Developing a Low Cost Capacitive ECG via Arduino and Single Board Computer Interfaced with Capacitive Electrodes for Prevention and Security Aspects

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Abstract

Coronary heart disease (CHD), and its different variants, is one of the major reasons of increased death rates in industrialized nations. As the beginning of the disease is symptom free, unconsciousness and sudden death, as well as health related distortions can trigger accidents at construction sites any time. Therefore, there is a need for systems, which can detect such silent symptoms, in order to prevent health related accidents on construction site. Nowadays, most common way to identify first symptoms of CHD is the electrocardiography (ECG). Therefore, in this paper a novel approach for the implementation of a contactless capacitive ECG, which can be straightforwardly embedded in a chair is proposed, in order to enable a pervasive user experience (e.g. while steering heavy machines). The capacitive electrodes were manufactured using of-the-shelf components, tested and calibrated. The main requirement during the design and development phase was fabrication of a basic low cost capacitive ECG system with wireless connectivity to a platform that could display the corresponding measurements to the user over a display. Such an approach could pave the way for future pervasive sensor fusion, i.e. interfaced with an automated emergency call gateway, in order to enhance the prevention of such diseases, before it is too late for the users. The achieved measurement quality of this contactless system is depicted by comparing measurements between measurements with direct skin contact and with measurements through cloths. The influence of the wireless data transmission using XBee antennas as a communication medium has been investigated, tested, and evaluated.

Keywords –

Capacitive Electrodes; ECG measurement; XBee; e-Health; contactless measurement

1 Introduction

Coronary heart diseases are in industrial nations one of the main reasons for death, as well as for working incapability. Bad lifestyle and demographic change in industrial nations (e.g. US, UK, Germany, Austria, etc.) increased the secondary diseases of the coronary heart disease, like heart attacks or heart rhythm distortions [1]. At moment, cardiologists use the ECG to identify these diseases for further prevention and treatment. Although the ECG is not very difficult to measure, only physicians in clinics or hospitals can properly perform it.

Nevertheless, the ECG is already used in lifestyle products, e.g. unobtrusively embedded in wristwatches, steering wheels, ergometers etc. However, it is mainly used for pulse measurements by the Einthoven I lead. Nowadays, through the technology of capacitive electrodes, it is even possible to measure the electroencephalogram (EEG), or the ECG through cloths [2, 3]. The automotive industry is one of the first institutions, which implemented the ECG into the driver's seat [4, 5, 6].

Inspired by this approach, the authors aim to install an ECG, by using a low cost capacitive sensor into a chair, and thereby to investigate the potential implementation of this technology e.g. into heavy machines like cranes. This approach can support to increase the security on construction site, as the health condition of an operator of heavy construction machines can be observed.

The basic module is already adequate as a standalone kit for the unobtrusive ECG measurement. The add-on extra modules aim to increase the adaptability into the environment, as well as to offer the opportunity for visual feedback towards the user, i.e. displaying the measurement. This approach will support the user to get informed, and predict his/her health state.

Furthermore, the aspect of low cost is in this prototype considered as well, since this technology can be seen as an upgrade to already very expensive construction machinery. The proposed modularity of the system allows the adaptability according to the needs and budget of user and/or company, i.e. wireless or wired data transfer of the ECG measurements can be implemented. Such an approach could pave the way for future pervasive sensor fusion, i.e. interfaced with an automated emergency call gateway, in order to enhance the prevention of such diseases, before it is too late for the user. Also the security aspects (e.g. as accidence avoidance) can benefit from the proposed system, e.g. when people operates heavy machines (e.g. an operator of construction machinery like a crane, excavator etc.). For example, Haslam, R. A., et al. [7] investigated several accidents on construction site, where proof have been found of accidents, triggered, or at least contributed, by health problems. Additionally, Gyi, D. et al even [8] published a study, showing that there is a consistent and integrated approach necessary to measure safety and health performance for accidents avoidance at contraction site. Even in newer research results the issues for safety and health problems in construction industry is a topic [9], which proofs that up to now there are no sufficient solutions existing. Therefore, the authors proposes a capacitive ECG system that can be used to identify dangerous symptoms, which could distract the operator, or warn from a potential upcoming unconsciousness, and thereby support the accidence avoidance on construction site.

