# Development of a Non-Contact ECG Application Unobtrusive Embedded into a Bed

Stefan Pehr
Technical University of Munich
*Chair of Building Realization and Robotics*
Munich, Germany
stefan.pehr@tum.de

Daniel Zollitsch
Technical University of Munich
*Chair of Building Realization and Robotics*
Munich, Germany
daniel.zollitsch@tum.de

Jörg Güttler
Technical University of Munich
*Chair of Building Realization and Robotics*
Munich, Germany
joerg.guettler@br2.ar.tum.de

Thomas Bock
Technical University of Munich
*Chair of Building Realization and Robotics*
Munich, Germany
info@br2.ar.tum.de

***Abstract*—In this paper the authors publish a novel designed capacitive ECG system, which can be unobtrusive implemented into a bed. To avoid user rejection, the capacitive electrodes were designed flexible and with a large surface. In addition, the electrode surface is interfaced by a wire to the circuit boards, which increases the noise sensitivity. Therefore, the proposed solution focus on noise filtering and shielding for the novel designed electrodes. Already in the design of these electrodes is a special guard and ground design considered, which reduces the impact of noise. Furthermore, different settings of analog filters improve the signal quality in addition, which is proved by test measurements. These test measurements were compared between each other regarding the different filter settings, in order to identify the most satisfying filter for future developments. Through using analog filters, a nearly real time data processing is possible. By the proposed application, the home security for heart diseases and for high aged can be improved, as well as offers different opportunities for sensor fusion in future.**

***Keywords*—*flexible electrodes, capacitive ECG, analog filter, sensor embedding, ambient sensors.***

## I. INTRODUCTION

Heart diseases are one of the biggest threats in high age. According to the Statistische Bundesamt [1], the most often death reasons in Germany are the chronic ischemic heart disease and the acute heart attack. Thanks to modern technology and medicine, someone who has a heart attack can be rescued and recover from a heart attack, if a quick treatment (i.e. within minutes) is provided [2]. In addition, studies proved already that if people have a healthy life style (i.e. reduced tobacco consume, healthy nutrition, and increased physical activity), heart diseases and heart attacks can be prevented [3, 4, 5]. Therefore AAL solutions, like the in this paper proposed capacitive ECG system, enables an unobtrusive health screening at home, which allows to intervene in case of a heart attack, or to detect harbinger for prevention of cardio vascular diseases early (e.g. warning the user in order to motivate changing lifestyle).

In both cases, for prevention of cardiovascular diseases, as well as for diagnosing a heart attack, the ECG is one of the most important tools in medicine, which provides important information about the health of the heart, the heart rate variability, or the psycho-physiological state of a person [6]. Furthermore, the ECG enables to detect arrhythmias [7], and potential diseases, which a physician can analyze via the shape of the ECG curve, e.g. a ST-elevation myocardial infarction [8].

Since the ECG proved its value for the medicine, in the past years a lot research efforts focused on automating the ECG alerts by machine learning [9]. In parallel, other research groups focused in embedding the ECG into the surrounding of the user and to extend the functionality by sensor fusion, e.g. in order to detect the blood pressure [10, 11]. Also the car industry successfully embedded an ECG application into a driver seat, in order to realize a stress monitoring [12]. For embedding ECG applications into the environment of a user (e.g. car or apartment), dry electrodes are preferred. However, if no direct skin contact is possible (e.g. because of clothes), capacitive electrodes are necessary. Today several capacitive electrodes were designed [12, 13, 14], and even capacitive electrode chips can be purchased [15].

Unfortunately, most existing solutions, which propose how to design such ECG systems, follow the same approach that leads to very stiff and hard electrodes. Since these hard electrode chips lead to an inconvenient feeling when laying on them, this kind of electrodes are not applicable for embedding into a bed. The reason why most electrodes where designed this way (i.e. hard electrode chips) is related to the artefact and noise sensitivity of capacitive electrodes. In order to minimize the impact of captured noise, the current state of the art proposes to place the non-inverting high impedance entrance of the operation amplifier as close as possible to the electrode surface [12, 14, 16].

