Cardiac monitoring with novel low power sensors measuring upper thoracic electrostatic charge variation for long lasting wearable devices

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Abstract— **Cardiovascular disease is a major cause of premature mortality, high healthcare costs, and disability-adjusted life years. Digital interventions such as continuous cardiac monitoring solutions can help to monitor the patient status and provide valuable feedback to clinicians to detect early warning signs and provide effective interventions. This paper presents the evaluation of a novel low-power sensor exploited to measure the electrostatic charge variation in the upper thorax to provide an energy-efficient and accurate detection of the electric activity of the heart. The sensor is investigated for measuring the heart activity in terms of the QRS complex. The paper presents the design of a wearable sensor device, optimization of electrode positions and incorporation into a wearable chest strap that can be integrated seamlessly under clothes. Due to the low power consumption of the sensor, the sensor node consumes only 87.3 µW of power and can provide multiple weeks of operation using a coin cell battery while providing the same functionality as that of commercially available sensors such as photoplethysmography and electrocardiogram (ECG) ICs. In addition, the chest strap was also characterised for different use scenarios during sedentary and activity periods. We evaluated both the signal quality and the power consumption compared with other sensors technology showing a power save of an order of magnitude when compared with photoplethysmography sensors.**

Keywords—cardiac activity monitoring, charge variation detection , wearable system, low power system

I. Introduction

Cardiovascular diseases (CVD) are the leading cause for disease burden around the world and continue to increase in prevalence[1], [2]. They are a major contributor to premature mortality and rising healthcare costs [3]. In order to achieve the targets for Sustainable Development Goal 3 established by the United Nations which aims to achieve at least 30% reduction in premature mortality due to non-communicable diseases by 2030, there is an urgent need to focus on implementing cost-effective interventions[4]. Recent research has shown that digital health interventions can contribute majorly to the risk reduction in CVD outcomes, particularly on secondary CVD prevention[5].

Smart sensors are gaining popularity in many applications, largely due to the push by huge markets of smart phones, internet of things and wearable devices[6]. Also, such sensor systems are becoming increasingly complex systems that combine not only transducers and their analog frontend, but also computation, memory, energy and data storage, software, firmware and connectivity in a myriad of ways[7]. Vital sign monitoring with sensors deployed on the skin surface has been demonstrated to be crucial for a wide range of applications such as health monitoring[8], [9], diagnostics[10], and human-machine interface[11], among others. In recent years, the interest in investigating and developing wearable smart sensors for healthcare and longitudinal monitoring[12] has significantly increased, and today there are many academic and commercial devices that enable long-term data acquisition and monitoring [13].

Recent advances in wearable technology has provided new avenues for diagnosis and management of CVD and its adjoining risk factors[14][15]. Many solutions for wearable cardiac monitoring are available today that include Holter monitors, event recorders, ECG patches, wristbands and smart textiles that provide heart rate and management of nonarterial fibrillation. However, direct-to-consumer cardiac rhythm monitors are mostly for surveillance or spot-checks and do not provide continuous monitoring. It has been proved that long-term recording is critical for capturing intermittent or transient events to inform appropriate treatment or predict an adverse event[9], [16]. Also, the data quality and quantity is dependent on the battery size and operational longevity[17][18]. Such dependencies further imply an interruption in continuous usage, loss of critical physiological data, high maintenance costs and environmental issues related to battery disposal[19]. Vast improvements in processing power, device miniaturization and network benefits provided by ubiquitous wireless connectivity have ushered in a new era of wireless health sensing[8]. The lifetime of smart sensors is limited in all real world applications by the use of batteries. Power consumption is further heightened when raw data is processed in-sensor to extract information[20]. Stringent constraints are set on the useable power, sensor accuracy, and lifetime of wearable devices due to the miniaturized and thin form factors[21], [22].