2 Proposed Hardware

The proposed capacitive ECG system consists of three units: The capacitive electrodes, the microcontroller unit (with wired or wireless data transmission), and the display unit (which is comprised by a compact, portable computer).

To implement the system adaptable to the user needs, and to keep it low-cost, the wireless data transmission, as well as the display unit are optional add-ons, which are not absolutely necessary in order to have an unobtrusive capacitive ECG measurement. This allows the user, to minimize the purchasing costs, in case an existing computer can be used for processing (e.g. by a wireless data transmission), storing and displaying the measurement data, or the display unit can be used as an add-on in the driver's cabin, to display directly the measurements. However, in case the complete system is required, the cost is still maintained in a relatively low range, by using a BeagleBone Black as a computer solution.

2.1 Capacitive ECG Electrodes and Microcontroller

As microcontroller, the Arduino Uno R3 has been used [10]. To enable the measurement of physiological signals by Arduino Uno, the e-Health Sensor Platform v1.0 from Cooking Hacks has been used [11]. The proposed system is also operable with normal electrodes, which require direct skin contact and are usually irritating to skin, as well as inconvenient.

To measure capacitive, the electrode surface has to be connected to a non-inverted power amplifier, with a very high input impedance. Thereby, the edge frequency gets shifted down, according to Eq. (1), in order not to get the physiological heart signal filtered (~ 1 Hz). Of course, a large electrode surface will lead to the same result. However, a small electrode surface allows multiple use and an easier unobtrusive implementation into the driver's cabin.

$$f_g = \frac{1}{2\pi RC} \tag{1}$$

As these components of the electrodes are, according to the small size of the components, difficult to build, as well as even more expensive than capacitive electrodes on the market, the authors purchased off-the-self components [12]. To interface these electrodes to a power supply, some additional electric components (LEDs, resistors and capacitors) were required (Figure 1).

In order to measure the ECG signal with capacitive electrodes a ground point is necessary. However, as the ground electrode requires direct skin contact the use of the capacitive electrodes would be doubtful.

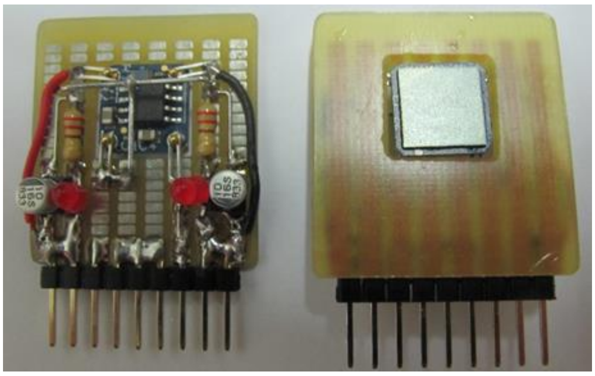

Figure 1. Capacitive electrodes including the connection for the power supply and Arduino microcontroller.

Therefore, the authors used a "Driven-Ground-Plane" circuit instead, as proposed in [13], which will lead the signal inverted and amplified on a third electrode surface. Thereby an active noise cancellation on the human body will take place, which finally leads to noise reduction. According to Eq. (2) the amplification of the Driven-Ground-Plane circuit can be calculated by:

$$G = 2 \cdot {}^{R_F}/_{R_A} = 2 \cdot \frac{10k\Omega}{220\Omega} = 90.91 \tag{2}$$

For R_A the authors used 220 Ω and for R_F 10 kΩ, which leads to an amplification factor of ~ G = 90.91. The functionality of this factor has been compared with the used amplification factor of (G = 1000) as suggested by [13]. However, there was no difference found in the signal quality, when comparing the two different amplification factors. Therefore, the authors empirically decided to use the amplification factor of G = 90.91.

The LEDs on the capacitive electrodes are used to give a visual feedback about the power supply (e.g. to identify wrong connection or broken components), whereas the capacitors support the stabilization of the power supply of the electrodes. The power supply for the electrodes is directly taken from the Arduino board itself. As the Arduino Uno only provides 5 V and 0 V, but the electrodes need a minimum power supply of +/- 2.4 V up to maximal +/- 4 V [14], the electrodes ground is connected to 2.5 V, in order to create a virtual mass.