Therefore, in this paper, the authors present a novel design of capacitive electrodes, which interface the non-inverting high impedance entrance of the instrumentation amplifier with the electrode surface by a wire. In addition, the electrodes are consisting out of soft PCB layers, which avoid that the user feels the pressure of the ECG sensors. To reduce the noise impact on this system, the electrode design considers a special shielding and guarding, which begins with the design of the electrode surface and covers as well as the wire. Nevertheless, noise can still disturb the measurements.

Therefore, the proposed ECG prototype considers also analog filters. The designed filters enable the researchers to activate or deactivate different filters (band pass and low-pass) via switches. Furthermore, the captured data is processed in a software, which displays the measurement values on a monitor, using a low cost single board computer (Raspberry Pi 3). The proposed ECG system was tested by a test person, laying on a bed, and measuring the ECG while being dressed with a cotton T-shirt. The different used filter settings and the related signal quality are plotted and discussed within this paper.

## II. HARDWARE DEVELOPMENT AND IMPLEMENTATION

The implementation of the proposed ECG system focuses on a flexible design for the capacitive electrodes and a new hardware (i.e. analog) filtering approach for all signals. Opposite to normal ECG devices is the electrode signal differentiated by software, which enables to program software insofar that it will be able to choose the best signal availability from a bunch of ECG sensors.

### A. *Sensor design of the flexible capacitive electrodes*

The first design approach mainly was inspired by the Paper of Thomas J. Sullivan [17]. This design consists of three concentric circles as depicted on the left in Fig. 1. The central circle is used for capturing the ECG signal. The second circle, which is surrounding the first one, contains a guard signal for shielding. The used integrated circuit chip for preamplification (Texas Instruments INA116) provides already a guard output.

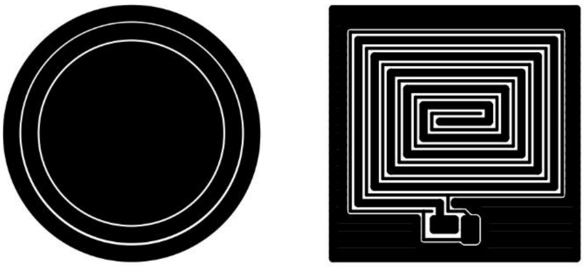

Fig. 1. The electrode design. Left: Stiff electrode. Right: Flexible electrode.

A guard contains the same signal as the input, but has a low resistance to the ground. Therefore, the guard acts as a shield where no parasitic capacitance or resistance interfere between the guard and the ECG signal. The third circle and the backside of the ECG electrode is also used for shielding and directly connected to the ground. This approach with three different signals on one sensor has the benefit that no extra ground contact to the body is needed and therefore only two capacitive electrodes are already sufficient for an ECG signal.

The second approach is a helix design of the sensing signal interweaved with the guard signal and surrounded by the ground signal (see right site of Fig. 1). With this approach, it is possible to cover a big area and nevertheless achieve an efficient shielding effect. Furthermore, the flexible production of this sensor is quite simple, because this sensor is printable with only one layer of conductive ink. Moreover, at this design and no additional dielectric layer is necessary. This electrode design was screen-printed with conductive silver ink on a PVC foil. In order to interface the electrodes with a cable, conductive epoxy glue was used. The electrodes are connected to the circuit boards via a one meter long twisted pair cable. Two pairs are used to connect the sensor signal and the guard, both connected with one cable of each pair. The ground signal is connected with the shield of the wire. For this purpose at the wires was a shielded RJ45 plug attached, in order to connect the preamplification circuit boards with the electrode surface.

### B. *Design of the capacitive ECG amplifiers and artefact dumping*

The amplification of the sensor signals was another very important aspect for this development. Due to the movement of a person on top of the sensors, some low frequency movement artefacts will be induced in the signal. According to Thomas J. Sullivan [17] this problem was solved with a feedback circuit, which feeds a low passed signal back to the inverting input of an instrumental amplifier. As in Fig. 2 can be seen, this approach was used with modified values of the electronic components, which improved the DC decoupling.

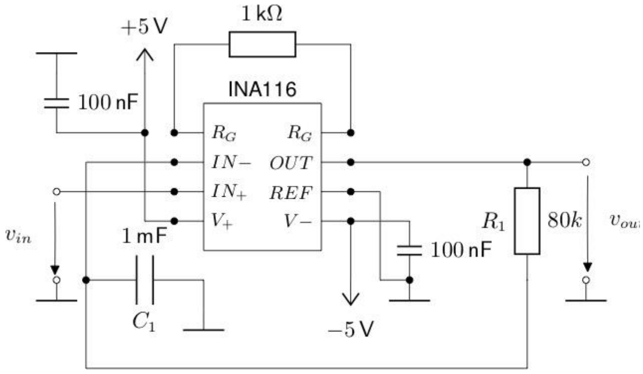

Fig. 2. Preamplification circuit.

