Towards a Mobile Galvanic Skin Response Measurement System for Mentally Disordered Patients

Franz Gravenhorst, Amir Muaremi, Gerhard Tröster
Wearable Computing Lab., ETH Zurich
Gloriastr. 35, 8092 Zurich, Switzerland
{lastname}@ife.ee.ethz.ch

Bert Arnrich
Computer Engineering Department, Bogazici University
Istanbul 34342, Turkey
bert.arnrich@boun.edu.tr

Agnes Gruenerbl
DFKI GmbH, Embedded Intelligence
Trippstadter Straße 122, 67663
Kaiserslautern, Germany
agnes.gruenerbl@dfki.de

ABSTRACT
This paper outlines the design and implementation of a mobile galvanic skin response (GSR) measurement system applied to feet. The system comprises an off-the-shelf node featuring acceleration and GSR sensors with customized firmware and a mobile phone with a customized Android application. The app serves as graphical user interface (GUI) and remote control for the sensor node. The devices communicate wirelessly while implementing a power-saving strategy to limit the amount of communication. The technical feasibility of the system is demonstrated through data recording in a study comprising 28 measurements from 11 patients. In each measurement, two conditions are recorded. 12 statistically and highly significant GSR features for these two conditions are identified, with the number of maxima in the second derivate of the GSR signal being the most significant one.

Categories and Subject Descriptors
H.4.m [**Information Systems Applications**]: Miscellaneous

General Terms
Measurement, Experimentation, Algorithms

Keywords
Galvanic Skin Response, Electrodermal Activity, Mental Disorder, Mobile Measurements

1. INTRODUCTION
Approximately 25% of people are affected by mental disorders during their lifetime. The numbers are expected to increase in the coming years [15]. This will strain government budgets and health providers, as the treatment of mental disorders is costly, time consuming and requires experienced medical practitioners.

Currently, many people suffering from mental disorders visit therapists frequently to enable the latter to understand the development of their disorder and thereby establish a better course of treatment.

The European research project MONARCA aims to develop a wearable multimodal sensor system that can monitor patients continuously. This has the potential to save time and money by reducing the amount of face time patients need to spend being monitored by doctors. It also has the potential to improve therapy by increasing the amount of data that doctors can obtain about their patients' conditions.

To enable the sensor systems to collect data continuously, patients must carry the device at all times. Therefore the MONARCA project focuses especially on wearable, unobtrusive sensors [1, 9] which can be used during daily life. In this paper, we focus on the mobile Galvanic Skin Response (GSR) measurement component.

1.1 Related Work
Several studies have been conducted involving GSR measurements with people who suffer from mental disorders [16], some studies involve bipolar patients [7, 8]. However, the current state-of-the-art measurement devices are bulky and require trained personnel to operate them. Thus, they are only applicable for stationary use in hospitals or laboratories, restrict the patients' activities significantly and cannot be used for continuous long-term measurements. A prototype of a mobile measurement device is presented in [5]. The authors attached a GSR device to one of the healthy subject's hands and used proprietary software to log the data to a mobile phone aggregator. Although, the hand is a commonly used sensing location for GSR measurements, patients feel stigmatized by wearing eye-catching measurement devices in daily life situations. To increase user acceptance of this kind of monitoring in everyday settings, the sensors need to be comfortable and invisible. Consequently, we opted to perform measurements at the foot location, where the devices can be hidden under regular socks. From a physiological point of view, the feet are known to serve as a suitable measurement location for GSR [2, 6, 4].

1.2 Previous Work
In previous work [12] we compared GSR measurements at the hand and foot. Our results suggest that the foot recording location is suitable for recording in daily life, even in the presence of moderate movement. In this former study we used custom-designed hardware devices [11], and a notebook was required to record the data. The annotations had to be performed manually by the experiment leader. In order to obtain ethics approval to collect GSR data from actual patients, the measurement devices need to comply with the requirements described in Annex I of Directive 93/42/EEC (Conformité Européenne, CE certificate). For that reason we switched to a commercially available GSR sensor, which fulfills these requirements. To devise a setup for medical use with patients we implemented the data recording and annotating tasks on a smartphone, which communicates wirelessly with one or more sensor devices. In an early version of the system [3], all recorded data was transmitted to the mobile phone and stored there. However, this required the phone to always be in proximity to the sensor and the continuous Bluetooth connection drained the battery of both the phone and the sensor device. In this work, we present a system which can still connect to the mobile phone and uses the phone as GUI for annotation tasks. However, the main data is stored on the sensor's local SD memory card.