This paper presents the design and evaluation of a wearable sensor node for cardiac monitoring exploiting a low power novel sensor that measures the changes in electrical activity of the upper thorax to reproduce the electrocardiogram. The sensor includes an analog front-end for charge-variation (QVAR) monitoring and it is integrated into the ILPS22QS by STMicroelectronics with integrated pressure sensor and accelerometer. The developed low power sensor node is easily conformed into a wearable system that can be worn as a chest strap or integrated into a smart textile garment.

II. Sensor System Description

A. *Charge Varaition (QVAR) Sensor*

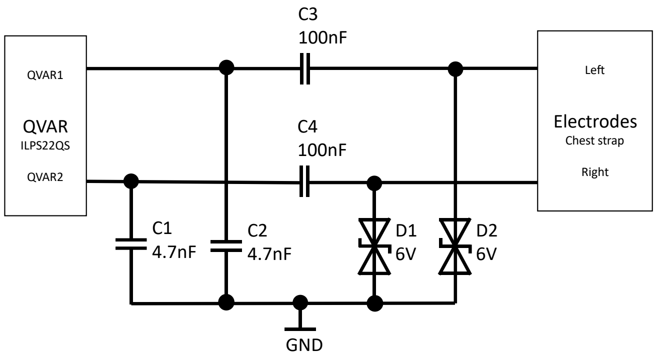

Fig1 : Electrode circuit to QVAR to remove ambient noise and decouple from human body

This paper presents the implementation of a wearable low power device that exploits the variation of charge of the skin to detect ECG and hearth bear. The main contribution of this paper is the evaluation, characterization and demonstration of the benefits of using the monitoring of electrostatic charge to have cardiac monitoring. In particular we exploited a novel sensor from STMicroelectonic that integrated a front-end called QVAR in a MEMS sensor ILPS22QS. The QVAR stands for charge (Q) variation (VAR) and is employed in the current sensor node to detect electrostatic charge changes in the upper thorax due to cardiac activity. The QVAR sensing channel can work with one or two electrodes. In both cases, QVAR works in differential mode but with a single electrode configuration, the sensitivity to the electrostatic field variation is enhanced since common modes are not well canceled. The QVAR is very sensitive to electric changes in its surroundings and requires efficient noise cancellation. Figure 1 shows the electrode circuit implemented on the sensor node to decouple the bio-signal from ambient noise and remove the DC bias when attached to the human body.

B. *Hardware Overview*

To characterise and evaluate the sensor's capability in a realistic application scenario of cardiac monitoring a wearable device has been developed. The low power high accuracy wireless sensor system consists of the STM32WB55 microcontroller from STMicroelectronics which has two cores : M4 for the user code and one M0 for the integrated Bluetooth Low Energy (BLE). Power management is implemented with a buck-boost converter TPS6303 that is supplied by a coin cell (CR2032) battery. The STM32CubeIDE from STMicroelectronics was used to configure the MCU and generate the hardware specific code. Data was transferred over BLE to an application that could view data in real time on an android phone.

Figure 2 shows the developed sensor node that has been designed such that the two electrode system can be incorporated in a wearable system as is or in smart garments. The coin cell battery easily fits into the strap casing and can be easily replaced when needed. Non-contact copper electrodes are used in the system's design with dimensions of 7cm × 1.5 cm. The elastic belt connector can is adjustable to fit different population groups.