Only one input of the very high impedance instrumental amplifier (e.g. the INA116 from Texas Instruments) is used for connecting of the electrode. This amplifier boosts the signal $v_{in}$ by factor $G = 51$ due to its resistor $R_g = 1\ k\Omega$ (see datasheet of INA116 for further information [18]). The feedback circuit feeds the low frequencies below 0.1 Hz back to the inverting input, and thereby this low frequency signal is not amplified. Thus, the movement artefacts are not damped, but not amplified and thereby this feedback circuit acts like a high pass filter. Equation (1) shows the calculated transfer function of the amplifier. A complete derivation of this equation and all needed values are investigated by Daniel Zollitsch [19].

$$\frac{V_{out}}{V_{in}} = \frac{G \times \sqrt{\{(G+1) + R^2\omega^2C^2\}^2 + (G\omega CR)^2}}{(G+1)^2 + R^2\omega^2C^2} \tag{1}$$

Using equation (1) with $R_g = 1\ k\Omega$, $R_1 = 80\ k\Omega$, $C_1 = 1000\ \mu F$, amplification factor $G = 51$, and $\omega = 2\pi f$ the transfer function was be plotted (see Fig. 3). Measurements and a simulation with LT-Spice confirmed the plotted transfer function.

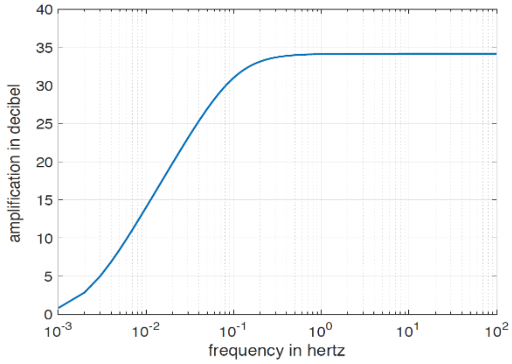

Fig. 3. Plotted transfer function of the preamplification circuit.

### C. *Optional analog filter design*

To minimize the impact of noise interferences, which can completely superimpose the desired ECG signal, an optional analog signal filtering is applied. The major disturbances are induced currents through the 50 Hz power supply line that can override the “analog-to-digital converter” (ADC) to the limit and make a measurement unfeasible. Therefore, a bandwidth limitation of the measuring arrangement adapted to the frequency spectrum of ECG signals (0.5-150 Hz), with a band-stop filter at 50 Hz, was designed and implemented. Depending on the ECG signal quality and the size of the interference signals, it can be chosen between a “Diagnostic-“, “enhanced-Diagnostic”, or “Monitoring-Mode”. Each of these modes has a different order number filtering behavior and frequency response, depending on the used components (see Table 1).

TABLE 1: FILTER FUNCTION OVERVIEW

| Name | Function | Implementation | Components |
|---|---|---|---|
| **Diagnostic Mode** | Default | Clock-tunable 6th order, 50 Hz Notch + 110 Hz LP | LTC1068-200 + LTC1069-1 |
| **Enhanced Diagnostic Mode** | Noisy environments | Clock-tunable 12th order, 50 Hz Notch + 110 Hz LP | 2x LTC1068-200 + LTC1069-1 |
| **Monitoring Mode** | Very Noisy Environments | Clock-tunable 8th order elliptical 37 Hz LP | LTC1069-1 |

The “Monitoring Mode” (Mon-Mode) consists of a clock-tunable, elliptical 8th-order LTC 1069-1 low pass filter with a cut-off frequency at 37 Hz and an 80 dB power supply line noise damping at 50 Hz (see Fig. 6, Mon-Mode). To preserve a maximum of frequency components of the ECG signal, the “notch” behavior of the Mon-Mode low-pass filter was used instead of its falling edge and were precisely trimmed to an attenuation minimum at 50 Hz via a clock generator. Otherwise, the cut-off frequency would have had to be set at approximately 20 Hz to realize comparable damping properties.