1.3 Contributions
With this work we aim to advance the state of the art in the following ways:

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- We describe the design and implementation of a mobile, unobtrusive GSR sensor system.
- We demonstrate the practical feasibility in a proof-of-concept study with N=11 mental disordered patients.
- We prove that GSR data collected with our system can be used to discriminate between two conditions that happen naturally in clinical environments: psychiatric analysis and measurement with audio stimuli.
- The source code of the sensor node's firmware as well as the Android App is made publically available for scientific use.

2. MOBILE MEASUREMENT SYSTEM

The proposed system consists of two devices, the actual sensor node and an Android application running on a mobile phone. The Android application serves as GUI to remote control the sensor device. Communication between the two devices is realized through the Bluetooth protocol.

2.1 Android Application as GUI

Since the sensor device itself has no buttons or screen, we opted to implement an Android GUI as a remote control (Figure 1). The application connects to the sensor via Bluetooth and implements the following functions:

- Start and stop the sampling and data logging process on the sensor device.
- Check the current signal for plausibility in real time by requesting samples from the sensor node and visualize them in a graph in real time.
- Record annotations during the experiment. During this phase, the connection between phone and sensor is not necessary; the labels are stored locally on the phone and merged with the sensor node's data after the recording is finished.
- In the presented study, the phone is additionally used as playback device for sound stimuli which are exposed to the patient during the GSR recording. Start and stop of the playback function are automatically annotated and simplify segmentation of the data later on.

Figure 1: Android Application asks for the patient ID to issue the connection to the sensor device. The real-time annotation functionality also works when the Bluetooth connection between phone and sensor is lost or terminated. The annotations and sensor data is merged afterwards.

2.2 Shimmer Sensor as GSR Sensor Node

We used the commercially available Shimmer [10] base unit, extended with the Shimmer GSR module (Figure 2). We opted for an off-the-shelf hardware device since we experienced legal issues with our custom-designed, and therefore not certified hardware when applying for a clinical study involving mental disordered patients. The Shimmer device is CE certified and bases on tinyOS, an open source development platform. We customized the firmware to enable the local logging functionality and the remote control by the Android mobile phone App (see above).

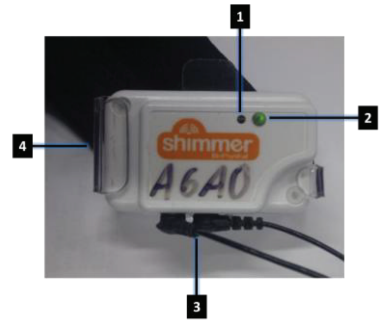

Figure 2: Sensor node with reset button (1), status LED (2), Connectors for GSR electrodes (3), holder and Velcro strap (4).

The device samples and stores locally GSR data and tri-axial accelerometer data with a sampling frequency of 51.2Hz. Further specifications can be found in Table 1.

Table 1: Specifications of GSR sensor node [10]

Parameter	Value
Size	54x25x32 mm^3
Weight	28 g
Current Draw	60 uA
Conductance Measurement Range	0.2-100 uS
Conductance Accuracy	+/- 10%
Sampling Frequency	51.2 Hz
Communication	Bluetooth, Class 2
Storage	MicroSD card, 2GB
CPU	8 MHz MSP430
Accelerometer	triaxial, Freescale MMA7361
Energy Supply	450 mAh battery

For data recording, the sensor is strapped around the ankle and the electrodes are attached at the foot (Figure 3).

2.3 Recording Procedure

The firmware of the sensor unit and the Android application are designed to facilitate an easy and secure handling for the data recording. The steps are described briefly:

1. Release sensor unit from the charger. Doing so automatically switches on the Bluetooth chip on the sensor.
2. Attach the sensor device and the electrodes to the patient's foot. In our study we opted for the non-dominant foot. As all participants were right-handed, the measurements were always done at the left foot.
3. Start the Android App on the mobile phone. After typing in the patient ID, the app automatically connects to the sensor device. The measurements are shown in a real-time graph on the phone. The caregiver can now check visually if the signal is reasonable and all cables are connected properly.
4. Hit "Start" button in the App. This starts the logging on the sensor device. At the same time, the app synchronizes its timestamp with the sensor and then shuts down the Bluetooth connection to increase flexibility and save energy.

