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Sensorized T-Shirt for Cardiological Patients in Telemonitoring †

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Abstract: Technological innovations in the development of wearable sensors have led to advancements in smart wearable devices targeted at health monitoring. In this work it was developed a multi sensor t-shirt for remote telemonitoring of vital signs related to cardiovascular diseases. The prototype includes a single-lead ECG, a pulse-oximeter, a temperature sensor, and a 3-axis accelerometer. Data collected are sent by a Bluetooth module, then filtered and visualized thanks to a specific MATLAB script to provide information about heart rhythm, average temperature and oxygen saturation, and respiratory rate. The result is a simple, low-cost, and low-power system, an easily applicable solution within everyone's reach.

Keywords: wearable sensors; telemonitoring; electrocardiography; pulse oximetry; body temperature; respiratory monitoring

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1. Introduction

The aim of this work is the development of a multi sensor t-shirt for telemonitoring vital signs in cardiological patients. This device can be used directly by the doctor, but it's especially useful in remote monitoring.

The term telemedicine, coined in the 1970s, means "healing at a distance" [1], and WHO defines health telematics like "health-related activities, services and systems carried out over a distance by means of information and communications technologies" [2]. Smart wearable devices targeted at health monitoring can be used in telemonitoring systems to unload the health care system and to provide remote and personalized patient care accessible to all [3]. These devices are particularly useful for the follow-up of chronic diseases because they offer the possibility of continuous remote assistance [4–6]. There are several applications reported in literature, like chronic obstructive pulmonary disease, diabetes, end stage kidney disease, hypertension, or heart failure [6–8]. Evidence supports the use of wearable devices, particularly successful for exploring cardiac health and detecting arrhythmias [9–12]. Cardiovascular diseases (CVDs) are the major cause of death: in 2019, 32% of all global deaths were due to CVDs [13]. Detecting these diseases as early as possible lead to several benefits in prevention, diagnosis, and management.

In [14] the 12-lead electrocardiogram (ECG) is presented as the non-invasive gold standard for detecting several heart conditions. On the other hand, the use of ECG machine doesn't offer the possibility of continuous and remote monitoring. When a longer recording during daily activities is needed, like in arrhythmias detection, Holter monitoring or external cardiac event recorders can be used for noninvasive monitoring.

Ambulatory ECG (Holter) can record multiple leads over 24–72 h, but it's uncomfortable because the patient must carry the device and keep sticky electrodes for all the recording duration [15]. Wearable devices entered in this contest to overcome these limitations: in [16] it's presented the state of art of wearables in cardiovascular care. Most of common smart wearable devices on the market provide information about heart rate (HR) and heart rhythm through electrocardiography (ECG). In fact, common arrhythmias, like atrial fibrillation (AF), can be detected using a single-lead ECG. AF is associated to stroke and heart failure, so ECG monitoring through wearable devices can play an important role in early diagnosis.

Another interesting vital sign associated with adverse cardiac events is the Respiratory Rate: it can be used to identify heart failure or heart attack [17–19] because RR can increase even hours before the event, so frequent monitoring can be fundamental. There are different ways to measure Respiratory Rate: [19] provides an overview of the available contact-based methods, while [18] presents a comprehensive overview of the design of respiratory sensing system, describing the results of literature research.

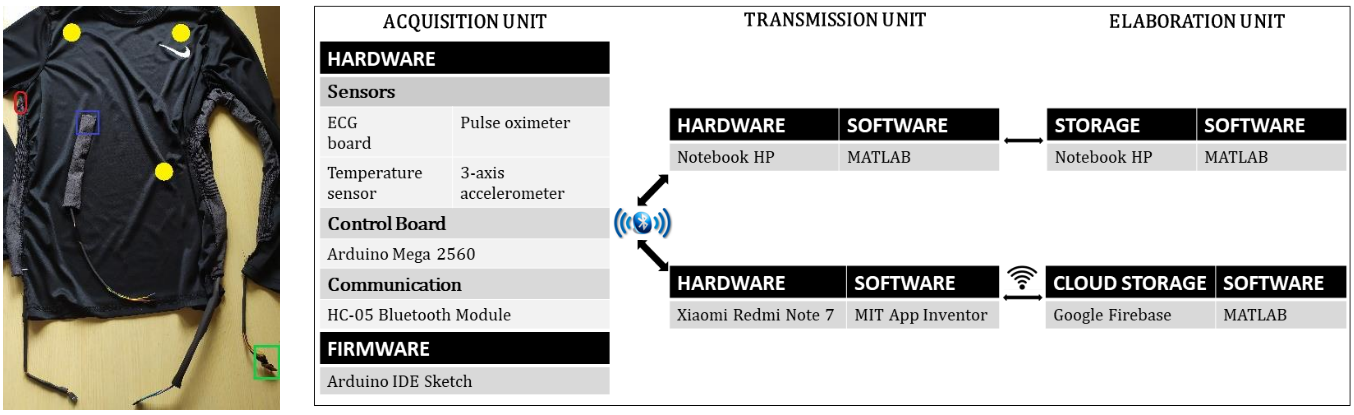
Other vital signs can be provided to assess patient health condition: a review on the state of research and development in these wearable systems for health monitoring is presented in [19]. Concerning CVDs, it's important to monitor oxygenated hemoglobin in the blood through Blood Oxygen Saturation (SpO2) Monitoring Systems because these diseases can provoke reduction of oxygen level in blood [20,21].

