixture of elastane (28%) and polyamide (62%) and elastane is heat sensitive and may burn the skin of its wearer. Due to this fact, and following international regulations, the firefighters' clothing had to be made with less than 2% of elastane. This means we had to "re-invent" the way we were embedding micro-cabling and micro-electronic components in the shirt to comply with this requirement.

Fig. 3. The new VR Vital Jacket for firefighters had to comply with both international safety regulations for textiles under high heat conditions and the Portuguese law on firefighter garments. As a result, the new shirt (left) visually mimics the normal shirt worn by firefighters and now has less than 2% elastane. Temperature, barometric pressure and carbon monoxide sensors were also embedded in a firefighter helmet model that complies with all EU safety regulations (right).

This development was performed by Biodevices in cooperation with Petratex and IEETA, involving a task-force of textile engineers, micro-electronics experts and textile machine technicians. This highly multi-partner (university and industry) interactive and iterative process focused on devising and implementing the new ways to embed micro-electronics/micro-cabling into non-elastane textile fabric. Furthermore, we had also to design the new VR Vital Jacket version (Fig. 3) following all the standards imposed by international and Portuguese law on a firefighter's garment. Several options were tested that included polyamides, high performance polyamides (HPPA) and cotton. The final solution reduced the elastane from 28% to 2% and incorporated 98% cotton instead of polyamides fabric. Moreover, we could design the new garment in a way that all the outer part (that heats more than the inner part) only had cotton fabric, making it even more protective and heat proof, being at the same time highly comfortable for a firefighters' daily routine. Changes in the fabrication process that involves nosew® textile technology and new micro-cabling components were developed after a long trial and error procedure.

3.2 Novel Sensing Technologies

During Vital Responder we have addressed the possibility of continuously monitoring blood pressure, measuring CO levels and temperatures and developing a dry electrode (without gel). Blood pressure is an important vital sign in the stress study, known to be more sensitive than heart rate variability (HRV) extracted from ECG. Motivated by this, we have initiated during the second year of the project the RTABP (Real Time Arterial Blood Pressure) project. This is a new prototype wearable device that allows comfortable monitoring of subjects (Fig. 4) and includes the estimation of their arterial blood pressure in an online manner. It is based on an algorithm that calculates arterial pulse-wave transit time (PWTT) derived from the electrocardiogram (ECG) and photoplethysmography (PPG) signals. The physiological signals are acquired

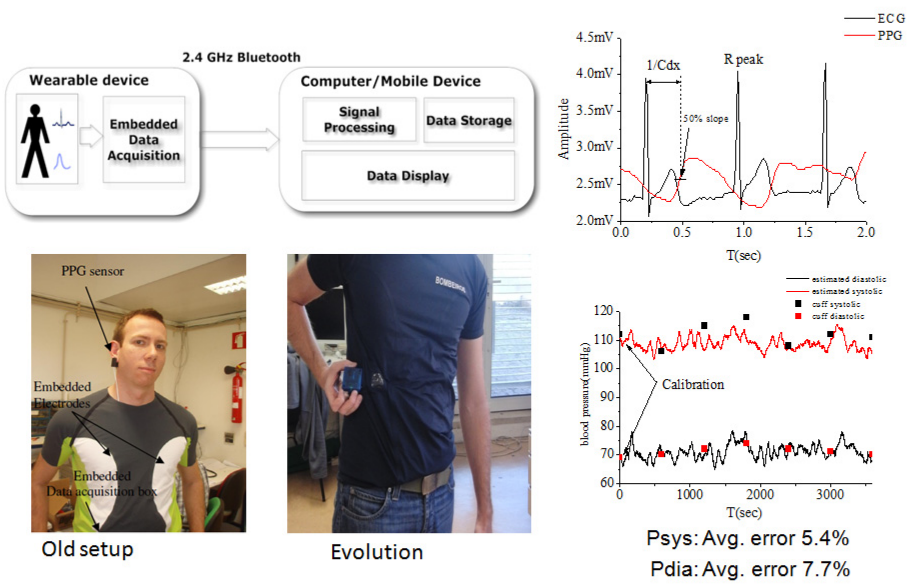

Fig. 4. The Real Time Arterial Blood Pressure device. By increasing the number of cardiac parameters that can be sensed in the field we will pave the way for superior cardiac health assessment in the future.