To enable the possibility to preserve also an expanded frequency component spectrum of the ECG signal the “Diagnostic Mode” (Diag-Mode) and “enhanced-Diagnostic Mode” (eDiag-Mode) got implemented as a cascaded clock-tunable, 6th-12th order LTC1068-200 band-stop filter at 50 Hz with a 110 Hz low pass filter for effectively rejecting the harmonics of the power supply line noise (see Fig. 6, Diag-Mode and eDiag-Mode).

In Fig. 6 can be seen that an effective damping of the 50 Hz noise at the power supply line, between 40 dB and 80 dB, is reached and a steep cut-off frequency at 110 Hz was realized. Furthermore, all filter modes provide a clock feedthrough and an anti-aliasing filter. In the SNR-Benchmark of the Mon-Mode a defined ECG test signal with a 46 dB overlaying sinusoidal noise offset of 50 Hz and 150 Hz was feed through the filter. Fig. 4 shows, that the analog signal filtering can reconstruct quite sufficient the ECG Signal upon a DC-offset and a negligible distortion.

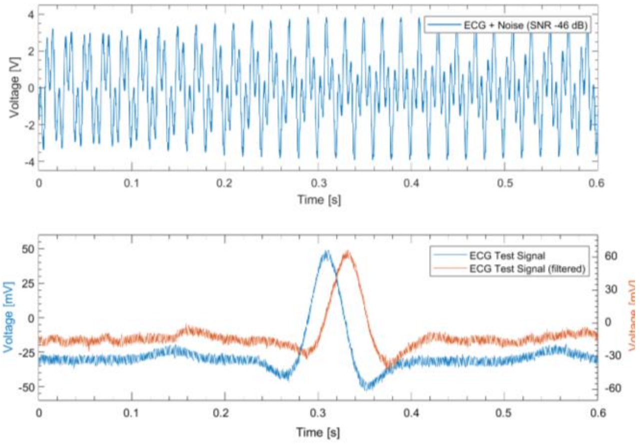

Fig. 4. Mon-Mode SNR-Benchmark.

## D. Human-machine-interface

The task of the program, which servers also as human-machine-interface via its graphical user interface (GUI), comprise the digitization and fusing of the differential ECG signals, as well as the real-time data processing and representation for the user (see Fig. 7, humane-machine-interface). Because of cost-efficiency a “Raspberry Pi 3” computer in combination with a “Waveshare High-Precision AD Board” was used for displaying the measurement via the GUI. For programming the GUI, “Qt Creator IDE” with the “QCustomPlot” widget was used.

The program for data capturing and displaying (see Fig. 5) digitize each of both separated ECG signals by the 8-channel, 24 bit ADC ADS1256 at 1 kSPS, in order to generate the differential ECG signal on the software level. I.e. both ECG signals are differentiated sample by sample in order to retrieve the ECG signal. Afterwards all curves are plotted nearly in real time, as depicted in Fig. 5.)

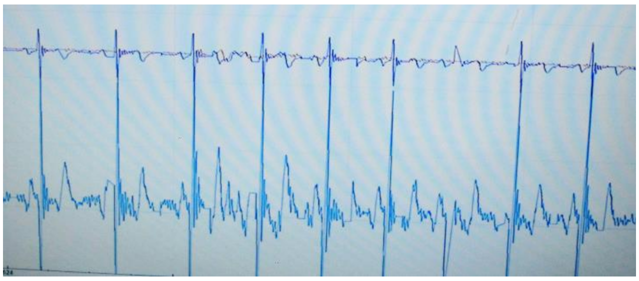

Fig. 5. Real-time data plot. Top: Both single electrode ECG signals. Bottom: the retrived ECG curve by differentiating both single electrode ECG signals.