In [20] it's also reported state of art of Body Temperature Monitoring Systems. It's difficult to establish a relation between body temperature and heart diseases: some researchers report a relationship with heart rate and respiration rate [22], others [23] say that temperature monitoring can be used to detect the symptoms of medical stress related to stroke and heart attacks. Although, there is an interesting correlation between temperature and strokes [24]: for example, in [25] was found that monitoring, and so preventing, high temperatures days after ischemic strokes can improve outcome.

In our study we want to provide a sensorized t-shirt that integrates more sensors related to cardiac monitoring. For that reason, we developed a system including a single-lead ECG, a pulse-oximeter, a temperature sensor, and a tri-axial accelerometer.

2. Materials and Methods

In this section, we discuss the details of hardware, software, and firmware of the developed prototype t-shirt (Figure 1a) for telemonitoring of cardiological patients. The design developed presents an acquisition unit, a transmission unit, and an elaboration unit (Figure 1b).



(**a**) (**b**)

Figure 1. (**a**) Sensorized t-shirt integrating temperature sensor (red), tri-axial accelerometer (blue) and pulse oximeter (green), and electrodes placement (yellow). (**b**) Illustration of system design with both transmission units. In particular, the Android App has been created for telemonitoring applications.

2.1. Sensors

A single-lead ECG, a pulse-oximeter, a temperature sensor, and a 3-axis accelerometer were used to monitor cardiac health.

The AD8232 SparkFun Single Lead Heart Rate Monitor [26–30] was chosen to measure the electrical activity of the heart. The AD8232 is an integrated signal conditioning block for ECG that acts as an op amp to extract, amplify, and filter biopotential signals in the presence of noisy conditions, such as those created by motion or remote electrode placement. The advantage of this sensor is that the electronic components needed for the ECG acquisition, like amplifiers and filters, are contained in a 35.6 mm × 27.8 mm board, powered with a 3.3V supply voltage. Data acquisition is made through three disposable foam solid hypoallergenic gel electrodes of FIAB SpA. These electrodes are CE marked according to the directive 93/42/EEC and low cost (€0.20/electrode).

To monitor blood oxygen saturation was used The SparkFun Pulse Oximeter and Heart Rate Sensor, a 3.3 V sensor. This board integrates two Maxim Integrated chips: the MAX32664 Biometric Sensor Hub and the MAX30101 Pulse Oximetry and Heart Rate Module [31]. The MAX30101 has an internal LED to light the finger and measures absorbed light through its photodetectors, while the MAX32664 processes the data and provides heart rate and blood oxygen saturation (SpO2), reported as percentage of hemoglobin that is saturated with oxygen. An interesting feature of this sensor is the possibility of reporting measurements' confidence and information about correct finger position. The MAX30101 has an internal ADC with 18-bit resolution, the device is easy to use and set, and it's very small (25.4 mm × 12.7 mm), so it's comfortable for the patient.

The DS18B20 digital thermometer [32,33] was chosen as temperature sensor because it provides up to 12-bit measurements and ±0.5 °C accuracy from −10 °C to +85 °C. Moreover, thanks to its size (5 mm × 4 mm × 6 mm.), it doesn't cause discomfort.

For an easy and fast evaluation of Respiratory Rate (RR), it was decided to use an accelerometer, like in more than 11% of works analyzed in [18]. It was chosen the ADXL335, a 3-axis accelerometer [19,34] powered with 3.3 V. It can measure acceleration with a minimum full-scale range of ±3 g, so it's used to measure the dynamic acceleration resulting from torso motion.