For the "Driven-Ground-Plane" circuit board the OPA177GB component has been used, which has similar technical specifications compared to the power amplifiers, which has been used by [13].

2.2 Wireless Communication between the capacitive ECG and Display unit

The proposed system can transfer the measurements by USB connection to a computer, or wirelessly by using XBee Pro Series 2B modules. These modules base on the ZigBee communication protocol [15]. The advantage of using this technology, instead of Wi-Fi or Bluetooth, is the increased security, as ZigBee supports also encryption, as well as it has a higher range than Wi-Fi and Bluetooth, and considerably lower power consumption compared to other wireless standards, which enables it for portable system realizations. In order to interface the XBee module, an Arduino shield is necessary (here the XBee Shield from SparkFun has been used, as shown in Figure 2).

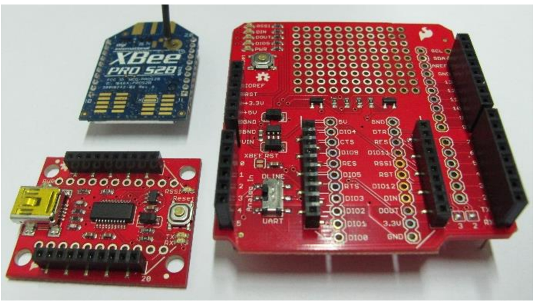

Figure 2. XBee module (top left), XBee Arduino Cape (right), XBee Explorer USB for interfacing with a PC (bottom left).

In Figure 3 the proposed hardware of the capacitive ECG is depicted. In order to enable that the system can be carried easily and safe (e.g. for implementation tests), a casing (visible in Figure 3) has been designed and developed using a 3D printer.

Two XBee modules are required for a communication to be established. To interface the other XBee modules with a computer, e.g. to display the capacitive ECG measurement, or to configure the XBee communication channel parameters [16], the in Figure 2 (bottom left corner) depicted XBee Explorer board from SparkFun has been used. However, in order to develop a low cost capacitive ECG system especially for implementation of small driver's cabins (e.g. crane, excavator etc.), a user display option must be provided.

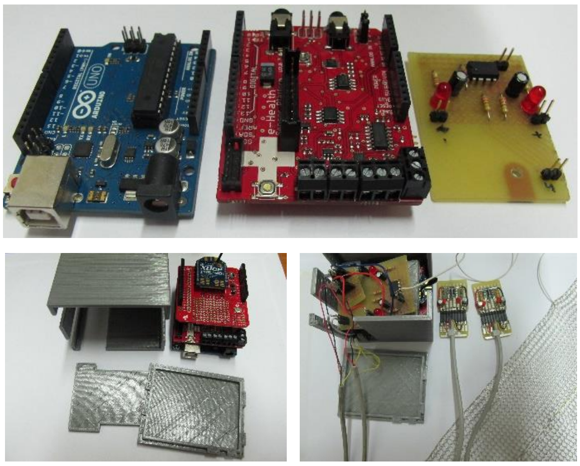

Figure 3. Hardware of the capacitive ECG, Arduino, e-Health shield & Driven-Ground-Plane board (top), case & assembled boards (bottom left), assembled ECG module including electrodes (bottom right).

For this purpose, the BeagleBone Black has been used [17] with an appropriate touch screen LCD display cape. The XBee module has been interfaced by an XBee cape. In Figure 4 the components of the visual display unit are depicted.

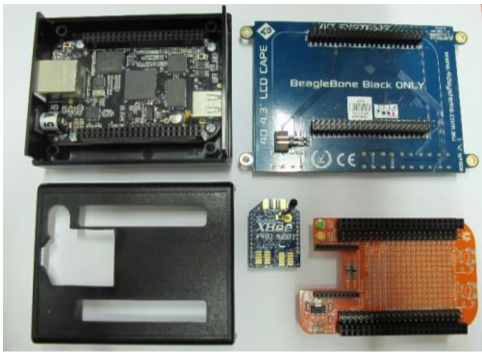

Figure 4. Components of the visual feedback unit, the BealgeBone Black (top left), the BealgeBone Black display cape (top right), the BeagleBone XBee cape (bottom right).