synchronously in real-time through a textile embedded and a custom built signal acquisition unit (extension of the Vital Jacket system). The sensor used for photoplethysmography (ear probe) permits the quantification of oxygen saturation levels, which is an important indicator of a first responder's physical condition. It also allows the storage of all data for off-line analysis or to transmit the data wirelessly to a computer or mobile device.

Other variables that were identified for monitoring were Carbon Monoxide (CO), barometric pressure and the temperatures that a firefighter was exposed to while on duty. To approach this we have developed the FREMU (First Responder External Measurement Unit). This unit is a device that is inserted into the fire-fighter's helmet that allows for continuous monitoring of environmental conditions in hazardous situations (Fig. 3). This Unit includes a Carbon Monoxide (CO) sensor, temperature sensor and a Barometric Pressure sensor. The CO sensor is important to assess local environmental conditions and give real-time feedback and alarms to the team leaders and commanders. Furthermore we can estimate altitude from values from the barometric pressure sensor. This sensor will be an important tool in order to locate first responder personnel in the field. Communication is handled wirelessly via Bluetooth and the power is drawn from a battery. The unit can be attached to the equipment (e.g. helmet) of the fire-fighter. This device is on lab tests and will be deployed in the next months.

Finally, we have noticed that the presence of high temperatures dries out the liquid gel used in Ag/AgCl ECG electrodes (most commonly used) and the signal loses quality faster than in normal conditions with room temperature. This poses a new problem to our firefighter's scenarios. So, we revisited previous R&D of the IEETA group in the area of active electrodes and developed a novel dry active ECG electrode that does not need gel to pick-up biosignals, being more resilient to temperature. The solution takes advantage of a hybrid organic-inorganic material and embedded microelectronics to perform impedance buffering. This was a major development that has been published on IEEE Sensors journal and resulted in the submission of a patent.

3.3 Multimedia Integration

The iVital system (Fig.5) is a solution to monitor teams of first responders, supporting the role of a team coordinator, with access to the aggregate data. This data includes individual vital signs (e.g. ECG) and location (through GPS, when available). iVital is able to trigger alerts to the end user that could be crucial to support decision in emergency operations, such as forest fires or rescue missions. The system has three main components: a wearable vital signs data collecting unit, using the Vital Jacket; a mobile device for processing and relay (DroidJacket running on a Android smartphone) and a mobile team coordination station (the iVital Base Station running on a iPad tablet) (Fig.6). DroidJacket is the main processing and relay element of the iVital system. It is responsible for processing over the received data in order to identify specific situations from technical issues (e.g. loss of connectivity) to more critical events found in ECG (such as arrhythmias) or in activity patterns (fall or low activity events) by means of the data received by the accelerometers and the smartphone gyroscope. The Base Station handles the incoming data from the DroidJackets through a Wi-Fi connection and displays the location of the team members, as well the individual status of both vital signs (e.g. real time heart rate, heart rate history, ECG) and the mobile device (e.g. battery and connection status).

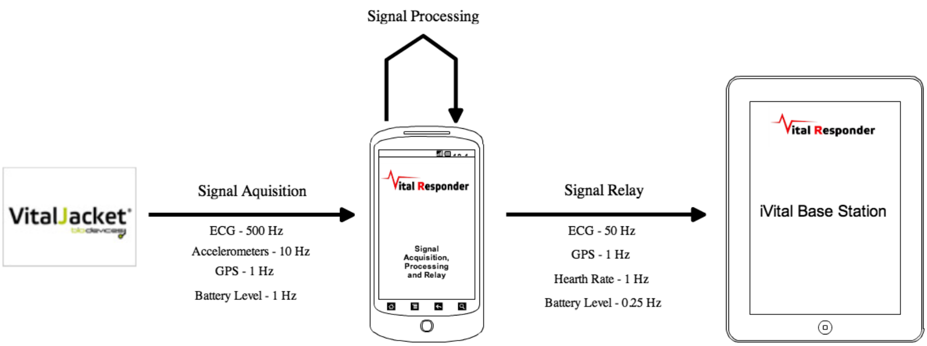

Fig. 5. The *iVital system*, including the *VR Vital Jacket*, the smartphone-based *DroidJacket*, and the tablet-based *iVital Base Station*

