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An Approach to Automotive ECG Measurement Validation Using a Car-Integrated Test Framework

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***Abstract*— Development and integration of physiological sensors into automotive applications is gaining importance. Assistance systems which possess knowledge about the driver's cognitive state could increase road safety. In this paper we present a flexible framework that enables the development, evaluation and verification of sensors and algorithms for automotive applications using physiological signals under realistic driving conditions. We have integrated a custom capacitive ECG measurement system into a test car and validated its performance in real world driving tests. During first test runs, the capacitive system achieved a sensitivity of up to 95.5% and a precision rate of up to 92.6%. Our system also records synchronized vehicle dynamics. We discuss the road test measurements which suggest that the driving situation highly impacts the quality of ECG signal. Therefore, information on driving dynamics could be used to improve the precision rate of future capacitive ECG measurement.**

I. INTRODUCTION

The development of physiological measurement systems for automotive applications has different stimuli. Providing medical assistance and personal health monitoring functionality is one motivation, especially against the background of demographic change and aging drivers. Another reason to develop applications that use biomedical instrumentation is the desire to use this novel human machine interface (HMI) as a channel of information about the driver state. This aims at unobtrusively assessing the driver's cognitive and affective state for future driver assistance systems. Discussed systems range from vigilance and stress detection to intention recognition and adaptation of comfort systems [1]–[3].

From an instrumentation perspective, literature research shows approaches that try to acquire physiological data via the steering wheel as in [4]–[6], as well as via the seat, using contactless capacitive electrocardiography (ECG) as presented in [7]–[10]. We have shown feasibility studies for both kinds of systems in our previous work in [11].

The work presented here was motivated by different use-cases that occur during the development of automotive applications with biosignals. One major goal of the work was to establish a system for capacitive ECG measurement inside a test vehicle and validate its functionality. Therefore, a ground truth is necessary that is provided by a reference ECG device. Furthermore it is desirable to aggregate context signals such as steering angle and acceleration during measurements. Context information is important for two reasons: first, it helps to interpret driving situations during data processing. Second, we expected this information to be useful to assess the signal quality of the physiological data.

The outcome of our work is a flexible framework which addresses the needs of many scenarios when developing sensor devices and processing algorithms. For example, the task of algorithm prototyping requires a rich programming environment and the possibility to work with both real and simulated sensor data. Therefore, many algorithms are developed using Matlab. Our framework supports this approach in that we are able to record databases containing ground truth signals in the field and to export the data to Matlab. Simultaneously, we record vehicular CAN bus traffic using a data logging device inside the test vehicle. This enables us to validate sensors and Electronic Control Unit (ECU) prototypes with real world driving tests. The validation process is strengthened by the possibility to easily integrate reference sensors. Thus, our platform covers the development cycle from algorithm to ECU prototyping.

Once a function is readily designed it can be poured into hardware and probed under real-life conditions. Such methodology turns out to be crucial for the design of future assistance functions. It will involve multiple layers from semantics down to data acquisition. For example, an intelligent assistant might rely on the driver's stress level. The stress level itself is derived from ECG meta data like heart rate (HR), heart rate variability (HRV) and possibly other physiological signals like electrodermal activity (EDA). The presented platform would allow to design and test stress level detection in a virtual environment. Afterwards, it could be turned into an ECU prototype and validated in road tests.

This paper is organized as follows. Section II gives an overview of the overall test platform. It starts by presenting the particular hardware components, such as instrumented test vehicle, textile ECG electrodes, ECG measurement module and data logging device. Afterwards, the software framework which merges and processes data from the numerous sensors is described. Last, we outline the specific application and test setup which we established in order to validate the capacitive ECG sensor with respect to a reference ECG device. Section III presents results from several test drives and discusses our key observations. Finally, we conclude in section IV and give an outlook to future works.