2.2. Control Board and Connectivity

The sensors are connected to an Arduino Mega 2560, a microcontroller board based on the ATmega2560. The choice was due to its 16 analog inputs, each of which provide 10 bits of resolution, useful for the future integration of other sensors. The Mega 2560 also supports TWI communication, through the pins SDA (data line) and SCL (clock line), so it can communicate with I2C devices, like the pulse oximeter.

Data acquired from the sensors are transmitted through HC-05 Bluetooth Module, a Serial Port Protocol module designed for wireless communication. It supports different baud rate [35], that can be set in AT mode. It has been chosen the minimum baud rate sufficient to send all the data, that is 115200. This module was already used in others ECG applications [29,30].

2.3. Acquisition Unit

The prototype was tested using disposable electrodes: for this reason, they aren't integrated in the t-shirt. As suggested in the Sparkfun Hookup Guide, two electrodes are placed on the chest near the arms, while the right leg electrode is placed on the right lower abdomen (Figure 1a).

After electrodes positioning, the patient can put on the sensorized t-shirt, in which are sewn pockets for the cables. The sensors can be connected after the fitting, so they can't be damaged during the operation. Furthermore, to wash the t-shirt every electronic component of the device can be easily removed and replaced.

The temperature sensor is fixed under the left armpit, while the pulse oximeter is in contact with the right index finger. For the accelerometer positioning, [36] reports that respiration frequency can be accurately measured from the placement "at the clavicular, pectoral and lateral sites on the chest as well the mid abdominal site". The accelerometer was fixed on the left costal margin to not interfere with ECG cables.

An Arduino sketch was written to acquire data from sensors at different frequencies. Each sensor has its function and it's called through its timer: temperature sensor and pulse oximeter are acquired every 1 s (1 Hz), accelerometer every 200 ms (5 Hz) and ECG every 4 ms (250 Hz). In this way, every second we collect 270 samples: there is a start character "s", 1 temperature sample, heart rate and SpO2 from pulse oximeter, 5 samples from each axis of the accelerometer, 250 samples from ECG board and a blank space as end character. Data are directly transmitted through HC-05 Bluetooth Module.

2.4. Transmission and Elaboration Unit

A serial connection between Arduino board and pc is created through the Bluetooth module. The transmission is managed by a MATLAB script, that allows to select acquisition time and to save data in a .txt file at the end of the procedure.

It has also been created an Android application, using MIT App Inventor, to develop a transmission unit usable in telemonitoring. The app receives data from the Arduino board and saves it to Google Firebase database, accessible through MATLAB script.

Depending on the modality of transmission, signals stored are processed with a MATLAB code, that allows to visualize the rearranged and filtered data.

3. Results and Discussion

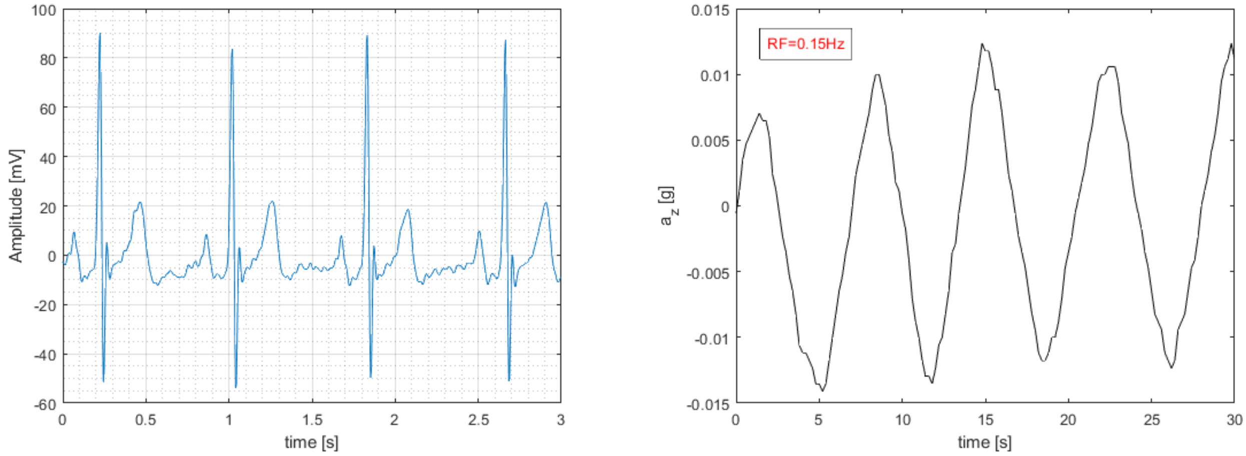
We tested the prototype in two different transmission modalities explained in the previous section. In both cases, we obtained what we expected, without loss of samples. In this section, we discuss the results obtained for each signal acquired at rest. After the fitting, participants sit on a chair without moving, with their back lying on the seatback and their hands on the table.