3 Software Development

The developed software is comprised by three levels: 1) Arduino, 2) C++ (using QT 4), and 3) the shell scripts on the BeagleBone Black level to enable the communication ports. The BeagleBone Black supports Debian and Angstrom as operation systems (OS) [18]. The authors used the OS Debian 7.8 – Wheezy.

3.1 BeagleBone Black Shell Script configuration

The XBee module is connected by the XBee cape to the BeagleBone Black, which is directly connected to the expansion GPIO headers. The data exchange takes normally place at the UART2 port (/dev/ttyO2). However, normally only the port UART0 (/dev/ttyO0) is enabled. To enable the port UART2 for XBee, the user must login as root and enable this port by a terminal, using the following shell command [19]:

```
echo BB-UART2 > /sys/devices/bone_capemgr.*/slots
```

To automate this process a shell script will execute the BB-UART2 command, which will be triggered by a service script, which executes as soon as the BeagleBone Black boots. Furthermore, a desktop icon has been made using the Linux script language, in order to allow an intuitive and quick start of the display program on the BeagleBone Black LCD display. Thereby, the display can serve additional tasks (e.g. control) in the future, next to the ECG displaying option.

3.2 Arduino Microcontroller Program Flow

On the Arduino level, the program is working as shown in Figure 5. For reading the ECG signal from the capacitive electrodes (visible in Figure 1), the serial port 0 of the Arduino Uno board has been used. For transmission of the XBee module serial port 2 and port 3 are used. As shown in Figure 5 the data are recorded and formatted, according to the format, which the display unit requires, before being sent. The XBee module on the Arduino is set up into the "Application Programming Interface" (API) mode [15]. The authors decided this because of two reasons:

1. The data transfer becomes more robust since in API mode the data must be send in a specific frame setting. If the frame setting contains mistakes, the message package (frame) receiving XBee module will ignore the message. Tests with the transparent (AT) mode of the XBee modules, where the data gets sent in ASCII form (serial port style), showed that transmission mistakes sometimes (although only rarely) disturb the displaying program.
2. The XBee modules, which uses the API mode can send frames to AT mode XBee modules. XBee modules in the AT mode translate a received message (from API and AT) immediately from byte to ASCI, before forwarding to the interfacing port. This allows to use the XBee module in AT mode equal, as a USB interface on the programming level. However, XBee modules in the AT mode cannot send messages to XBee modules in the API mode [15].

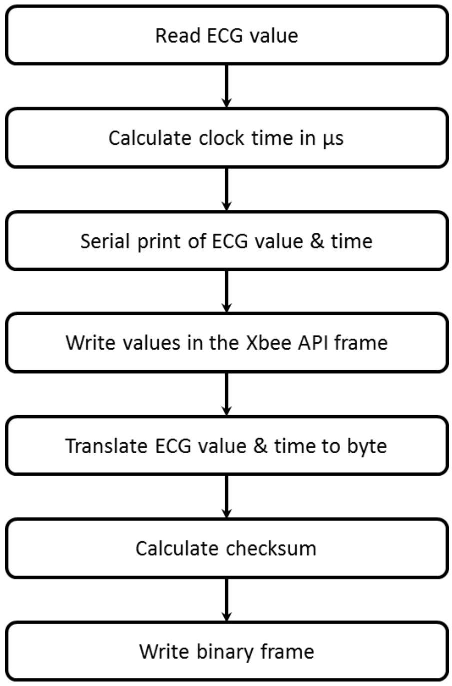

Figure 5. Proposed Arduino algorithm for measurment acquisition and transmission.

The frame has been hard-coded into the Arduino using hexadecimal values, which describe the destination address and message kind. Thereby no additional libraries are necessary. Only the message part and the checksum are updated with each new value captured by the electrodes. These measurement values have to be transformed to byte values, before they can be written into the frame. A necessary storage of 19 bytes has been calculated, so that the XBee module can permanently run up to ~31 years (because the time value will continuously increase, up to the point where the reserved storage is depleted), as the first 17 bytes of the frame are used for addressing and formatting, and therefore can be hard-coded.