Fig. 1. Integration of the electrodes

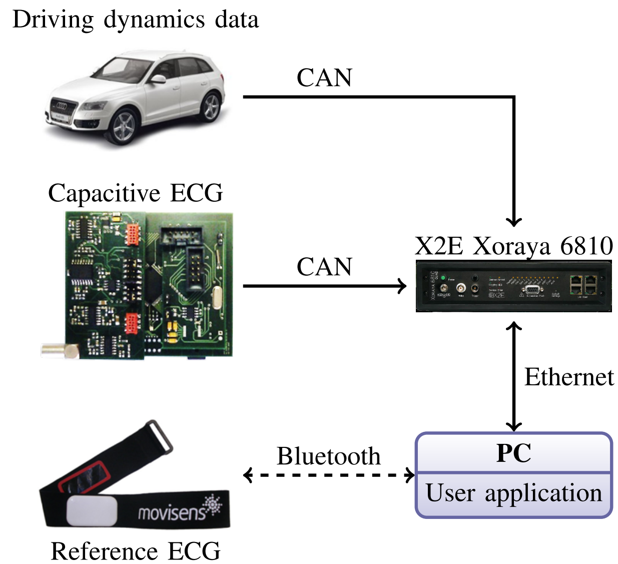

Fig. 2. System concept and communication flow between the different components.

II. MATERIAL AND METHOD

In the following section, the different hardware and software components of our framework and test setup are presented.

A. Test vehicle

Our test vehicle is an instrumented Audi Q5. The car is equipped with steering actuator, breaking actuator, electronic throttle, an actuator to control the automatic gear-shift lever, multiple cameras for environment and driver observation, inertial measurement unit (IMU) with differential GPS tracking and a gateway device which allows to control all actuators. The gateway also provides data from the vehicle's built-in sensors, such as Electronic Stability Program (ESP). Both IMU and gateway are accessible by CAN bus. As driving intervention was not a goal of this work, read-only access to the vehicle's sensor information was sufficient. During the driving tests described below, the following sensor signals were included into our experiments:

- Vehicle speed (provided by gateway)
- Steering angle (provided by gateway)
- Yaw rate (acquired by ESP, provided by gateway)
- Acceleration in X, Y and Z direction (provided by IMU)
- Current position as GPS coordinates (provided by IMU)

B. Integration of textile capacitive ECG electrodes

For the acquisition of ECG signals, we integrated textile capacitive electrodes described in [11] into the driver's seat. As requirements, the electrodes had to be attached non-invasively to the seat and the position of the electrodes had to be adjustable. In addition, safety-relevant components such as airbags had to remain functional.

As damaging the driver's seat was out of question and because the electrodes had to be removable, we attached them non-invasively. We also had to take care of the airbag function, so it was not possible to use a seat cover. As the perfect electrode positions might vary with different driver sizes, we mounted them vertically adjustable. The final set up is shown in Figure 1.

C. Hardware

1) Embedded system for capacitive ECG measurement: For acquisition and digitalization of the ECG signal we developed a modular embedded system. Its main component is an extensible mainboard with a Texas Instruments MSP430 microcontroller. It implements an algorithm for QRS detection based on [12] and HR calculation. An analog/digital preprocessing board filters and amplifies the differential signal from the capacitive electrodes and converts it to a digital signal with 16 bit resolution. For common mode rejection, this board also offers a driven seat connector. The third component is a communication module which connects the ECG module to the CAN bus.

2) ECG reference: As a reference and ground truth for the capacitive ECG measurement system, a wearable ECG chest strap was used (EKGmove, movisens GmbH). Depending on the configuration, a single lead ECG and activity (3-axis acceleration) ECG can be recorded. It features a sample rate of up to 1024 Hz. The data can be streamed online via Bluetooth protocol or saved to an microSD flash card and transferred to a PC/PDA offline.