C. *Chest Strap for Cardiac Monitoring*

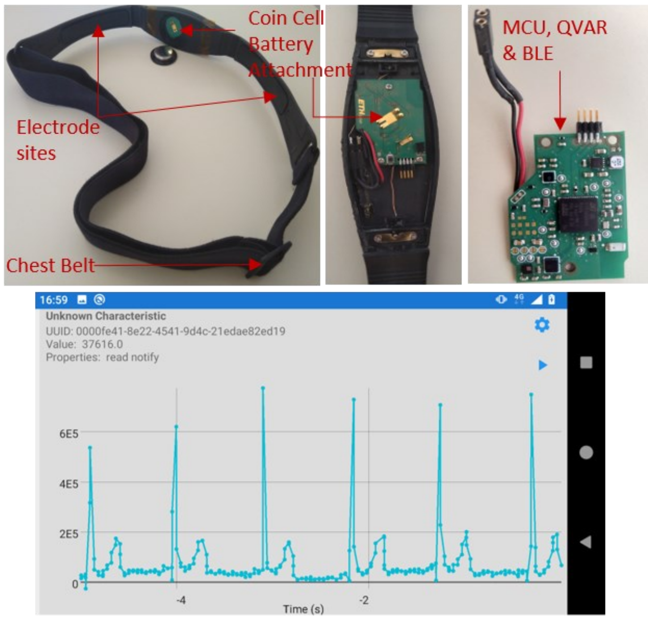

Fig 2: *(top)* QVAR based cardiac monitoring chest strap powered by a coin cell battery. *(below)* Cardiac electrical activity recorded by the QVAR based chest strap logged on a mobile phone application via BLE

III. Methods

The following experiments were carried out to evaluate the capabilities of the QVAR sensor node to monitor cardiac activity:

- The developed sensor node was compared for performance with respect to functionality (accurate capture of heart activity)and power consumption against commercially available photoplethysmography (PPG) sensor MAX30102[23] and ECG front end MAX30003[24].
- The electrode positions were investigated on the chest to optimize the system for a two electrode QVAR based cardiac monitoring chest strap. Four positions were investigated on the upper sternum at a separation of 5cm from each other as shown in Figure 3(left) to finalize the design for a chest strap.
- In order to facilitate continuous and ambulatory cardiac monitoring, the signal acquisition with the QVAR sensor node was investigated in five use case scenarios that included motionless sitting and standing, walking, running and exercise (push-ups).

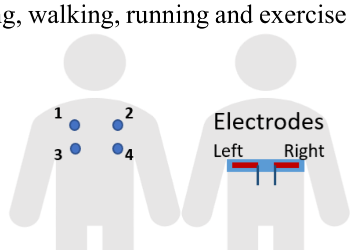

Fig 3: *(left)* Electrode positions evaluated for signal acquisition, *(right)* concept design for used chest strap

IV. Experimental Results

A. Signal acquisition

The cardiac chest strap is compared to the PPG and ECG. reference sensors. Figure 4 shows the comparison of the chest strap with the Polar H10 in detecting the heart activity. To compare with other sensor nodes, Figure 5, shows the concurrent data acquired from a PPG sensor attached at the index finger, an ECG analog front end and the QVAR sensor applied to the chest. Since the aim is to assess accuracy with lowest possible power overhead and computational overhead, the QVAR sensor is able to detect the Q, R and T peaks just as well as the ECG and PPG sensors.

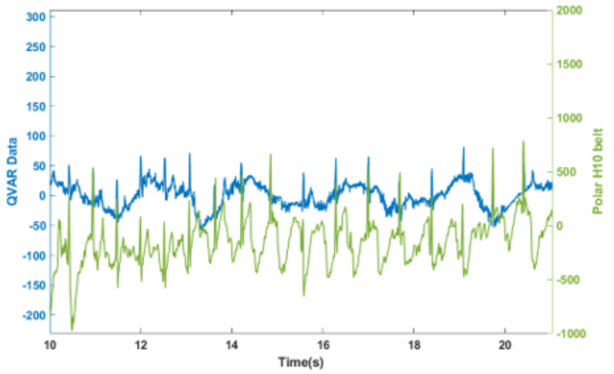

Fig4: Comparison between reference device, Polar H10 and the QVAR based chest strap in detecting heart activity