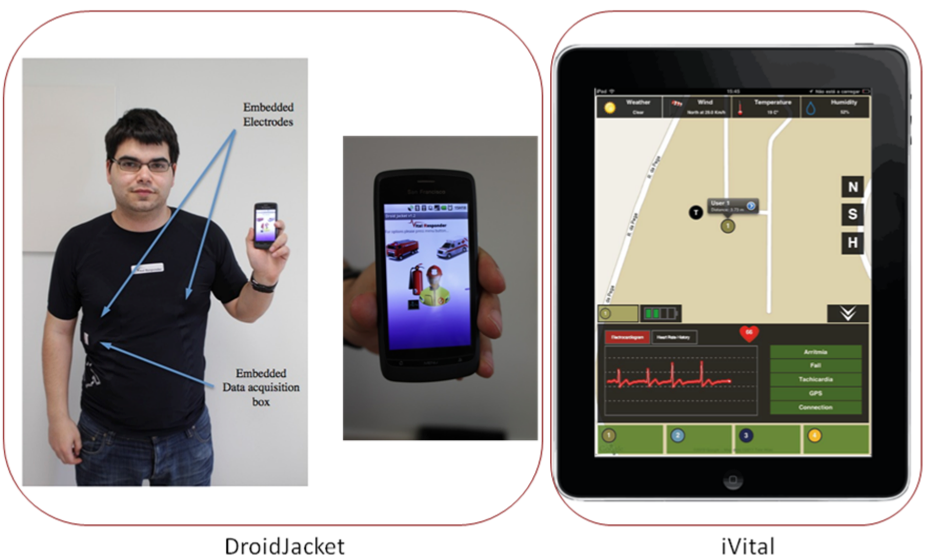

Fig. 6. Two of the Vital Responder prototypes. DroidJacket is the main processing and relay element of the iVital system. It is responsible for processing over the received data in order to identify specific situations from technical issues to more critical events found in ECG. The iPad Base Station handles the incoming data from the DroidJackets through a Wi-Fi connection and displays the location of the team members, as well the individual status of both vital and the mobile device.

4 Signal Annotation for Uncontrolled Critical Environments

Gathering large amounts of vital signals from first responders in critical events is but the first step for researching automatic stress and fatigue estimation algorithms. The currently used Vital Jacket version for firefighters (FF) is capable of gathering clinical quality electrocardiogram, 3 axis accelerometers and GPS signals that are sent to a base station, in real time, in order to be analyzed. A new version is on the way that will add temperature, barometric pressure and carbon monoxide through the helmet embedded unit. However, signal processing and machine learning research, aiming to combine these signals into an estimation of an individual's stress levels, requires the data to be complemented by adequate annotation that can contextualize it. Did an individual's heart rate rise because he was stressed? Or did he simply start running? Was he doing a training exercise or in a real dangerous life-threatening situation? For this purpose, we have created the Vital Analysis Framework (VA), which is a smartphone based solution capable of annotating physiological signals of FF in action with both context (details about the event the FF was involved) and perceived psychological stress levels (retrieved from the analysis of psychological questionnaires).

4.1 Annotating Stress Levels

When investigating stress, it seems important to acknowledge that over the last decades the term has increased popularity across different areas of study such as behavior and health sciences. As a result, it remains difficult to define the concept, at least in simple terms [12], and therefore the necessity to use standardized measures of assessment. We will follow the transactional model of stress, defined as "a situation that taxes or exceeds one's personal resources or threatens the person well-being has the potential to cause stress" [13] (p.19). Thus, the emotions experienced and physiological responses are initiated due to the person interpretation of the event and its perceived meaning to their well-being [14].

