BandReader – A Mobile Application for Data Acquisition from Wearable Devices in Affective Computing Experiments*

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Abstract

As technology becomes more ubiquitous and pervasive, special attention should be given to human-computer interaction, especially to the aspect related to the emotional states of the user. However, this approach assumes very specific mode of data collection and storage. This data is used in the affective computing experiments for human emotion recognition. In the paper we describe a new software solution for mobile devices that allows for data acquisition from wristbands. The application reads physiological signals from wristbands and supports multiple recent devices. In our work we focus on the Heart Rate (HR) and Galvanic Skin Response (GSR) readings. The recorded data is conveniently stored in CSV files, ready for further interpretation. We provide the evaluation of our application with several experiments. The results indicate that the BandReader is a reliable software for data acquisition in affective computing scenarios.

I. Introduction

People nowadays are getting more and more accustomed to technology that is pervasive and ubiquitous. Besides using computers at work and at home, many own at least one mobile device, be it a smartphone or a tablet. To address individual preferences of each user, mobile systems offer various methods of personalization and customization of these devices. However, as they become more and more miniature, they can be fit to pieces of hardware of a size of an accessory. Today's wearable technologies, such as wristbands, provide a number of advanced sensors to monitor human activity and health condition. Furthermore, these devices could be used for de-

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livering data on human physiological states for affective computing applications. Affective Computing (AfC) [1] is a new computing paradigm that has been gaining a lot of interest recently. Affective computing systems can use a range of signals for the classification of a person's emotional state. Physiological signal monitoring is one of the commonly considered cases. For many AfC systems it is important to use non-intrusive and pervasive technologies. Therefore, wearable devices, including wristbands, seem a promising solution.

Emotional aspect of human-computer interaction is crucial for the process to have a natural and easy flow [2]. A number of studies on usability[1] has proven that careful system design, mindful of user's emotional states and responses has a great impact on the overall user's performance with the application. Our tool can simplify the implementation of practical AfC software on mobile devices, while also taking the affective aspect of interaction into consideration.

The rest of the paper is organized as follows: In Section II we stress the affective loop's role in HCI, In Section III we describe selected hardware. Then in Section IV we specify our application. In Section V we provide an experimental evaluation of our solution and situate our approach in the context of other studies in Section VI. Finally, in Section VII we summarize the paper and give directions for future work.

II. Affective Loop in Human-Computer Interaction

Recent methods in HCI emphasize the use of information regarding human emotion on the interface and interaction level. The so-called emotive interfaces aim at such an interface design that addresses the user's affective state directly, with use of various emotion inducing techniques such as colors, photographs of human facial expressions of emotions, and careful choice of words for slogans, titles, etc. However, as technology is becoming more advanced and pervasive, a prescribed design begins to lag behind the possibilities brought by the potential modern conveniences. An important aspect of AfC systems is their ability to gather data, process it and generate an answer dynamically, and in real time – a mechanism widely known as an affective loop. This basic concept of AfC applications refers to the continuous chain of interactions between the user and the software. As a response to the user's operations in the software, the system generates new content or modifies its characteristics, by means of colors, animations, or more subtle changes in the parameters. Then, the user can react to these new conditions, and so on. In order to implement this in the application, however, one needs to adapt a specific approach and be aware of several issues that arise.

One difficulty in this context regards proper data acquisition. Oftentimes, AfC systems use multiple sensors or complex platforms consisting of various devices. To ensure reliable data interpretation, it is reasonable to consider signals from more than one modality – by which we mean both audiovisual data and other user's behavior metrics. Another problem is related to the temporal resolution of data handling. Collecting affective information from the environment in asynchronous manner and processing it offline is not sufficient for applying the affective loop [3] in the interaction. Synchronization and integration of multimodal and multichannel data is therefore a grave issue.

From the practical point of view, in order to create AfC systems that support wristbands as input devices, specific software solutions need to be provided. In our work, we are interested in ubiquitous solutions that integrate wearable sensors with mobile technologies. To acquire and process data from wristbands, dedicated mobile applications have to be developed. These applications need to address several of important requirements, such as operating in real time, or the support for different hardware solutions. In this paper we present

[1] Usability refers to the characteristics of software that determine the degree of ease and efficiency with which the application is used.

such an application that we developed and successfully evaluated in a number of AfC experiments. BandReader is an important step in satisfying these concerns, as it offers software support for wearable devices that provide physiological data, which is necessary to develop the affective loop.