3) X2E Xoraya 6810: X2E Xoraya 6810 is a real-time data logging device which supports common automotive bus standards (CAN, LIN, FlexRay, MOST). It is able to store recorded data internally but also able to dispatch it via Ethernet protocol. Using a software development kit (SDK), the device is programmable by custom software. The SDK supports the C++ programming language as well as Microsoft .NET framework.

D. Software

The software architecture of the framework presented here is developed around a Java-based sensor middleware called xAffect[1]. Figure 4 illustrates the framework structure and the different components it connects. xAffect manages data sources, data sinks, and data processors and allows online data processing. A major advantage is that concurrent access to a single data source by multiple data processors is handled transparently by xAffect. The object-oriented structure enables the integration of additional sensors and analysis algorithms. In order to connect and test new components it is only necessary to adapt the configuration, this way rapid prototyping is supported.

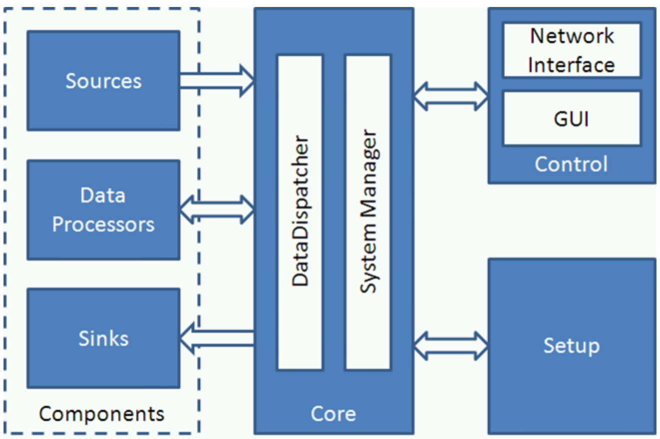

Fig. 3. The structure of the xAffect middleware.

In order to enable communication between the middleware and the Xoraya data logger, we developed a .NET based application. It is connected to xAffect by a TCP/IP server/client interface. The Java client is treated as a sensor (data source) by xAffect. It controls the logger, receives CAN messages from capacitive ECG system, IMU and gateway and extracts the contained signal data. The reference ECG system was integrated as a second data source. A logging component saves all sensor data into a single data set and stores it using the Unisens data format[2] [13]. Additionally, we have integrated a GPS logger as an xAffect data sink. It converts GPS coordinates coming from the IMU and saves the track in the GoogleEarth compatible KML file format [3]. Hence, we are able to visualize each test drive on an interactive map. All information about test runs and drivers is stored in a database, supporting the need for systematic data analysis and evaluation.

In order to facilitate the acquisition of subject data for experiments, a graphical user interface (GUI) was designed that is displayed on a screen inside the car. It guides the subject through the measurement setup, allowing her to provide statistical data (gender, age, body height, weight) and information about her clothing. During the test drive, the

[1]Developed as part of the EU-funded xDelia project, see www.xaffect.org/
[2]www.unisens.org/
[3]www.opengeospatial.org/standards/kml/