5. During the data recording the app can be used to annotate the experiment phases.
6. After the recording, the sensor is released from the foot and put back on the charging station.

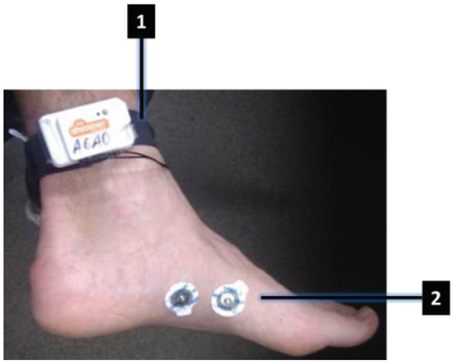

Figure 3: Sensor device strapped around the patient's ankle (1), and sticky electrodes (2) applied to the patient's left foot. All parts can be hidden unobtrusively under the sock.

3. DATA ANALYSIS

3.1 Merge data sources

After data recording is finished, there are two data files. One file is stored on the GSR sensor node and includes the actual measurements. The other file is stored on the mobile phone and includes the live annotations which can be done through the Mobile GSR Application on the Android mobile phone. This second file is optional and only needed if live annotations have been done. Both files are transferred to a PC through the sensor's and phone's USB connection. Matlab is used to read in and merge both files. Finally, the annotations' timestamps are in synch with the GSR data logging timestamps.

In case multiple measurements are done and multiple data files from both the mobile phone and the sensor node exist, this step also ensures to find the matching pairs of files appropriately. This is done through unique IDs and timestamps which are exchanged between phone and sensor at the beginning of each recording.

3.2 Extract Raw Data

For the data analysis there are usually only these parts of the recording considered which correspond to a well-defined experiment condition, thus the data segments with the appropriate label have to be extracted. This is done with a Matlab script. In case one specific label appears more than one time in the recording, the longest appearance is considered.

In our case the data which is recorded during the meeting with the therapist and the data recorded during the audio stimuli measurement are extracted.

3.3 Adjust Segment Lengths

Some of the features we are going to extract and compare perform best with data sources of equal lengths. In case the two extracted data segments are of different lengths, the longer one is being shortened until the lengths are matched. For the shortening process we want to keep the part of the segment which is least likely to be disturbed by movement artifacts. For this purpose, we calculate a measure for the movement intensity by adding the magnitudes of the three axis of the accelerometer:

$$move(n) = |acc_x(n)| + |acc_y(n)| + |acc_z(n)| \quad (1)$$

In the shortening process, the continuous part of the segment is chosen whose accumulated movement is minimum.

3.4 Feature Extraction

To avoid errors due to the transition phases at the segment's boundaries and due to potentially inaccurate annotation timestamps, we consider only 90% of each data segment, the first and the last 5% of the data are ignored for the feature extraction process.

We post-process the raw data and calculate GSR features as proposed by Wagner et al. [14]. The following features are extracted and considered for the data analysis: Mean median, standard deviation, minimum value, maximum value, number of local minima, and number of local maxima. The same seven features are extracted additionally from both the first and second derivative of the GSR signal. So, in total, there are 21 features extracted for each segment.

3.5 ANOVA

The analysis of variance (ANOVA) is used to find out for each feature whether its value differs significantly between our two conditions.

4. APPLICATION IN CLINICAL USE

4.1 Proof-of-Concept Study

To prove the feasibility of the proposed system in everyday clinical use, we performed an exemplary data collection study. In collaboration with the Psychiatric Hospital in Tirol, Austria, we recruited 11 participants (10 female, 1 male). They were all patients diagnosed with bipolar disorder, they participated voluntary and signed an informed consent. Ethical approval for this study was granted by the appropriate authority. The data was recorded during 7 months. During this time, each of the participating patients visited the clinic in average 3-4 times. From the total of 36 visits, we carried out 28 appointments with GSR data recordings which are used for this study. In each session, the GSR recording was performed in two different conditions, which are typical for treatments in psychiatric clinics:

1. Talk condition: Patient is sitting on a chair and talking with a psychiatric doctor for 10-30 minutes about his mental state during the last three weeks.
2. Oddball condition: Patient is lying on a bench and listens to an auditory oddball paradigm stimulus [13] which is played back through a loudspeaker for 15 minutes.