III. Selected Wristbands for Affective Computing

Analysis of current market state led us to selection of bands that could be useful for presented applications: Empatica E4, Microsoft Band 2, Xiaomi Mi Band 2, Apple Watch 3 and Scosche Rhythm+. All of the devices listed here provide at least a certain mode of HR monitoring, which forms a basic condition from pervasive AfC development point of view. Considering fitness tracking appliances developed by Fitbit, Garmin, Polar, Xiaomi or Apple, continuous HR measurement is provided in each case. Some companies, such as Scosche, decided to focus just on rough cardiovascular activity monitoring. Few developers, namely Empatica E4 and Microsoft Band 2, enhanced their wristbands with more complex biometrics tracking. Both devices include Electrodermal Activity (EDA) or GSR sensors, which aid the user's feedback with more comprehensive physiological body state overview. Wristbands are a solution that provides a compromise between convenience and capability. This is not, however, sufficient for achieving decent level of affect recognition and enhancing interaction.

Easy and user-friendly body activity tracking comes with numerous disadvantages regarding unusual use cases. Collected data is often preprocessed before being presented to the user. Therefore, the information that the user acquires is already interpreted in a specific, undocumented way. This is unfortunate for researchers who would prefer access to raw data. Information processing should be fully controllable in order to apply best models for further interpretation. In the following paragraphs we show that most of currently purchasable (from everyday user perspective) biometrical instruments are not supported by any satisfactory software enabling to collect, store and meaningfully interpret data.

Xiaomi Mi Band 2 is a simple band aimed at fitness and sleep tracking. It is equipped with, among others, an optical HR sensor and a step counter. Xiaomi Mi Band 2 allows to check one's HR at a certain point of time and shows it on its display. In order to track it continuously, though, the device has to maintain the connection with the official smartphone software, Mi Fit. The full functionality is brought by using the band with one or both of the developer's applications: Mi Band Notify & Fitness and Mi Band Tools.

Apple Watch 3 is a brand new technology for smartwatches. This wristband is essentially the only smartwatch we included in our analysis. The integrated components include accelerometer, barometric altimeter, and ambient light, gyro and HR sensors. With the preloaded Apple watchOS operation system and Siri software, unlike Mi Band 2, Rhythm+ or E4, it is meant to be a fully-developed smartwatch that supports SMS messaging, email, push mail and IM.

Scosche Rhythm+ is a HR sensor for exercise intensity measurement. The distinctive feature for this device, as claimed by the developer, is its unmatching accuracy provided with the application of Green/Yellow Optical Sensors technology. Another notable feature is its dual-mode processor, which allows simultaneous data transmission between the Rhythm+, multiple ANT+ displays (such as sport equipment at fitness centers) and the smarthphone app (paired via Bluetooth SMART) as well. The device, however is not equipped with any sort of display or screen, so any real-time data monitoring has to be performed with external software.

Empatica E4 is an advanced sensory wristband based on the technologies previously developed in the Affective Computing division of MIT Media Lab. The device is equipped with Blood Volume Pulse (BVP) and Electrodermal Activity (EDA) sensors, as well as an accelerometer and an infrared thermometer.

To benefit from full capability of this device, the connection with user's smartphone and official app via low energy Bluetooth Smart is necessary. In order to access the detailed information, assembled in the CSV file generated by the app, the user needs to download and install the Empatica Manager software.

Microsoft Band 2 (MS Band 2), was designed as a wearable device for health, fitness, and basic everyday activity purposes. The sensors on board include barometer sensor, gyrometer, GPS, accelerometer, capacitive sensor, optical HR monitor, UV sensor, ambient light sensor, and GSR sensor.

The software provided by the developers together with each commercially released wristband is designed in a way to support the everyday user. In consequence, each feature is devised in a way that balances the efficiency, on the developer's end, and user-friendliness, on the consumer's part. While the specific hardware itself is often theoretically capable of providing reliable data, its full capacity is restricted by the software that processes and interprets the signals before presenting them to the user. Based on the available software overview, we provide a critique of the present alternatives and propose a set of features that would comprise to the application suitable for various developers needs.