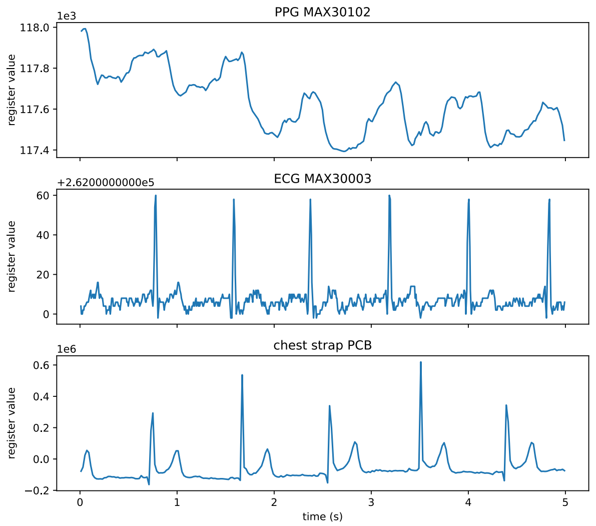

Fig5: Comparison between Qvar based chest strap with PPG and ECG sensors.

B. Electrode positions

The heart beat signal was acquired with two electrodes placed at different electrode positions as shown in Figure1. Figure 6 shows the captured electrical charge change by the QVAR sensor. It can be seen that acquiring the signal between electrodes 4 → 2 and electrodes 4 →1 captures the P wave in addition to the Q,R,S and T waves. Hence, for further evaluation, we used electrode position 4 → 2 as it was easier to incorporate into a chest strap for cardiac monitoring.

To further evaluate the reliability of measurements, the chest trap was evaluated on two subjects as shown in Figure 7 and the developed sensor node was able to measure the electrical activity in both subjects. The slight variations in the measured ECG could be due to the age and BMI of the two subjects (person 1: BMI 22, Age 59 yrs; person2 : BMI 19, Age 19 yrs) and representative of the heterogeneity in heart activity in different individuals.

For comparison and to evaluate the QVAR for applications in another packaging, commonly used disposable ECG electrodes were also used for measuring the heart rhythms. Figure 8 shows the comparison between the electrodes of the chest strap and the Tigamed ECG electrodes applied at the same position. It can be seen that the non-contact electrodes incorporated into the chest strap filter out changes in the baseline DC level better than the disposable ECG electrodes. Hence, other application scenarios with further constraints on space would require a more investigation of electrode design.

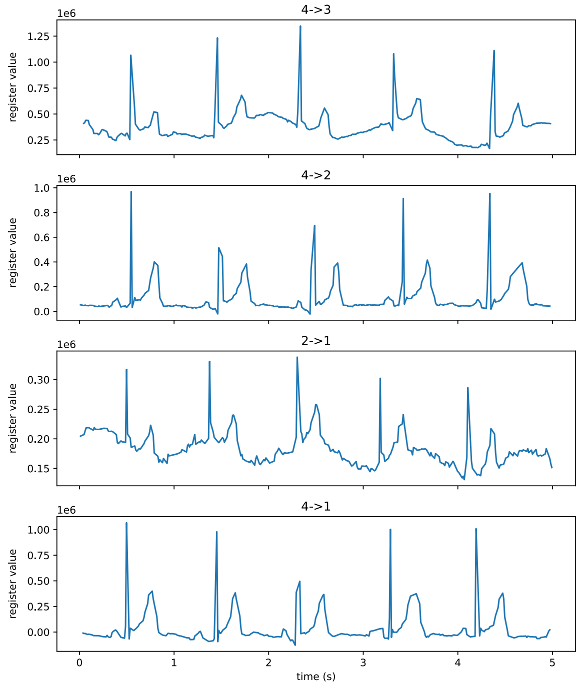

Fig6: Heart beat signal between different electrode positions.