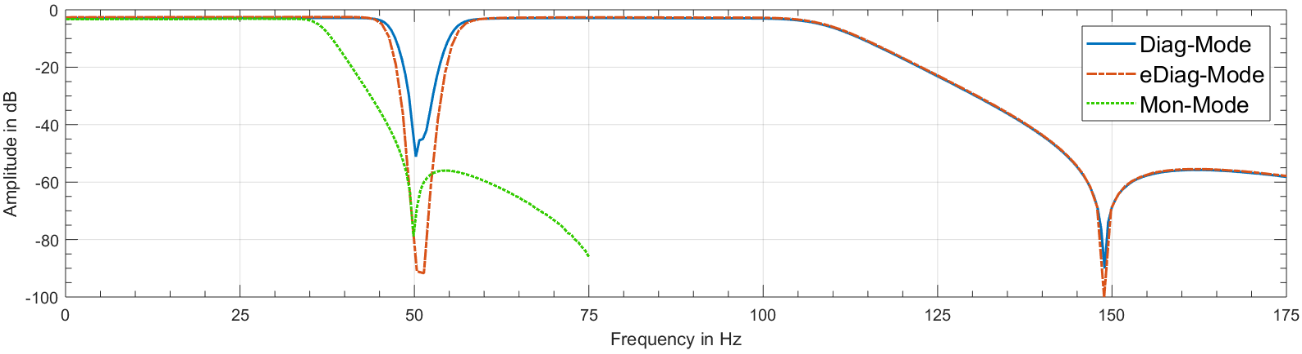

Fig. 6. Bode-plot of the Mon-Mode, Diag-Mode and eDiag-Mode.

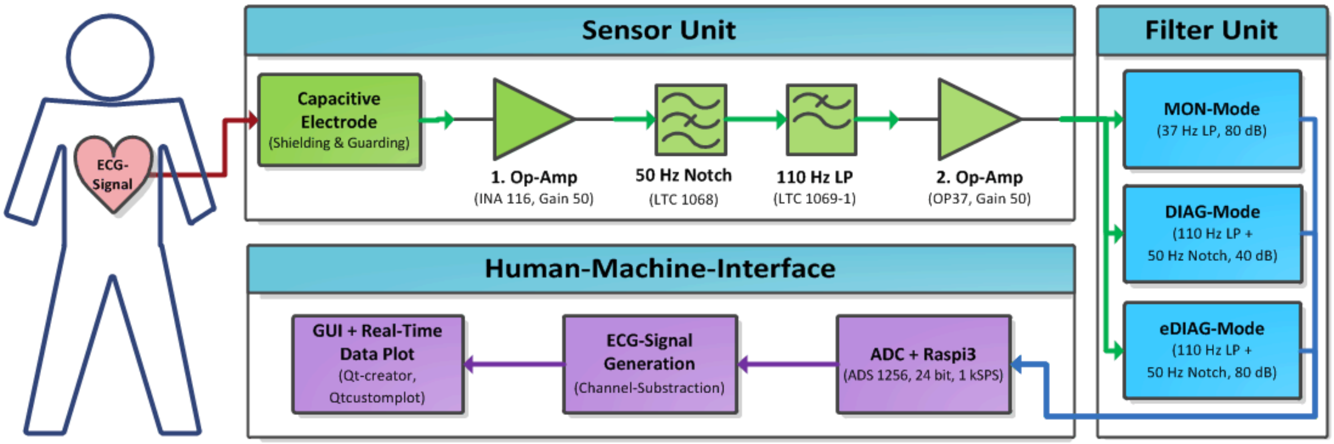

Fig. 7. ENCEL project block diagram.

## III. MEASUREMENT RESULTS AND QUALITY

Thanks to the different analog filter, two settings were investigated. First, the signal resolution of the two different ECG electrodes (i.e. the stiff and the flexible electrodes) was compared. Afterwards using the flexible electrodes, the most sufficient filter mode (i.e. Mon-Mode, Diag-Mode, and eDiag-Mode) was investigated by comparing the different signal resolutions.

### A. *Environmental conditions while measuring*

The test measurements were executed in a bed, which consists out of aluminum profiles. The bed was rectangular framed (for prototypical implementation) and had three electrical actuators embedded beneath the mattress. These motors also induced some 100 Hz noise into the proposed electrodes. In addition, the frame of the bed was not connected to any ground.

These circumstances allow assuming that the noise behavior is very similar compared to a hospital bed, where lots of noise generators surrounded the bed, and where electric motors are mostly embedded. The ECG had no connection to the bed except of the electrodes laying on the mattress, and they did not share the same ground potential of the bed. The sensors were placed below the patient, one underneath the hip and the other below the right shoulder blade, according to the ECG measurement definition of Willem Einthoven, i.e. the electrode placement was arranged according to the Einthoven II lead (see Fig. 8).