Xiaomi Mi Band 2 comes along with the Mi Fit mobile app, which can be used both on Android and iOS. It allows for band management and visualisation of historical data. Unfortunately, there is no open API or SDK available for developers. However, there are successful attempts to "hack" the transmission done via Bluetooth and gather the data sent from the band by accessing proper bytes of raw signal. Many values can be accessed this way, which has been demonstrated in previous work done by our team [4].

The first thing that makes *Apple Watch 3* unique is that it comes with its own opearting system called Watch OS. It can be easily extended using external applications. Apple provides developers with full support of API and Software Development Kit (SDK). From the perspective of the everyday user, Apple Watch provides exhaustive statistical information like amount of burned calories, sleep length or training progress. On the other hand, the device is supported only by iOS and thanks to that its accessibility is restricted.

Rhythm+ comes with no official mobile, PC or Web app, but there are more than one hundred unofficial apps available in Google Play or App Store that support it and allow activity tracking. The device uses Bluetooth SMART and ANT+ protocols, so the user can connect it the application of choice, including other fitness watches, bike computers and fitness equipment. Producers of Scosche Rhythm+ provide developers with API support and Fitness Utility app for iOS to test third-party apps. This software can be used for accessing raw data from the band and generating real-time charts. Despite having a dual-mode processor, this band is not equipped with any internal storage, nor does the developer allow for direct, raw data download.

Data gathered in the *Empatica E4* internal memory can be easily imported through USB and stored in the developer's cloud platform (E4 Connect) using a software tool, E4 Manager. In turn, the platform, alongside with mobile app (E4 Realtime app), enables an overview of the data. The user is able to inspect realtime charts of gathered data, check status of battery and duration of current session. After uploading data to the cloud platform, the processed data and charts can be downloaded anytime from any device. Nonetheless, the quality of data provided and, hence, amount of information that can be derived from it, is erroneously limited and flawed.

MS Band 2 is supported by most mobile devices. In order to use its full functionality, it is mandatory to pair it via Bluetooth with the mobile Microsoft Band app. Similarly to Empatica, all of the data collected by MS Band 2 is stored in the cloud and can be accessed using the provided software. After connecting to Microsoft Account, the user is able to see her activiy history, including burned calories (based on amount of steps), track sleep activity and record changes in weight. Using Microsoft Health Web app, the user can access a lot of statistical information, which is based on the processed data. Raw data collected by MS Band 2 is practically unaccessible for the user.

IV. Design and Implementation of BandReader

i. Requirements for a new application

Review of current software status and our previous preliminary research in AfC field [5, 6] led us to specification of a set of use cases and requirements for the software to be a convenient asset for studies:

1. The technology should introduce modular architecture to be easily expanded with new devices support and new functionalities.

2. The solution should give a possibility to save data from all available sensors for each band. It should take care of the fact that different devices have different sets of sensors.

3. The applications should facilitate recording data from several different wristbands simultaneously, as it is a common experimental scenario.

4. The software should allow synchronization with other data sources (e.g. procedure markers from PC). Incorporation of Lab Stream Layer system[2] should be considered, as it is a mature solution for this issue.

5. There should be a possibility for arbitrary file naming and tagging to provide more control over data and to facilitate future processing.

6. The data should be saved in convenient file format (such as i.e. CSV).

7. The data should be available for other applications that run on the same device, i.e. there should be a service that feeds clients (other applications) with the current stream of data.

8. The application should output raw data gathered from wristband(s).

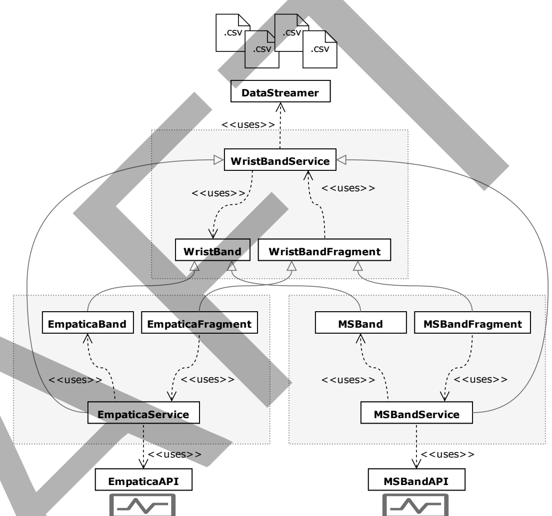

Figure 1: *BandReader application architecture.*

ii. Details of implementation

Considering the features of described hardware solutions, we decided to focus the implementation of the prototype on MS Band 2 and Empatica E4.