Following these theoretical conceptualization of stress, its assessment should combine physiologic and psychological measures [15], including a longitudinal research design and decreased time delay between real world experience of an event and stress ratings [13] since previous research methodologies rely mainly on self-report measures of the concept (e.g., questionnaires) and are fulfilled in paper several hours after the event [16]. To overcome issues related with recall errors, the current study will use the experience sampling method (ESM) developed for in situ recording [17]. ESM in the current study will ask firefighters to rate their stress levels at predetermined times (e.g. beginning, and end of the day and following an event). While ESM originally relied on paper surveys, for the purpose of the current study, ESM will be conducted using a smartphone based framework as successfully used in previous research [18].

4.2 The Vital Analysis Prototype

Given that our target is firefighters in action during real events, we designed a simple to use smartphone framework that can adapt itself to their daily routines. Three annotation methodologies were designed that together provide context to an event and to the collected signals (screens depicted in Fig. 7). These are the Stress Annotation Methodology (stress levels annotation), the Event-driven Annotation Methodology (event context), and the Voice Annotation Methodology ("break the glass" mechanism).

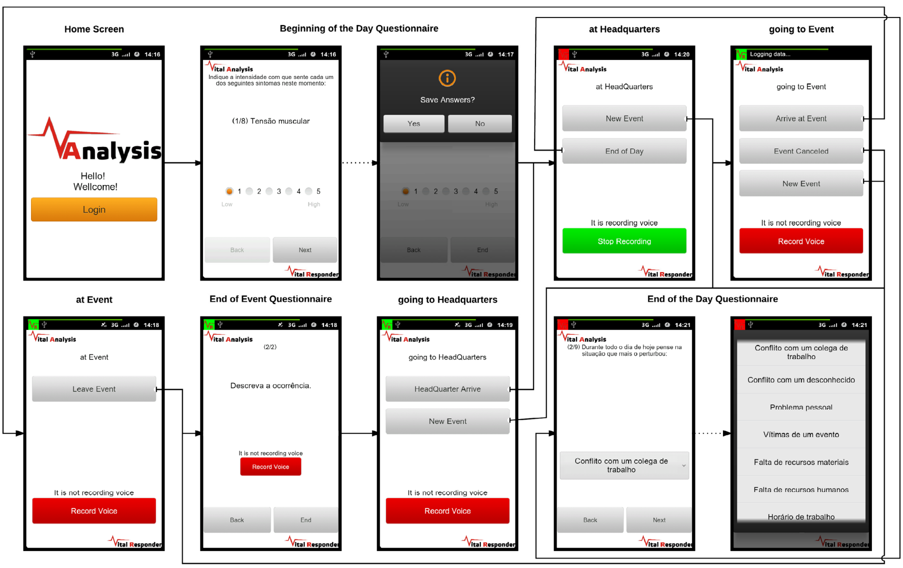

Fig. 7. System image of the Vital Analysis prototype

Stress Annotation Methodology - Due to the complexity of the definition of the stress concept, several self-report measures exist. Despite differences in types of questions, those vary according to the context and population under study. Most self-report measures aiming to access stress levels include questions related with physical and cognitive symptoms of stress. Thus, following this principle, our measures of stress included 4 questions related with physical and 4 questions related with cognitive aspects, used previously in validated stress questionnaires. An example of a physical symptom question is: "I have a stiff neck"; an example of a cognitive symptom question is "I lack concentration". Participants were asked to rate each item on a free scale ranging from "0" to "4" kinds of ratings, where a rating of "0" was used to represent not felt at all, and a rating of "4" extremely felt. These questions were fulfilled at the beginning and end of the day, aiming to evaluate whether there were alterations in stress symptoms experienced, from beginning to end of the day. Furthermore, end of the day and beginning of the day stress symptoms mean scores will be subtracted in order to accomplish an overall mean score, symbolizing accumulated stress symptoms over the day. Internal consistency of the 8 questions was calculated using Cronbach's alphas. This value provides a coefficient of reliability, and it is used as a measure of internal consistency for participants' answers. In the current study, the Cronbach's alphas found for the 8 questions was 0.93. Additionally, another question was fulfilled after each event, indicating stress appraisal of the event. Participants were asked to rate how they appraised each stressful event, on a free scale ranging from "0" to "4" kinds of ratings, where a rating of "0" was not at all stressful, and a rating of "4"was extremely stressful.