Fig. 8. Test measrument with the proposed ECG system.

The subject wore a 100 % cotton T-shirt. Because it was a warm day and the shirt was worn for 2 hours at measurement time, it was slightly sweaty, but not in a way that it was palpable wet. This circumstance can be compared with a patient, who lies in the bed for a longer time.

### B. *ECG measurement results with the capacitive electrodes*

With the electrode of the first type (i.e. the hard electrode, see Fig. 1 left side), a measurement trough a T-shirt failed due to too much noise in the signal. Therefore, the sensors were placed directly on the chest of the subject. With the direct skin contact, a measurement of the ECG with only two sensors was possible as in Fig. 9 visible. There is some noise in the signal, but all parts of the ECG (i.e. the P-wave, the QRS-complex and the T-wave) are recognizable.

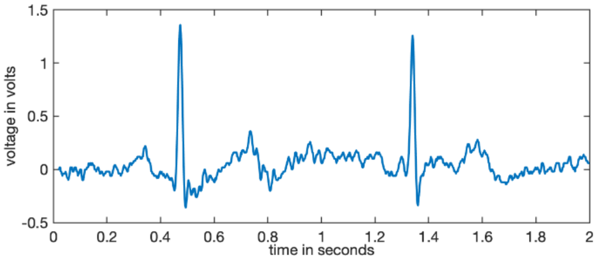

Fig. 9. ECG measurement with stiff capacitive electrodes with direct skin contact.

The second electrode (i.e. the flexible electrode, see Fig. 1 right side) succeeded when trying to measure through the T-shirt while lying in the bed, as in Fig. 10 can be seen. Especially the R-Peak is clearly visible, although the very noisy environment. Movements of the subject did not result in floating of the signal, however movement artefacts still interfered when the subject moved in the bed. A reallocation of the electrodes results in smaller/higher amplitude of the signal, but as long the electrodes are aligned, according to the Einthoven II lead, the signal was clearly received. The offset of 2.5 V, which can be seen in Fig. 10, is a result of the used ADC, because it supports only positive voltages.

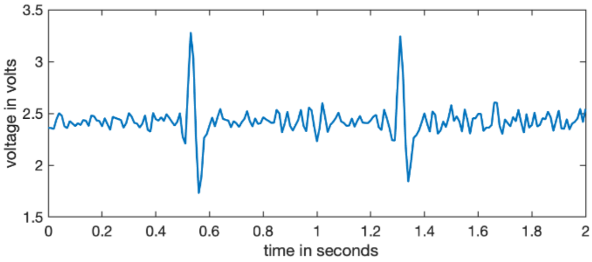

Fig. 10. ECG measurement with flexible capacitive electrodes without direct skin contact, obscured by a T-shirt.

Based on these promising results, a third version of the in Fig. 1 proposed electrodes is currently under development, which should have an improved shielding effect and bases on the design of the electrode type of Fig. 1 left. This electrode will have three separated conductive layers with the electrode surface on top, a guarding core in the middle, and a ground at the backside.