The collected data was processed according to the previous chapter. It is researched if the two conditions can be discriminated by analyzing the GSR data.

4.2 Results

21 features were extracted; 12 of them scored a statistically highly significant p-value ($p<0.001$). The most significant ones according to its p-values are listed in Table 2. The first and third features are visualized in Figure 4.

Table 2: Most significant features with p-values

Feature	p-value
1. Number of local maxima in 2nd derivate	1.032e-5
2. Number of local minima in 2nd derivate	1.035e-5
3. Standard deviation of original signal	6.817e-5

4.3 Limitations

The authors are aware that this work is only one step towards an ideal mobile GSR measurement system:

- The system is not applicable in case of injuries which limit the accessibility of the feet, i.e. foot in plaster.

- The metal connector on top of the sticky electrodes feels inconvenient for some patients, especially for long-term experiments.
- The conclusions of the presented study from a medical point of view are very restricted, since the number of participants is very low and the two measurement conditions were not defined very accurately. However, the goal of this work is to describe the design and implementation of the new measurement system. The study was performed to prove the feasibility from a technical point of view.

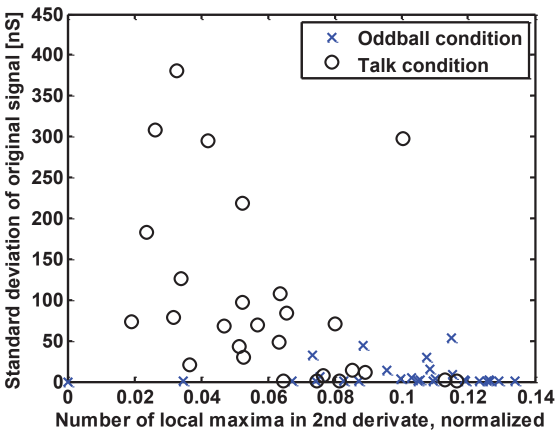

Figure 4: Two of the total 21 calculated GSR features on the x and y axis respectively. Oddball and Talk condition can be discriminated by using these two features.

5. CONCLUSION AND OUTLOOK

Tools for monitoring patients with mental disorders could improve their quality of life as well as reduce costs to health care systems. Previous research showed that GSR measurements are one of the promising objective health status parameters.

We presented the design and implementation of a mobile GSR measurement system. It consists of a commercially available and certified tri-axial acceleration and GSR sensor node and an Android application for mobile phones. The implemented software for the sensor node, the Android app and the data post-processing in Matlab are specified.

The Android application connects through Bluetooth to the sensor device and serves as a remote control. It allows for starting the data collection as well as for annotation the experiment phases and evaluation of sensor readings in real-time to assess their plausibility. In collaboration with a hospital in Tirol, Austria, the technical feasibility of the system was demonstrated with a data recording in a study with 28 measurements from 11 patients in a clinical environment. In each measurement two conditions were recorded. One condition was the routine interview for diagnosis updates between the patient and the caregiver. The other condition was an auditory oddball paradigm, where the patient listens to audio stimuli played back and annotated by the Android application. After the data recording was finished, the data from the sensor devices and from the mobile phone is post-processed. Only data during the two defined experiment conditions is considered and data with too much physical activity (detected by acceleration sensors) is filtered out to avoid movement artifacts. Finally, from each measurement and condition 21 features are calculated and ANOVA is performed. 12 features proved to be statistically highly significant for our two considered conditions, with the number of maxima in the second derivate of the original GSR signal being the most significant feature.

The main goal of this study is to show the technical feasibility and functionality of our new system. The source code for both, the sensor firmware and the Android Application can be obtained free of charge from the author.

The performed study did not aim to find medical explanations as to why the GSR signal differs under the two tested conditions. In fact, the two conditions were selected with the goal of having a high probability to have discriminative features, which confirmed the plausibility of our system.

The measurements for this study were performed on the foot, which is potentially the most unobtrusive location for long-term GSR measurements. We are currently working on integrating textile electrodes into socks which avoid the inconvenience of sticky electrodes.

In a next step, we will evaluate different stimuli for GSR signals, explore the dependency between GSR and the mood status of bipolar patients. Our vision is to fuse the GSR data with other modalities and eventually be able to predict the long-term development of the mental status of patients and alert the doctor if necessary to have a closer look at critical patients.

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