The prototype acquires an ECG signal, that allows to distinguish all the stages of the cardiac cycle (Figure 2a). It was obtained a single lead ECG, that provides enough information to identify cardiac rhythm disturbances, such as atrial fibrillation. Even when some noises appear in the acquisition, waves and intervals are detectable.

The application of only three electrodes was enough, but it represents a limitation. In fact, it's necessary to acquire 12 derivations to explore all range of cardiac diseases, like myocardium damages.

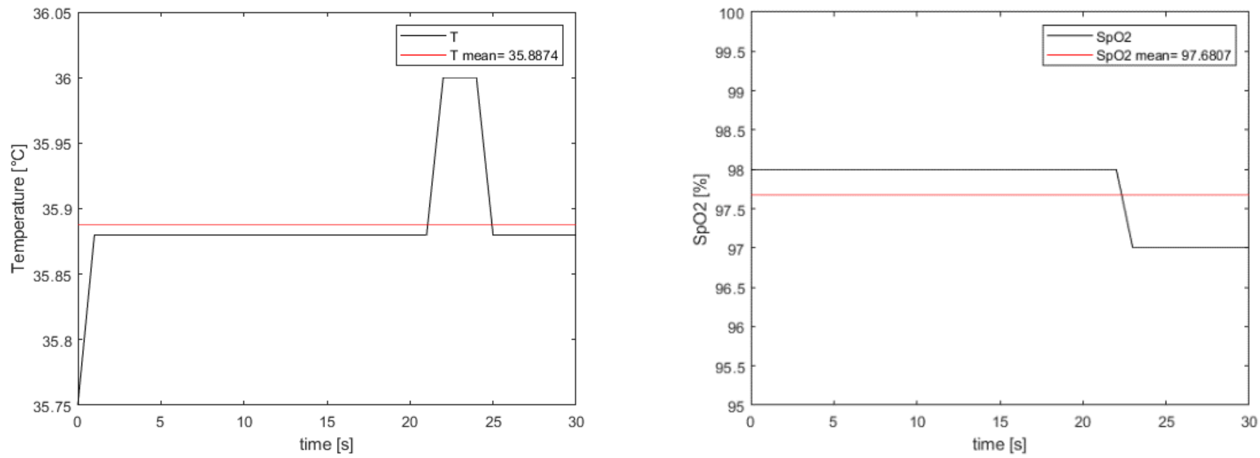
In this work, it was studied the variation of acceleration along the z-axis (Fig. 2b), perpendicular to the chest, to evaluate the Respiratory Rate, that is the number of breaths taken per minutes. This is a fast and easy method to have an approximation of the RR value, also usable in motion test with the integration of another accelerometer. Respiratory frequency is calculated as the frequency corresponding to the maximum value of the acceleration power spectrum.

Temperature sensor and pulse oximeter are integrated in the t-shirt to provide a wider cardiac monitoring. Even if huge variations in temperature and SpO2 values weren't expected at rest, they were acquired to test the functionality of the electronics and the ability of transmission for future developments. After the elaboration, it was supplied the mean values of samples acquired. In Figure 3 it's reported an extract of sensors output plotted with the mean values.



(**a**) (**b**)

Figure 2. (**a**) Three cardiac cycles extracted from an ECG acquisition. (**b**) Accelerometer output along z-axis, perpendicular to the torso. In the first 5 seconds, the subject wasn't breathing**.**



(**a**) (**b**)

Figure 3. (**a**) Temperature sensor output and mean value; (**b**) Pulse oximeter output and SpO2 mean value.

4. Conclusions

In this work was developed a multi sensor t-shirt realized to measure vital signs important for heart monitoring: the prototype integrates a single-lead ECG, a pulse oximeter, a temperature sensor, and a tri-axial accelerometer. The result is a simple, low cost, and low power telemonitoring system, able to collect enough data for machine learning applications. Future developments will concern the measure of 12-lead ECG and the use of the prototype in motion tests, for the evaluation of health condition during daily activities.

Institutional Review Board Statement:

Informed Consent Statement:

Data Availability Statement:

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