Only if more storage for the message will be given, the length of the frame must be updated (which consists out of the quantity of all bytes after the first 3 bytes, and excluding the byte for the checksum). The checksum is calculated by summing the single frames together and final subtracted from the hex value FF (= 255 decimal) [15].

3.3 Displaying the Information on the LCD Screen module

The program for displaying the measured data is simultaneously storing them on the hard disc (in case of the BeagleBone Black on an eMMC 4GB chip [17]). In order to enable the program to store all measured samples, and displaying in real-time, the program is operating as depicted in Figure 6. While the main program loop is busy with displaying data (using QCustomPlot [20]), a sub thread, trigged by the class “Read Value”, (using QExtSerialPort [21]) is reading the data either from USB or the XBee module and storing.

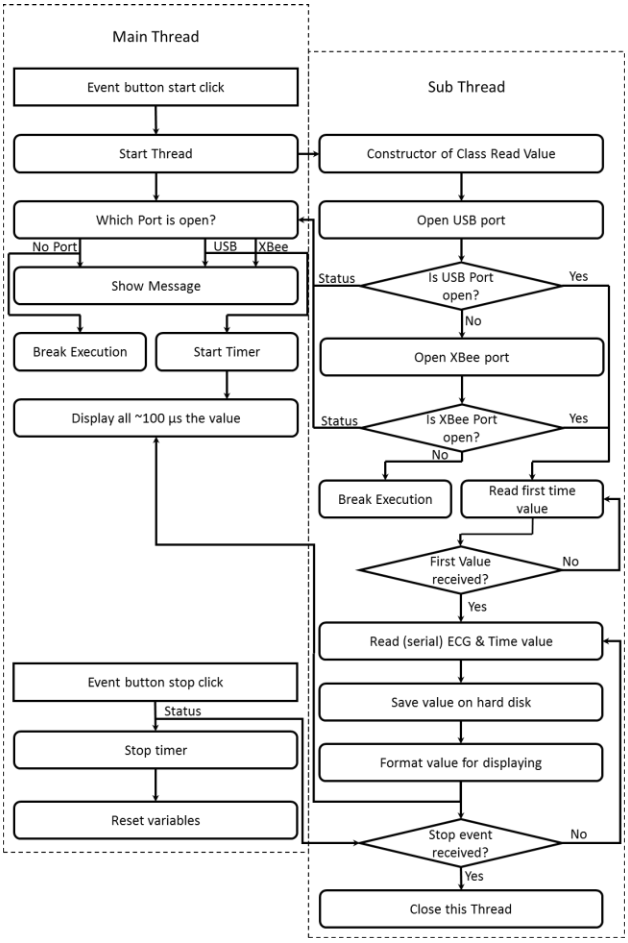

Figure 6. Proposed flow diagram of the Display unit.

The program checks always if a USB connection is existing. If the USB connection is existing, the data transfer by wire is preferred. If the program detects that there is no USB connection available, it is checking the UART2 (/dev/ttyO2) port. Only in the case the port is not occupied by another process (e.g. not enabled, or already busy), the program returns an error message. Otherwise, the program is waiting for incoming data from the XBee modules.

Thereby, the displaying of the program breaks and restarts automatically, according to the data transfer, until the user requests the program termination. As the XBee module on the BeagleBone Black is not thought to send information, only to receive information, this module has been set to AT mode. This allows to treat the incoming XBee data in the same way as a USB serial port. Because the BeagleBone Black provides only one USB slot, the serial port is also hard-coded for the USB transmission. Furthermore, the BeagleBone XBee Cape is only supporting one XBee module, whereas also here the UART2 (/dev/ttyO2) port is hard-coded. The designed Graphical User Interface (GUI) provides to the user only three buttons to control the program: start, stop, and close (see Figure 8).

Of course, if a USB wire is used for the data transfer between the microcontroller and the display unit, the possibility of Wi-Fi is disabled, because there is no further USB slot left for the Wi-Fi module.

4 Software Development

In Figure 7 the measurement results using the capacitive electrodes (shown in Figure 1) with direct skin contact and through cloths are shown.