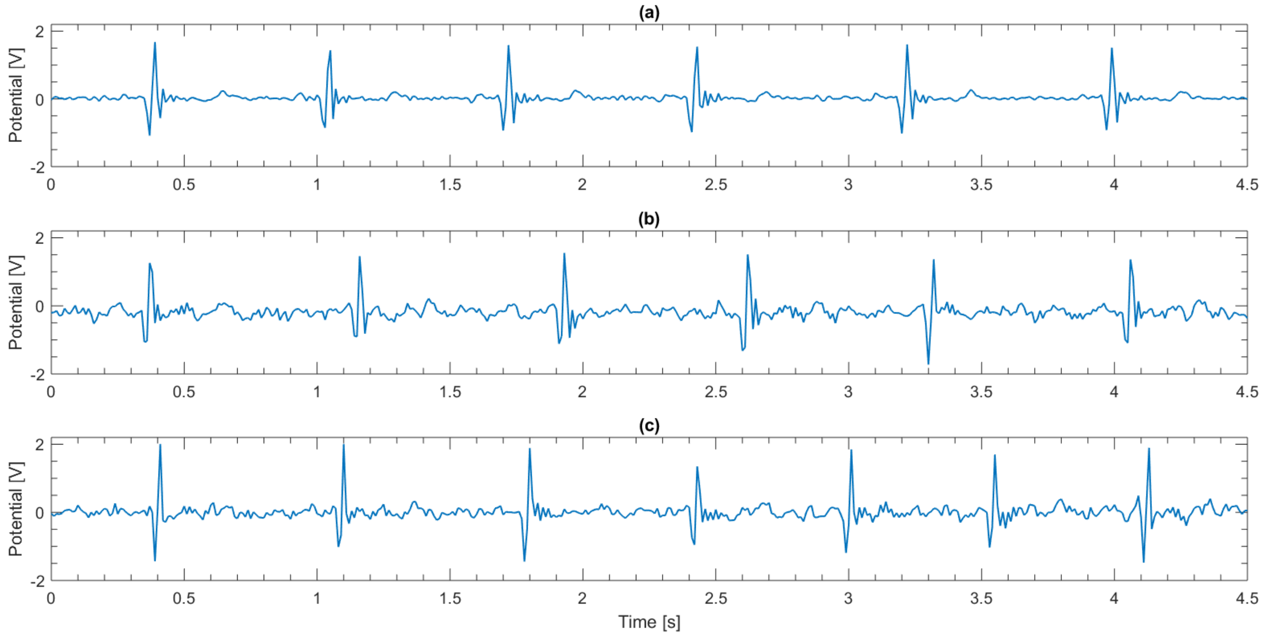

Fig. 11. ECG signals of the different filter modes. Top: Mon-Mode. Middle: eDiag-Mode. Bottom: Diag-Mode.

### C. *ECG measurement results by comparing the different filters*

The comparison measurement of the ECG measurement performance in relation to the three different analog filter modes was carried out with direct skin contact of the sensors to the human body. For this measurement, the subject was laying as depicted in Fig. 8 on the electrodes, while the ECG signals plotted in Fig. 11 were recorded. First, the Mon-Mode was recorded. By a switch, the filter mode was changed quickly, so the subject did not move when the different filter modes were tested. After the eDiag-Mode was recorded, the Diag-Mode was directly afterwards captured.

All records are plotted in Fig. 11, which shows that in all filter modes the QRS-complex is clearly visible. For detecting the T-wave, the Diag-Mode and eDiag-Mode lead to the best results. However, due to the expended passband more noise is overlaying the signal at the Diag-Mode and eDiag-Mode. Finally, the best filtering method has to be determined by trial and error. If the ECG signal is not visible with the Diag-Mode setting, the eDiag-Mode setting should be switched on. If the ECG signal cannot be recognized with the eDiag-Mode, the filter should be set to Mon-Mode.

## IV. CONCLUSION AND DISCUSSION

In this paper, the authors proposed a novel way to design capacitive electrodes. One big difference to existing solutions is that the electrode surface is decoupled from the circuit boards. Thereby it was possible to design flexible (i.e. soft) capacitive electrodes, which a person cannot feel when laying on them. This approach is essential when ECG applications should be embedded into furniture in future.

Also the design and arrangement of the guard and the ground showed an impact in the signal quality. The filter design was analog, due to the fast data processing, since no digital preprocessing delayed plotting the data on a small display. For the filtering, several filter modes were designed (e.g. Mon-Mode, Diag-Mode and eDiag-Mode), which enabled a simple investigation, which filter design is the most promising for capacitive ECG applications. The tests showed that for a clear PQRST-ECG curve the Mon-Mode filter was most sufficiently. However, the authors suspect that this mode could filter so drastically that potential harbingers for heart attacks could be filtered. The Diag-Mode or eDiag-Mode avoid this issue, however enable also more noise to disturb the signal, so that finally only the QRS-Complex is always clearly detectable.

However, the test measurements were executed in an environment, which was very noisy. Nevertheless, the second electrode design (depicted in Fig. 1 on the right) was able to measure even through a T-shirt the ECG reliable. At the moment, a third version of the electrodes is under development, which could additionally improve the signal-noise-ratio. Nevertheless, already at this current state, a modular and unobtrusive ECG integration is already possible. In order to receive more important health related data, the authors will also consider the aspect of the sensor fusion e.g. in order to receive a blood pressure value with the help of the ECG [10, 11]. In future follows this approach, automated health alerts e.g. in the home environment become possible and leads to a permanently increased security for young and old.

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