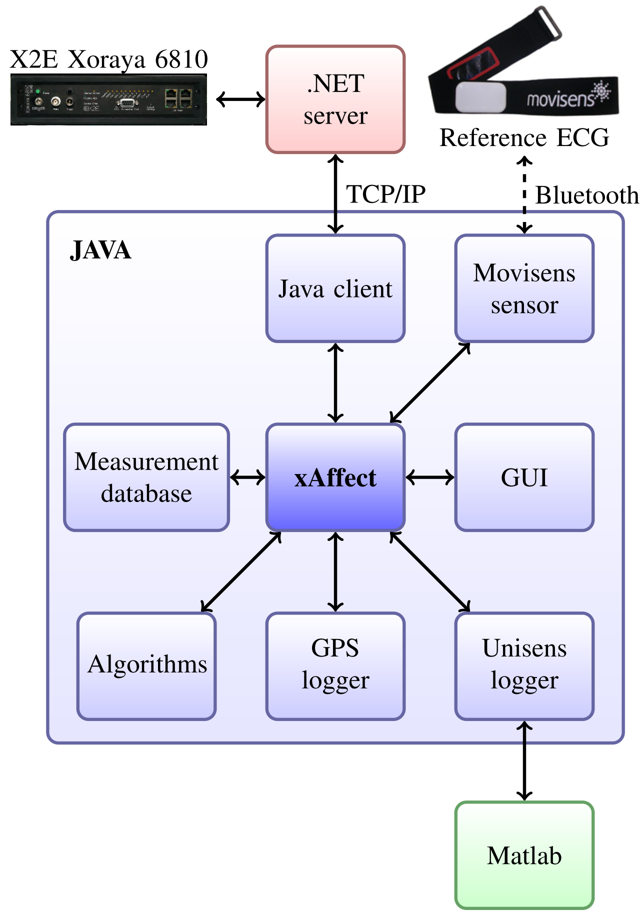

Fig. 4. Communication and software architecture of the integrated test framework.

sensor status and capacitive ECG signal can be displayed. This provides a convenient possibility to supervise any measurement. The GUI was designed with focus on usability. It is easily operated even by unexperienced users, so it does not require any technical understanding of the underlying processing framework. This aspect becomes helpful when it comes to collecting measurement data by a larger cohort with many subjects.

E. Application and Test Setup

Main goal of this work was the validation of the capacitive ECG measurement system under realistic driving conditions. As a secondary goal, we wanted to analyze the relation between QRS detection errors due to signal artifacts and driving context, the goal of which is to identify which context signals might provide suitable artifact predictors. For our experiment, we defined a test track composed of urban streets, interurban streets and highway. The average drive time for each test run was approximately one hour. For safety regulations which are enforced by German authorities, only subjects with a special training were allowed to participate in driving experiments with our test car. So far, two drivers

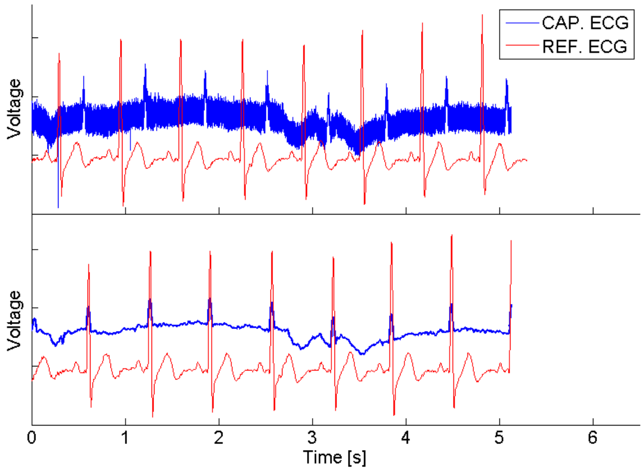

Fig. 5. Signal samples from a test drive before (upper row) and after synchronization and filtering (lower row).

(male, BMI[4] of 24.5 kg/m^2 and 29.4 kg/m^2 respectively) wearing cotton shirts were performing test drives with our set up.

After the test drives, an ex-post analysis of the QRS detections of the capacitive ECG System compared to the wearable reference device was made. In order to get a meaningful comparison, it was necessary to compensate for two effects:

- *Time offset:* As both measurement systems had different startup delays, one recording showed a time offset with respect to the other.
- *Clock drift:* Both ECG systems operate independently with different internal system clocks. Therefore a drift between both clocks occurred. This caused one recording to be stretched or compressed with respect to the other although nominally the same sample rates had been configured (in our case approximately one second of drift per hour).

