SIGNAL QUALITY ASSESSMENT FOR CAPACITIVE ECG MONITORING SYSTEMS USING BODY-SENSOR-IMPEDANCE

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Abstract: Contactless capacitive ECG measurement is an unobtrusive way of acquiring cardiovascular data. However, movement artifacts present a common problem with this technique. A means of assessing signal quality and confidence is therefore desirable. In this paper we present a capacitive ECG measurement system with an integrated module that constantly monitors the electrode-body-impedance. Moreover, we present a method to derive an artifact level signal from this electrode-body-impedance that can be used to estimate the signal quality of the capacitive ECG measurement. First results of measurements with this system are shown.

1 INTRODUCTION

Continuous cardiovascular health monitoring systems enable a wide range of applications both in the domain of physiological long-term monitoring and in psychophysiological monitoring. Both fields of application require unobtrusive system concepts, that are for the most part realized as wearable devices and smart clothing or as ambient unobtrusive sensor systems. Examples for such systems can be found in (Park et al., 2006; Lamparth et al., 2009; Lim et al., 2006).

The amount of data acquired with said systems is often large, especially in long-term applications, demanding automatic (pre-)analysis. Reliable accurate analysis is yet difficult to achieve due to artifacts resulting from motion during daily routine activities. Additionally, there is often a trade-off between signal quality and sensor integration aspects. Taking this into consideration, system design must not only consider sensor development for the respective application but also requires tight integration of well adapted algorithms for automatic signal analysis.

In ECG monitoring tasks, artifacts from external noise and motion are the most common factors that impair signal quality. Reliable detection of R-peaks, for example as a necessary step in heart rhythm analysis, is not given during intervals with artifacts, leading to wrong detection results. This is especially a problem with contactless, capacitively coupled ECG systems, specifically when coupling is weak and body-sensor-distance is not constant, as for example in chair-integrated solutions (Aleksandrowicz et al., 2007). It is therefore desirable to improve the detection accuracy in automatic ECG analysis for contactless ECG measurement systems.

2 RELATED WORK

Using a mobile ECG measurement system with galvanic dry electrodes, (Ottenbacher et al., 2008) simultaneously acquire ECG and electrode-skin-impedance data (as well as acceleration data). In order to validate the results a reference ECG signal with wet electrodes is recorded in parallel.

They propose a method to improve an automatic QRS detector by calculating an artifact level from the recorded electrode-skin-impedance using adaptive filtering and post-processing. Thus they are able to mark artifact regions in the ECG signal and exclude them from automatic detection, considerably decreasing false positive and false negative QRS detections.

Adapting parts of this method to a contactless

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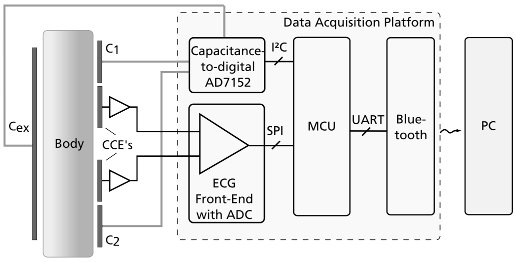

Figure 1: Block diagram of the developed contactless ECG system with integrated capacitance measurement module. The textile electrode C_{ex} carries the excitation signal generated by the AD7152. Body movements generate capacitance variations that are sensed by C_1 and C_2.

ECG-system in an air-plane seat, (Schumm et al., 2009) propose a method to predict the signal quality of a contactless ECG recording. A number of statistical measures derived from the ECG signal itself as well as additional pressure sensors attached to the back of the capacitive electrodes are used as features to derive a quality signal for the measurement.

3 METHOD

The most prominent source of artifacts in capacitive ECG measurement is the relative movement between the body and the capacitive electrodes. This changes the capacitive coupling between sensor and body, resulting in a voltage peak in the signal if a voltage difference between the subject and the measurement system exists. Additionally, CMRR of the differential stage is reduced, because a mismatch in source impedances occurs.

As impedance between sensor and body changes with movement, we propose a method to monitor this impedance and use it as an indicator for the quality of the sensor-body-contact. We therefore present an unobtrusive measurement system with capacitive ECG electrodes that records the sensor-body-capacitance of each electrode in addition to a differential capacitive ECG lead.