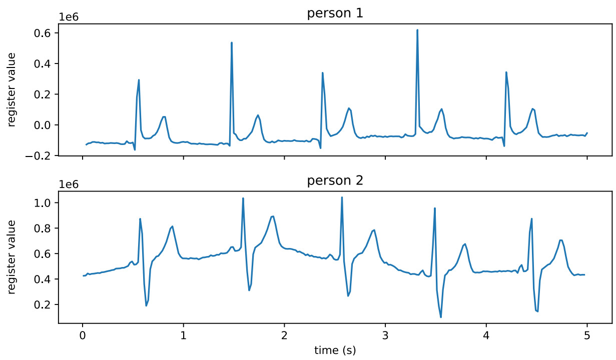

Fig8: Cardiac rhythm recorded in a . 4 → 2 electrode configuration from the QVAR sensor node from two subjects

Additionally, we also tested the setup of the chest strap: main sensing unit with processor and the non-contact monitoring electrodes, on different body positions. This was an exploratory investigation to see if the QVAR could be adapted for different application scenarios, such as a wearable sensing patch, ring or a wristwatch. Figure 9 shows the results from different positions, which are as follows:

- Chest: Electrodes in 4>3 electrode position (as described in Figure 3)
- Fingers: Each index finger pressed on the one electrode
- Wrist: Electrodes placed on top and bottom of the wrist

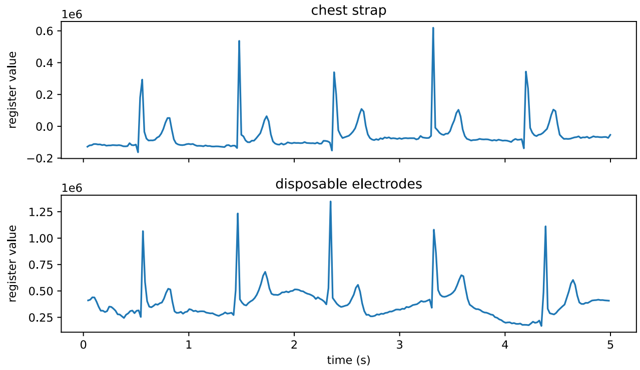

Fig8: Effect of using disposable ECG electrodes when compared to non-contact monitoring electrodes used in the chest strap.

The chest position is able to recreate the QRS and T waveforms. The finger positions report pulsatile flows but not an ECG, while the wrist does show the pulsatile flow of blood to the extremities but cannot provide a stable baseline for measurement.

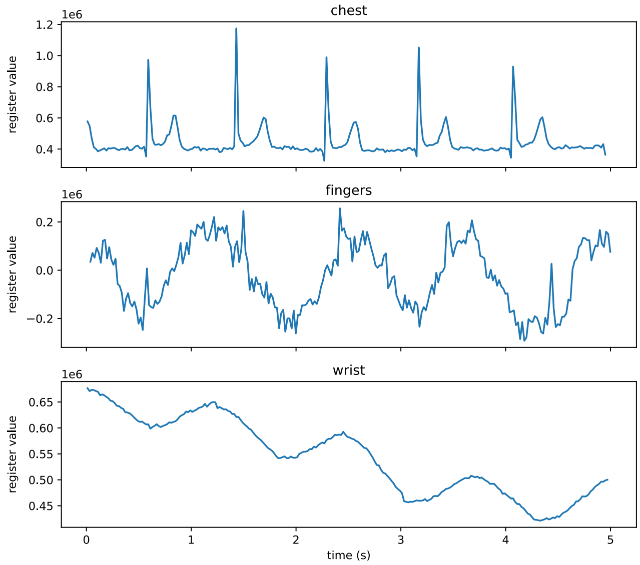

Fig 9: Developed QVAR sensor measuring heart activity in different positions on the body