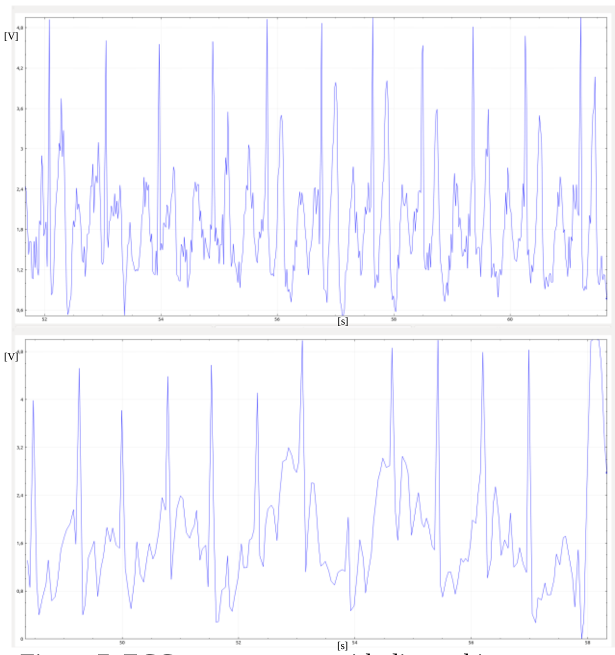

Figure 7. ECG measurement with direct skin contact at the hands (top), ECG measurement through T-shirt on the chest (bottom).

Hereby it can be seen, that both measurement methods (with and without direct skin contact) can capture the ECG signal, however, the capacitive measurement is more disturbed by noise.

The proposed system (of a capacitive ECG measurement system) has been used for test implementation in a chair, as shown in Figure 8, in order to verify that the system receive reasonable values.

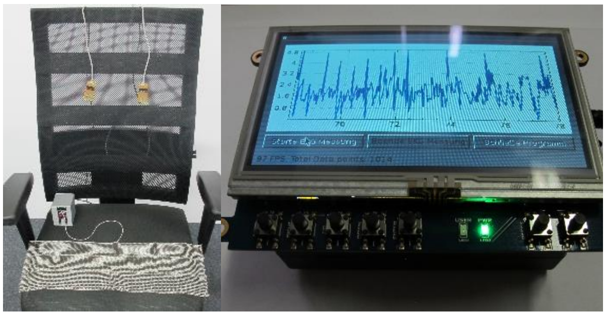

Figure 8. The proposed capacitive ECG for a test scenario embedded into a chair (left), the display unit receiving wireless a measurement by XBee module (right).

As described in [4, 22] the authors can confirm, that pressure (between body and electrode), as well as the thickness of the cloths material have an influence on the signal quality. Furthermore, because of the high sensitivity of the capacitive electrodes, noise and artifacts, caused by the surrounding electronic devices and user movements, the measurement can be disturb.

Whereas it is necessary to mention that the electrodes are not shielded, which increase the impact of noise. However, a larger impact regarding the ECG signal quality was found on the settings of the XBee modules. It was noted that the XBee modules could decrease the signal quality, if they are using broadcast transmission to all XBee modules in the network. The number of XBee modules in the network is thereby irrelevant. This finding resulted from an XBee network with five modules, where 1 × Coordinator (API), 2 × Routers (API), 1 × End Device have been used in API and 1 × in AT mode. Data throughput had the same deteriorated performance (when broadcasting messages) compared with an XBee network, where only 1 × XBee Coordinator and 1 × XBee End Device communicated. The broadcast data transfer is too slow, and thereby already hurting the Nyquist-Shannon sampling theorem, which leads to wrong value displaying and signal loss. Using unicast frames (means frame transmission to specifically addressed XBee modules [15]) the transmitted signal quality improves, because of a higher data throughput. However, the USB Data throughput still leads to most robust signal transmission. The transmission quality between XBee API mode and XBee AT mode was found nearly similar, as in Figure 9 shown.