With these signals we derive an artifact indicator signal similar to (Ottenbacher et al., 2008) that can be used in conjunction with automatic QRS detection algorithms to reduce false detections and improve the overall detection quality in unobtrusive ECG measurement applications.

4 INSTRUMENTATION

4.1 Measurement System

For the experiment a contactless capacitive ECG measurement system has been developed and integrated into the backrest of a chair. Additionally, we have integrated a capacitance measurement module in order to continuously monitor the CCE-to-body capacitance.

The overall system structure is shown in Figure 1 and consists of

- a battery-powered, wireless 16-bit data acquisition platform with an analog front-end for capacitive coupled ECG electrodes,
- a capacitive driven-seat electrode (as described by (Keun Kim et al., 2005)) that can be disabled, depending on common-mode noise level,
- active capacitively coupled ECG electrodes (CCEs) with a dedicated sensor area for sensor-to-body capacitance measurement ($C_{1,2}$) and
- a two channel capacitance measurement module featuring the AD7152 capacitance-to-digital converter by Analog Devices (Analog Devices Inc., 2008).

The two combined CCE/Capacitance-monitoring electrodes are realized as multi layer PCBs with isolated sensor areas for ECG and capacitance measurement, details of such an electrode are shown in Figure 2.

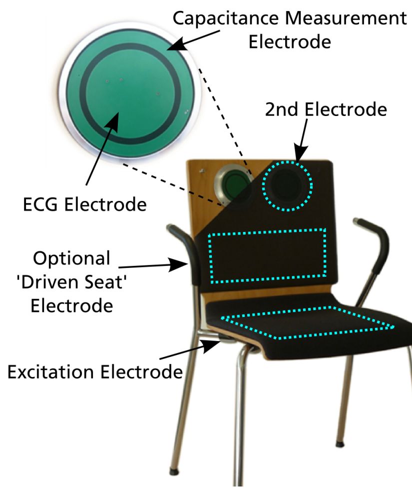

Figure 2: Contactless ECG chair with combined electrodes for capacitance and ECG measurement. Measurements can be performed with or without backrest cover.

The inner area of each electrode ($A_{CCE} \approx 28\,\mathrm{cm}^2$) was connected to the capacitive ECG front-end whereas the outer ring ($A_{C_{1,2}} \approx 19\,\mathrm{cm}^2$) was connected to the input of the capacitance-to-digital module (compare Figure 1). The ECG sampling rate was set to 500 Hz while the capacitance measurement was running with 200 Hz per channel, the maximum sampling rate possible with the AD7152.

4.2 Capacitance Measurement Configuration

In order for the AD7152 to perform the capacitance measurement, a square wave excitation signal with $f_{ex} \approx 32\,\mathrm{kHz}$ and $V_{ex} = 3.2\,\mathrm{V}$ is generated on-chip. The value of a capacitance connected between the excitation signal output and the measurement input of the chip is directly converted to a 12-bit digital value and can be read via an $\mathrm{I}^2\mathrm{C}$-compatible interface. The device offers two channels that can either be operated in single-ended mode or in differential mode (Analog Devices Inc., 2008).

Using one-channel differential mode in our setup, we have connected the excitation signal to a large sheet of conductive textile ($A_{ex} \approx 300\,\mathrm{cm}^2$) that was located on the seat area, as indicated in Figure 2. As $A_{ex} \gg A_{C_{1,2}}$, this setup can be considered a "Human Transmitter" (Zimmerman et al., 1995). The excitation signal becomes a common-mode signal on the body and movements of the upper body result in capacitance changes that can be registered by the AD7152.

The device's maximum input range is $\pm 2\,\mathrm{pF}$ in differential mode. Common-mode capacitances of up to 5 pF can be compensated on-chip. In our experiment, we intended to monitor movements within a range of $\Delta x = 0.5\,\mathrm{mm} \ldots 5\,\mathrm{mm}$. This results in a coupling capacitance range between body and ring-electrode of $\Delta C_c = 47\,\mathrm{pF} \ldots 4.7\,\mathrm{pF}$ when the body-electrode contact is considered a plate capacitor with cotton ($\varepsilon_r = 1.4$) as dielectric.
In order to adjust the coupling capacitance ΔC_c to the chip's input range, series capacitors of 4.7 pF were inserted between the electrodes and the inputs of the AD7152. This results in an effective capacitance range of $\Delta C_{eff} = 1.9\,\mathrm{pF}$ per electrode with an offset of $C_o = 2.4\,\mathrm{pF}$.