Event-driven Annotation Methodology - The Event-driven Annotation gives us the possibility to detail an event by dividing it into several predefined stages, allowing us to evaluate and quantify the collected physiological signals differently for each one. These predefined stages are the basic stages for every single event, and are usually consecutive. A normal event starts with an emergency call, followed by the trip to the event location, the event itself, and finally the return trip to the headquarters. Nevertheless special occasions can occur such as: a high priority call during any period of other event; or the cancellation of an event. This workflow is represented in Fig. 7, where all the options available in the framework can be seen.

Voice Annotation Methodology - Motivated by the unpredictability of a firefighter's job we have design the Voice Annotation Methodology. This methodology will be our "break the glass" mechanism, allowing at least one of the firefighters to report unexpected activities that happen during an event, or add valuable psychological information, allowing for rich and expressive contributions. This methodology is also used to allow the user to add annotation to outside events and to enrich the data gathered using the previous methodologies.

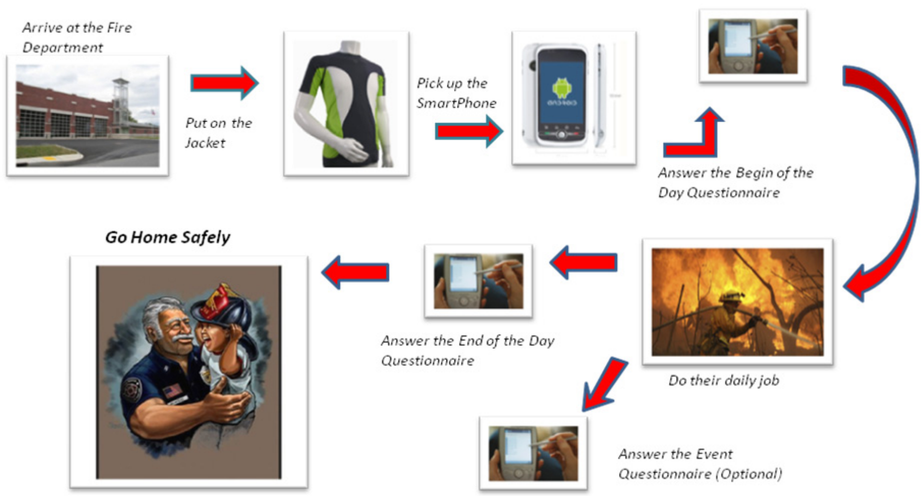

Fig. 8. Integration of the Vital Jacket device and the Vital Analysis prototype in a firefighter's daily routine. More than 4600 hours of Vital Analysis were collected with this methodology.

4.3 Results

The dataset compiled for this study was collected from 12 firefighters, with a mean age of 37.8 and a standard deviation of 5.3, between July, 2011 and January, 2012. During this time we have collected more than 4600 hours of Vital Analysis data from which we have retrieved a total of 717 answers to the event questionnaires from 454 different events. We have also retrieved 319 stress evaluations from the differences between the beginning of day and end of day questionnaires.