To compensate for both errors, we incorporated a preprocessing algorithm which synchronizes both ECG recordings. The algorithm estimates an optimal offset and scaling parameter maximizing the cross correlation between both ECG signals. In its core, it adjusts offset and scaling of one signal and cross-correlates it to the other. The procedure is repeated until the accuracy of both estimated parameters reaches a given accuracy. Signal samples from a test drive are shown in Figure 5. The upper row shows capacitive ECG raw data and data from the reference device. The lower row shows both signals after synchronization and additional low pass filtering of the capacitive ECG signal.

III. MEASUREMENT RESULTS AND DISCUSSION

A. Measurement Results

A total of five test runs were performed with two different drivers. After the synchronization of the ECG signals, the QRS detections of the capacitive measurements were classified into "true positives", "false positives" and "false negatives" by comparing them to the reference ECG. Results are shown in table I.

Drive Number	1	2	3	4	5
Driver ID	1	2	1	1	2
Clothing	T-shirt	T-shirt	T-shirt	T-shirt	T-shirt
Drive Length [min]	44	53	81	59	60
TP[a]	3904	2187	7087	5795	4147
FP[b]	1243	2909	703	460	993
FN[c]	702	1664	333	314	447
Se[d] [%]	84.8	56.8	95.5	94.9	90.3
FNR[e] [%]	15.2	43.2	4.5	5.1	9.7
PPV[f] [%]	75.9	42.9	91.0	92.6	80.7

[a]True positives
[b]False positives
[c]False negatives
[d]Sensitivity: Se $= \frac{\text{TP}}{\text{TP+FN}}$
[e]False negative rate: FNR $= \frac{\text{FN}}{\text{TP+FN}}$
[f]Positive predictive value: PPV $= \frac{\text{TP}}{\text{TP+FP}}$

TABLE I

RESULTS OF THE ECG MEASUREMENTS USING THE OSEA QRS DETECTOR W/O ANY ARTIFACT DETECTION.

In comparison to the test drives 1 and 2, the rides 3 to 5 showed improved results. This was caused by a change in the measurement setup. To improve the contact to the subject and to reduce the influence of vibrations, we placed a compressible foam between the textile electrodes and the seat back rest, yielding better signal to noise ratio (SNR). In addition to that, we were able to identify a strong source of common mode noise in the car interior. For test drives 3 to 5 this was effectively shielded which further improved ECG SNR.

As a next step, we analyzed the dependency between detection errors and driving context signals. Especially Z acceleration (acceleration down) which captures road bumps correlates strongly with artifacts in the ECG signal. Bumps in the road lead to a relative movement of the driver versus the electrodes. This causes electrostatic charging and a change in the coupling capacitances between body and electrodes. Figure 6 shows an exemplary episode: each artifact corresponds to a local Z acceleration maximum.

Figure 7 illustrates another effect that could be observed: The driver's steering movements mostly involve the upper body and can cause artifacts if the electrodes are positioned to high on the back rest of the seat. For small steering movements, the baseline of the ECG signal changes. Bigger movements, e.g. during parking, cause strong artifacts. In this case, we found QRS detection to be nearly impossible. The measured signal is dominated by noise and artifacts. Therefore, steering angle qualifies as a good indicator for signal

[4]body mass index

disturbances. We also found car acceleration and breaking events (captured by X acceleration signal) to correlate with some artifacts.

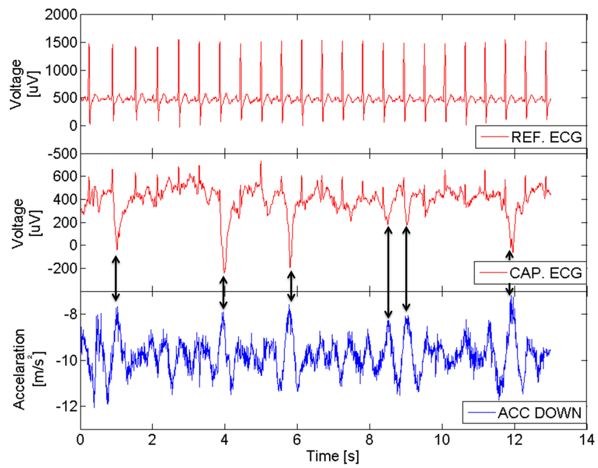

Fig. 6. Z acceleration during driving and the effect on the capacitive ECG signal.