5 ARTIFACT DETECTION ALGORITHM

The motion artifact detection algorithm we have implemented consists basically of four steps: At first an artifact level representing the intensity of artifacts in the ECG signal is computed. The generated artifact level is post-processed and in a third step it is converted by means of a threshold detector into a binary artifact indicator signal. As a last step, this artifact indicator signal is logically ANDed with an additional parameter derived directly from the ECG signal waveform. This signal is finally used to mark artifact regions in the original ECG signal.

Artifact Level from Capacitance Data. The differential capacitance signal from the AD7152 was high pass filtered to remove offsets with a 4^{th} order Butterworth filter, cutting off signals below 1 Hz, and the absolute value was taken. Then adaptive filtering (Haykin, 2001) was applied in order to estimate artifacts in the ECG signal from the capacitance signal. A filter with LMS algorithm has been used, the filter length was set to 0.2 s.

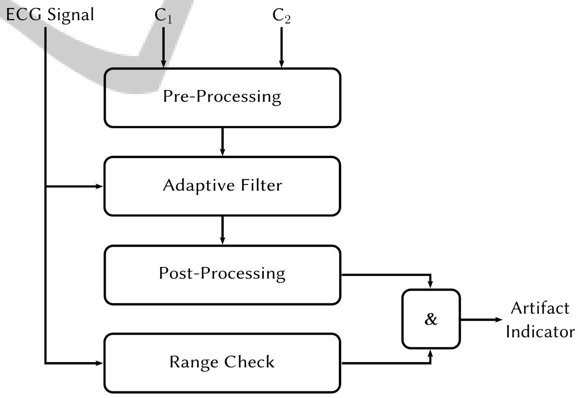

Figure 3: Signal processing chain: the artifact indicator signal is derived from ECG and impedance data.

Post-processing & Threshold Filtering. As a post-processing step the signal containing the artifact level from the previous adaptive filter step was squared and filtered with a moving average filter. The filter length was set to 0.5 s.

This was the input to the threshold detection that transforms the continuous artifact level signal into a binary artifact indicator signal.

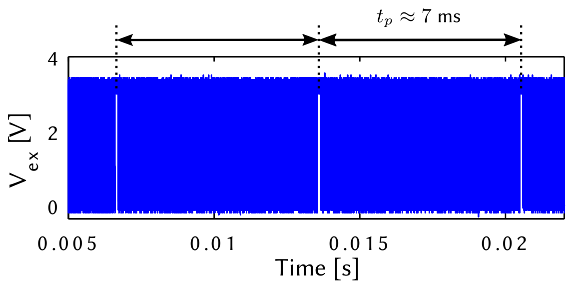

Figure 4: The 32 kHz excitation signal shows gaps every 7 ms, resulting in 140 Hz common-mode noise in the ECG signal if no further measures are taken.

Final Artifact Marker Signal. Supplementary to the artifact indicator, we have taken an additional parameter into account: using the original ECG data, we verify that the signal lies within the range of $[10,90]\%$ LSB_{ADC} of the analog-digital-converter, in order to eliminate regions where the signal is near saturation.

Then the artifact indicator and the in-range indicator were logically ANDed to generate the final artifact marker signal. When this signal is high, the corresponding region in the ECG signal is marked as artifact region. Furthermore, artifact regions that do not have a minimum distance of 1 s are joined.

6 EVALUATION & RESULTS

With the system presented above, we have conducted measurements with several subjects. The driven-seat circuit was not necessary because the systems' coupling to earth ground was very weak due to the battery-powered, wireless concept. Yet with the capacitance measurement circuit enabled, we observed a large amount of common-mode noise on the ECG signal with a frequency of approximately 140 Hz, the source of which was not obvious at first. A closer look at the excitation signal of the AD7152 revealed that even though the device was used in one-channel differential mode with continuous conversion, gaps in the excitation signal occurred with a distance of approximately 7 ms (see Figure 4). This was visible as common-mode noise in the ECG signal.