To evaluate the usability of our framework we have collected the official information about the events, already gathered using today's firefighter (FF) protocol, and we compared it with our annotations. The measures chosen were: the percentage of real events that were annotated; the percentage of annotations that were done correctly, in which a correct (good) annotation is one that has all the stages implemented in the Event-driven Methodology (in subsection III-B), with a time difference between them superior to 1 minute; the percentage of annotated events with audio annotation; and the percentage of event questionnaires with audio annotation. Results showed that our framework was used in 53.5% of all events and that 64.2% of them were correctly annotated. We can generically consider this as a good result, given the harsh environments that these FF have faced. Nevertheless, some results require a special attention. Low percentages of annotation are obtained when a single FF is sent to an event with VA, which was an expected result. Our solution requires that the FF by himself both remembers and has the time to use the VA which does not exploit the redundancy of the team. Another interesting result is the low percentage of good annotations in events where we have 3 or 4 firefighters with VA present. We would expect to see an increase in this percentage but an explanation might be that situations when many men are deployed tend to be more serious and chaotic, making them less prone to use the system. Interestingly, when we have low percentages of good annotations, we have higher percentages of audio annotations, making us speculate that the firefighters were aware that they were not able to perform proper annotations, compensating this by giving us extra information after the event using audio annotation. Globally, results support that our framework works well in these environments, either using the conventional methodology or the provided "break the glass" alternative.

Table 1. Mean, standard deviation (SD), minimum (Min) and maximum (Max) values for the stress appraisal of various types of events

Event categories	Mean	SD	Min	Max
Fire	1,23	1,00	0	4
Accident	1,40	0,86	0	3
Infrastructure/Communications	0,50	0,80	0	2
Pre-hospital assistance	1,11	0,81	0	4
Legal conflict	0,80	0,83	0	2
Technological/Industrial	0,50	0,55	0	1
Services	1,01	1,03	0	3
Activities	0,77	0,73	0	2
Total	1,10	0,92	0	4

Table 1 provides the mean and standard deviation for the stress appraisal of various events. To analyze whether means for each stress category differed, One-Way Anova analysis was conducted. As expected, we found significant differences between the stress appraisal categorization of the various events, as can be observed by F value (F= 2.518) which is found by dividing the between group variance by the within group variance. When testing the statistical significance, the p-value found was 0.01. It is important to highlight, that higher ratings of stress were provided for certain events such as fire, accidents and pre-hospital assistance. These findings are similar to those found in the literature using detailed psychological methods to assess stress among firefighters. This fact is likely to support the accuracy of the measure to assess stress appraisal of FF across different events.

5 Associating ECG features with Stressful Activities

Most interesting results on stress estimation using ECG signals are based on heart rate variability (HRV) measurements [2,3,4,5]. We are however concerned that in these scenarios the individual being monitored is not under significant amounts of fatigue or short-term physical stress, which is not the case of first responders in action. We aimed to inspect how these cardiac features obtained from ECG signals behaved in a scenario where both high levels of fatigue and stress are expected. To accomplish this we measured the associations between HRV features and certain types of emergency and non-emergency events in which varying degrees of stress are expected.

5.1 Materials

The data used for these experiments consist of records from five male firefighters from the Bombeiros Voluntários de Amarante, which is a team of volunteer firefighters based in Amarante, Portugal. To collect the data, in the beginning of the working day the firefighters put on a shirt under their clothes with the ability to collect clinically valid ECG signals during very long periods (VJ - Vital Jacket) [19]. The VJ then records the firefighter's ECG signal together with a time stamp until the end of his shift, which in most of our recorded cases takes 8 to 12 hours. Afterwards the ECG signal is transferred from the internal memory of the Vital Jacket to a database.

Together with the ECG data recorded by the Vital Jacket the timestamps and types of activities occurred during a specific shift were logged. We have used the official daily log of each firefighter that participated in this study. The Portuguese law implies that these logs include the following information: date and time of the beginning and of the end of every event; type of event, according to a national scheme for classifying events; and the tactical position within the team. The categorization of events is divided into nine main classes with a varying number of sub classes. The main classes are: Fire, Car Accident, Infrastructures/ Communications, Pre-Hospital Assistance, Legal Conflict, Technological/ Industrial, Services, Activities and Civil Protection Events.