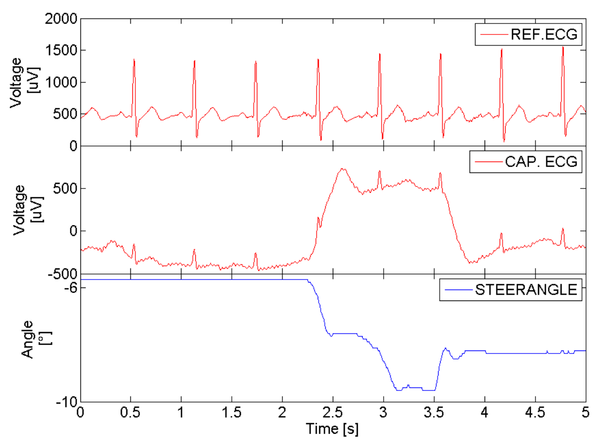

Fig. 7. Steering angle during driving and the effect on the capacitive ECG signal.

B. Discussion

The results of the completed test drives show that capacitive ECG measurement is feasible under realistic driving conditions and give a quantitative impression of the quality of the data that can be acquired. The results indicate that special attention needs to be paid to artifact detection. However, driving context signals provide a strong indicator for artifact prediction. Our data suggests that false QRS detections could be drastically reduced by incorporating context signals from driving dynamics data into the detection process.

Due to traffic safety regulations it was not yet possible to recruit a statistically significant number of subjects. Therefore the results can only be considered preliminary of course. But with the integrated framework presented in this paper we have created an infrastructure that represents an appropriate tool to build a database with real world data.

IV. CONCLUSION AND FUTURE WORKS

A. Conclusion

With the test framework presented here, it is possible validate both sensors and algorithms for automotive applications that acquire or process physiological data. We have demonstrated this by integrating a capacitive ECG measurement system into an Audi Q5 test car. With this system, validation can be carried out under realistic driving conditions. Using an wearable reference ECG system as ground truth, we were able to quantitatively assess the performance of our capacitive ECG system. First road tests have shown promising results. A sensitivity of up to 95.5% and a positive predictive value of up to 92.6% could be achieved.

Furthermore, our frameworks allows us to investigate the influence of vehicle dynamics on ECG signal quality. Our results suggest that especially forward acceleration, down acceleration and steer angle, correlate strongly with signal artifacts. Therefore, these signals should be considered as artifact predictors for future QRS detection algorithms. A robust QRS detection is the essential basis for any assistance system using ECG data or meta data. With the possibility to integrate arbitrary devices serving as ground truth providers, a quantitative benchmark of developed algorithms is now possible.

Due to the object-oriented and modular nature of the framework, the integration of new sensors or algorithms is simplified considerably. Therefore, the framework offers an optimal basis for the development, test and validation of both new sensors concepts and processing algorithms under realistic conditions.

B. Future Works

In order to establish a database for statistically sound assessment of capacitive ECG measurements, further test series have to be completed. Such data will also enable the design and test of algorithms for artifact detection which include driving dynamics context. For example, a support vector machine (SVM) could handle the classification of the ECG signal into episodes with sufficient signal quality for a respective application. To train the SVM, correctly classified training sets are necessary.

A long-term goal is to enrich the driver context with more physiological measures and to develop driver assistance using this context. Ongoing research deals with the integration of additional sensors like electro-dermal activity (EDA), skin temperature and blood oxygen saturation (SpO_2) into our test vehicle, specifically into the steering wheel. Further steps will include both the evaluation of which physiological parameters are most reliable in real driving situations and the evaluation of which features can be derived from these parameters.

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