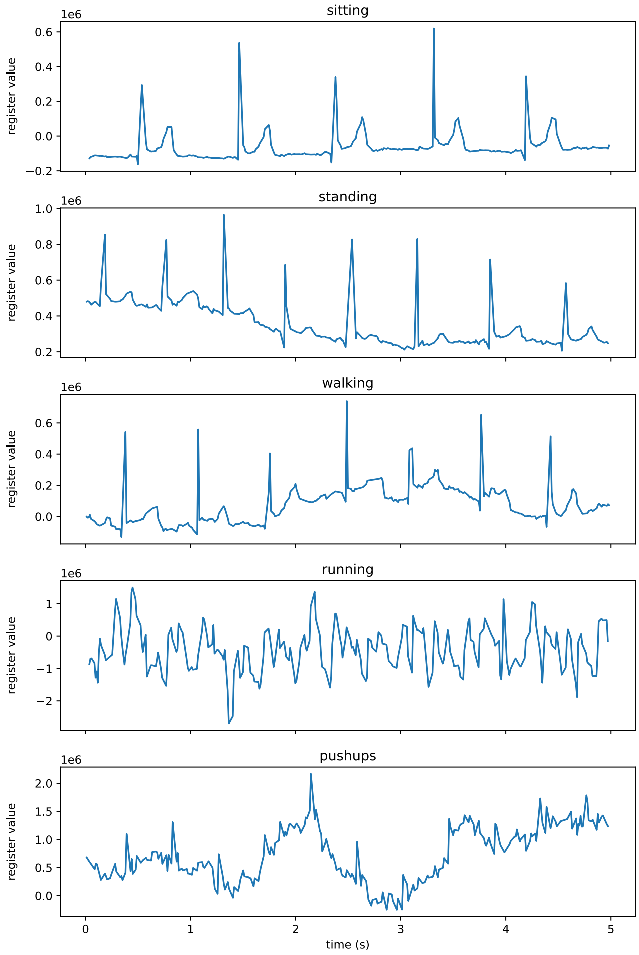

Fig 10: Cardiac monitoring with QVAR based chest strap during different activities.

C. Ambulatory cardiac monitoring

Figure 10 shows the output of monitoring the cardiac signal with the QVAR based chest strap during different activities. It can be seen that the QVAR sensor is very sensitive to motion and is heavily degraded during vigorous activities such as running. However, lower levels of relative changes between the electrode contacts and the subject's skin, such as seen during walking and push-ups, can still detect the R wave that can be used for heart rate monitoring. Our aim was to evaluate the novel QVAR sensor performance without overlaying signal processing and feature extraction. Hence, we did not benchmark this experiment against reference device like the Polar H10.

D. Power Consumption

The power consumption of the QVAR based wearable is compared to commercially available ICs for PPG and ECG. Table 1 shows the run-time power consumption for the used ICs. During the power measurement, current and voltage were measured with two multimeters at the power supply pins of the sensor system while in continuous operation with the maximum operability of all on-board subsystems.

Sensor	*Voltage*	*Current*	*Power*
QVAR	2.53V	34.5μA	87.3μW
ECG	3.29V	116 μA	382μW
PPG	3.29V	7.69mA	25.3mW

Table1: Power consumption of the different sensors

It can be seen that the QVAR consumes almost 4.5 times less power than the ECG front end and 10^3 orders of magnitude less power than the PPG sensor. This ultra-low power consumption makes QVAR a highly suitable sensor for always-on and long-lasting wearable sensors that can be used for at-home or clinical monitoring.

V. Conclusion

In this work, a novel sensor based on measuring the electrostatic charge changes during cardiac activity was designed, developed and evaluated for cardiac monitoring. The QVAR sensor is capable of non-invasively measuring heart rhythms and recording the electrocardiogram. The electrode positions were optimized to reproduce the signal with maximum features and the highest signal to noise ratio. The QVAR was also orders of magnitude lower than commercially available sensors such as PPG and ECG front-end ICs and could provide continuous monitoring with a small power consumption of only 83 μW. The QVAR sensor provides a low power alternative to ECG front end module (with comparable functionality for detecting the QRS complex) and the power intensive, pressure artefact prone PPG sensor. It is more robust and accurate than a PPG sensor in providing an accurate representation of the cardiac activity while also being independent from artefacts due to applied pressure ,such as those seen in the PPG sensor. A wearable chest strap incorporating a coin cell battery thus developed which was comfortable to wear under normal clothes and could be included in smart garments for health monitoring.

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