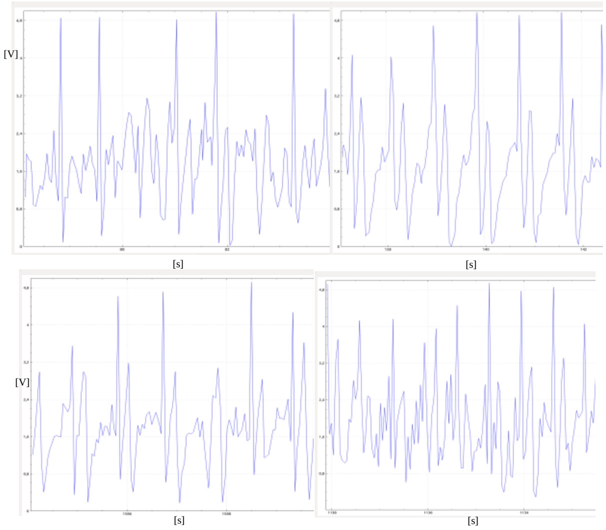

Figure 9. Signal displaying by data transfer using XBee module, measured by direct skin contact (left), measured through cloth (T-shirt) (right), XBee AT mode (top), XBee API mode (bottom).

5 Conclusion and Discussion

The authors proposed the development of a novel contactless capacitive ECG system, including wireless data transfer and a mobile embedded single board computer as a display unit, which allows a modular, unobtrusive, and portable system realization (see Figure 8).

The system has been tested with direct skin contact and without skin contact (through clothes), as well as with USB, and wireless communication (via XBee Pro Series 2B). In all proposed scenarios, the ECG signal was successfully captured and displayed, as shown in Figure 7 and Figure 9. The overall system is designed and developed in a modular way, whereas the prototyping costs (summarized in Table 1) are kept to a minimum.

Through the compact, handheld size of all three hardware parts (electrodes, Arduino board, and BeagleBone Black), it is possible to straightforwardly to embed the proposed system unobtrusive into a driver's cabin.

The proposed wireless data transfer by XBee allows a more robust implementation, since it does not require any preinstalled Wi-Fi infrastructure. The Arduino microcontroller and display unit can also use normal electrodes, instead of capacitive electrodes. However, the advantage of the capacitive electrodes is that they are not irritating the skin, and they stay functional, even if the operator is wearing cloths. Of course, some disadvantages have been identified as described in [22]. E.g., ambient noise disturbs the acquired signal, or user movements can cause strong artefacts.

Table 1. Costs of the proposed ECG system including wireless transmission and low cost computer for displaying.

Product	**Price (€)/ Unit**	**Necessary Units**	**Cost(€)**
Arduino Uno R3	24	1	24
e-Health Sensor Shield V1.0	75	1	75
PLS-PS25203 (Capacitive Electrodes)	18	2	36
Electronic components			20
Costs for wired Capacitive ECG			**155**
SparkFun XBee Shield	15	1	15
XBee PRO 60mW Series 2	38	1	38
Costs for wireless capacitive ECG			**208**
BeagleBone Black	55	1	55
XBee Cape	13	1	13
4D 4.3" LCD CAPE	100	1	100
XBee PRO 60mW Series 2	38	1	38
Total Costs for wireless capacitive ECG including mobile display unit			**414**

In future, to reduce these unwanted disturbances, the entire system must be proper shielded. This very first prototype shows promising results concerning the realization of a low cost, portable, contactless ECG measurement system solution for construction security purposes. Once the improvements are implemented in order to reduce the noise by shielding, as mentioned in [23], this system can be built to a 3 up to 6 lead ECG, in order to enable unobtrusive ECG measurements, according to Einthoven (I, II, III), and Goldberger (aVR, aVL, aVF) [24]. Also for this approach, appropriate Arduino shields are already available on the market [25], which would even decrease the developing cost, if only 1 lead is used, as it is done with the proposed system.

Through the possibility, given by this technology, to implement the ECG measurement unobtrusive into a driver's cabin, the operator health condition can be observed, either by himself, or by a security central. Thereby, it can be assured that the operator is present, mentally not stressed (e.g. because of increased heart rhythm), and healthy. By observing for harbinger e.g. of heart attacks, this approach would allow to interfere before accidents happens, e.g. caused by unconsciousness on construction site.

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