With this setup around 447 hours of ECG were recorded between February 2010 and July 2010 from five firefighters. The average age for these firefighters was 35.4 years, with a maximum of 41 years and a minimum of 24 years and at least five years of experience in firefighting. The harsh environment and unexpected situations that these individuals face led to a substantial amount of bad signal recordings due to inadequate electrodes, broken hardware, and incorrect time stamping of the data. As a result, this study led to a clear improvement of the data collection system, which is now much more robust and reliable. After this screening, 238 hours of recordings were selected, out of which 59 hours were collected during missions. The distribution of these 59 hours divided by types of events can be seen in Fig. 9.

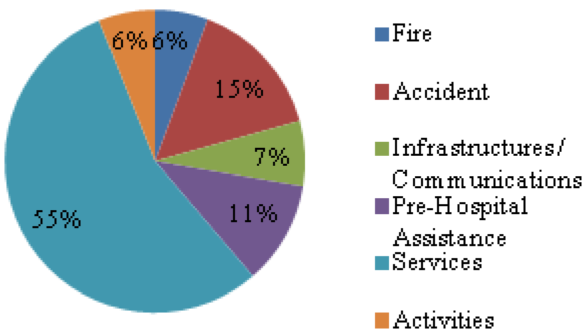

Fig. 9. Distribution of the 59 hours of collected ECG signal according to the type of event

5.2 HRV Features

The detection of QRS complexes used is based on the algorithm by Pan and Tompkins [20] implemented together with further improvements in the open source EP Limited QRS detection software [21] which was used to detect R peaks in the ECG recordings. Besides instantaneous heart rate (HR) measured in beats per minute (bpm), six standard measurements proposed by the task force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology were used for the heart rate variability (HRV) analysis. The following three time domain measurements were used:

- **SDNN:** Standard deviation of all NN (normal to normal beat) intervals in ms;
- **RMSSD:** Square root of the mean of the sum of the squares of successive differences between NN intervals in ms;
- **HRV triangular index (HRVti):** Total number of all NN intervals divided by the height of the histogram of all NN intervals measured on a discrete scale with bins of 7.8125 ms.

Together with the time domain measures, three frequency domain measures were also used. To obtain these measures the series of NN intervals was transformed to a power spectral density (PSD) using the Lomb Periodogram [22]. The spectrum then was analyzed using:

- **Low frequency (LF) part**: ranging from 0.04-0.15 Hz;
- **High frequency (HF) part**: from 0.15-0.4 Hz.

The two previous measures were then divided by the total frequency in the 0-0.4 Hz frequency band. Finally, the third measure is:

- **LF/HF**: ratio between the LF and HF component.

All measures were calculated in consecutive windows of five minutes, until the whole record was covered.

5.3 Associating ECG Features with Types of Events

Association measures are important and useful when evaluating a predictive relation between two variables [23]. The most used measures are the correlation measures, which are adequate for continuous variables, e.g. Pearson correlation. However, in the presence of discrete variables (such as the stress ranking) these popular measures could not be applied. In this special case, another kind of association measures should be used. The ideal measure, in our study, should describe the stress/fatigue as a monotonically nondecreasing mathematical function of the HRV measurements. The Kim's dyx measure is described as adequate for the present problem [23]. However, the Pk measurement by Smith et al. [24] was used, which is an easier to interpret modification of the underlying dyx measure by Kim [25] and often used to evaluate the quality of indicators of anesthetic depth. Briefly, when comparing indicator values (in this case the HRV measurements) to an ordinary scale (the stress ranking) the value of Pk with a range from 0 to 1 can be interpreted as the probability of a concordant relationship of both sides, which means that if the indicator value increases, the assigned level of the ordinary scale is also increasing. The full methodology is depicted in Fig. 10.