Enabling the driven-seat circuit to remove this noise was not an option, as a 180° phase shift is necessary to destructively interfere with the undesired frequencies. In the case of 140 Hz, this would result in a rather high bandwidth of the driven-seat stage. Then, the excitation signal of 32 kHz would have been attenuated too, resulting in incorrect capacitance measurement values. The solution for us was to simply narrow the bandwidth of the CCEs by adding 50 Hz low-pass filters.

6.1 Artifact Signal

The proposed algorithm generates an artifact signal with very high dynamics. For slight capacitance changes generated by breathing and light movements, the signal amplitudes stay very low. Higher movement amplitudes can increase the artifact amplitudes up to 4 orders of magnitude. Hence, a threshold could be identified that separates regular ECG episodes from the ones with artifacts. First results showed, that no adaptation of the threshold was necessary for different subjects.

6.2 Sample Measurement

Figure 5 finally shows an example of the computation of artifact regions for a capacitive ECG signal recorded with the system proposed in this paper. The gray trace represents the artifact level generated by adaptive filtering of the differential capacitance values captured by the AD7152. Above a certain threshold, the artifact indicator goes high. The artifact region can be marked in the ECG signal.

7 SUMMARY & OUTLOOK

Non-contact capacitive ECG systems represent an unobtrusive way to acquire cardiovascular data. Yet, due to the measurement principle, these systems are sensitive to motion artifacts. For automatic signal analysis, a means of estimating signal quality is therefore desired.

Combining a capacitive ECG measurement system with a capacitance-to-digital conversion device, we have presented an unobtrusive ECG system that continuously monitors the electrode-body-capacitance. This capacitance value represents a context signal that can be used to derive a quality signal for the capacitive ECG measurement.

Using adaptive filtering and post-processing we were able to show first results of the system performance. With the system, it is possible to mark regions with artifacts in the capacitive ECG signal, and exclude them from further processing thus improving automatic analyzability.

Currently we are building a database with measurements recorded with our system. With the data we will be able to quantify the improvement of automatic analysis of unobtrusively acquired ECG data due to our method. For automatic QRS detection, a considerable decrease in false (positive and negative) detections due to the proposed method should be possible, yielding an increase in sensitivity and positive

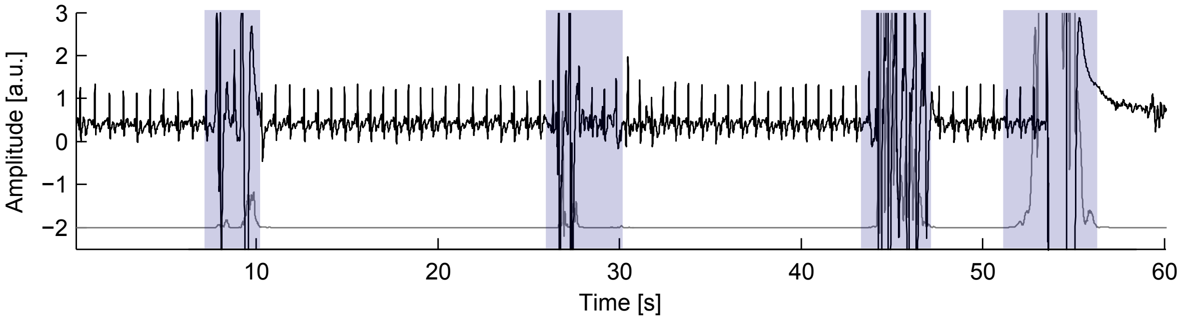

Figure 5: Using the adaptively filtered capacitance signal (*lower trace*) it is possible to generate an indicator signal that can be used to mark artifact regions (*shaded*) in a capacitive ECG measurement.

predictivity. Excluding artifact-contaminated parts of the signal also prevents the internal thresholds of the QRS-detector from assuming suboptimal values. The evaluation will also help to understand the application limits of the system and the applicability of the method.

Further work will comprise the improvement of the artifact detection algorithm by optimizing the adaptive filter parameters and timing parameters, as well as investigations whether the system can also be used for the correction of artifacts.

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