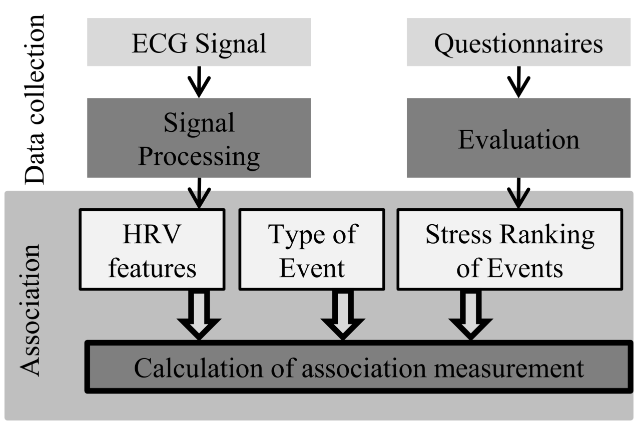

Fig. 10. Data processing methodology

5.4 Results

Due to the answers given in the questionnaires the categories were ranked from low to high stress as following: 1) services, 2) activities, 3) pre-hospital assistance, 4) infrastructures / communications, 5) fire and 6) car accidents. This ranking method produced the same ordering for stress and for fatigue.

Calculating the Pk measure for all six classes and the mentioned HRV measurements including heart rate resulted in Pk values around 0.5 which means a probability of 50% to predict an increased stress level according to an increased value of the measure. But considering only the extreme levels of low stress and high stress at both ends of the scale showed interesting results, as observed in Table 2. The mean values over all five minute segments for the five firefighters are shown divided into the three extreme types of activities: services, fires and car accidents.

Although this is a rather generalized approach, it can be seen that the average heart rate, as the strongest predictor, clearly distinguishes differences between these types of activities and in 76% of all cases supports the order estimated by the questionnaires. Also, the time domain features, mainly HRVti and SDNN, show a negative association with our ordering. This means that the HRV tends to go down during events, which were ranked as more stressful, like fires and car accidents, compared to a low stress service activity, like cleaning route, unblocking passageways or patient transportation.

Table 2. Pk association measure and mean values for 5 minute segments over five firefighters according to three different activities: services, fires and car accidents

Ranking position	Classes	HR (bpm)	SDNN (ms)	RMSSD (ms)	HRVti	LF norm	HF norm	LF/HF	rand
1	Service	87.07	77.44	44.69	12.79	0.35	0.11	5.56	
5	Fire	101.54	65.12	31.01	10.21	0.34	0.09	4.71	
6	Car ac.	103.96	57.71	30.63	9.47	0.41	0.10	5.30	
P_k		0.76	0.39	0.43	0.32	0.57	0.49	0.54	0.53

Although a rather coarse classification of events was used as the basis for the stress ranking of the events, an association between the activities which were ranked as least stressful and most stressful was observed as an increased heart rate and decreased HRV in the time domain. In previous studies the standard frequency domain HRV features, especially the ratio between LF and HF, showed to be a promising parameter as an estimation of the sympathovagal balance. However, in this study it turned out not to be a potential indicator of stress. At least using the standard definition under the uncontrolled conditions of a firefighter's working day, which implies a high level of physical activity. The reason behind this could be that during most of the events the largest part of the power spectrum does not lie within the HF or LF band, but in lower frequency parts. These parts probably should be assessed in more detail in future works.

6 Discussion

Wearable sensing will most probably play a major role in all future health monitoring. The "self monitoring" or the "quantified self" concepts are new and promising trends that will take advantage of this type of technologies. Novel sensing devices appear every year and smartphones are now a very powerful and popular tool that can be exploited. In this paper we have shared some of the experiences of the Vital Responder project, with a stronger emphasis on the problems that arise by demanding uncontrolled critical environments. These are most probably some of the most demanding environments for approaching vital signs monitoring. Sensing technology must adapt and cope with these environments, gathering large annotated datasets that can be useful for signal processing and machine learning research is not a trivial challenge, and traditional state-of-the-art biomedical signal processing research does not necessarily translate well to uncontrolled environments. These are but some the various take home messages produced by the Vital Responder projects and more details can be obtained in the project website (www.vitalresponder.org) and the many scientific publications that resulted from it. We look forward to continue pursuing this line of research in the coming years.

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