Therefore, to ensure the greatest openness, availability and the possibility of further independent development, the BandReader application was created for the Android Operating System. The developed application was written in Java language and consists of five main modules (see Figure 1):

- *WristBand* (31 LOC[3]) is an entity that describes the type of the band and its possible states (e.g. connecting, connected) and list of sensors available.

[2] See: `https://github.com/sccn/labstreaminglayer`.

[3] Lines of Code.

- *DataStreamer* (156 LOC) is a module for handling serialization of data streams to CSV files. It converts the data to specified file format and physically writes the files to smartphone storage.

- *WristBandService* (287 LOC) is the main module of BandReader. It supports every stage of communication with the band with the use of band definition written down as WristBand entity. Among the important methods of the service there are:
  - `connect()` connects with the wristband using the provided API or other available method;
  - `startSubscription()` switches the application to listening mode, i.e. it registers callback methods that are called when new data arrives from the band. Current sensor readings are now displayed in the application UI;
  - `startRecording()` turns on the recording mode, i.e. received values are not only displayed, but also saved to CSV files;
  - `stream()` is a generic method executed for each new sensor reading. It checks the current mode and executes the proper actions, i.e. delegates data saving to DataSteamer in the recording mode. This method can be easily extended in the future to handle more modes of operation, e.g. synchronization through Lab Stream Layer system or broadcasting of data to other Android applications.

  It is important to note that WristBandService is implemented as real service, i.e. it receives and handles data even if BandReader UI is closed.

- *WristBandFragment* (455 LOC) is responsible for UI panel for specific wirstband. With the use of methods provided by WristbandService, it allows user to connect with the band, display the current status or start recording. There is also LoggerFragment responsible for displaying the logs collected from DataStreamer and WristBandService.

- *Utils* (4 classes, 192 LOC in total) is a set of additional functionalities (not mentioned on Figure 1), responsible for, among others, tags handling and saving and reading application settings from the phone's memory.

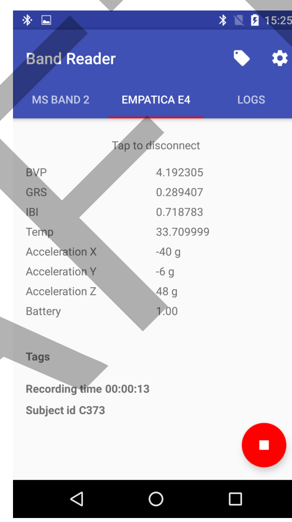

Figure 2: *A screencapture of BandReader application during the recording session.*

The modular architecture of the application allows it to be *easily extended* in the future. To support a new band, one must define three classes that inherit from the abovementioned abstract classes: (a) *WristBand*, with the definition of band's states and sensors, (b) *WristBandService*, with the implementation of band connection and (c) *WristBandFragment*, with the UI panel for the user. The range of extension of the application impacts the complexity of implementation. If it is a high-level change, e.g. adding synchronization through Lab Stream Layer, it will be associated only with the extension of the appropriate method (e.g. `stream()`). Low-level functionalities that depend on the specific device implementation, may require changes in individual wristband classes. Depending on the communication methods used by the wirstbands' developers, the addition of a new device may involve a diversified number of LOC that need to be written in order to be able to handle the instrument. In the case of Empatica E4, it is about 500 LOC, and MS Band 2 requires as many as 600 LOC.

iii. Use Cases and Current Development

BandReader is an important part of mobile sensor platform we propose as a base for AfC use cases [7, 8]. Various scenarios for BandReader in such a setting are currently under development in our team.

Data collection in AfC experiments A subject takes part in experiment. She is exposed to some stimuli and at the same time her physiological reaction is monitored by the BandReader. Signals are saved and synchronised with stimuli-related markers from experimental PC. Such data is then processed during post-experimental analysis in order to find valuable observations about emotional physiological reactions, e.g. in order to prepare models for emotion prediction based on physiological signals.

Music recommendations system BandReader gathers live HR and GSR streams while the user is listening to music. As music tracks have assigned affective labels in valence and arousal space [9], it is possible to train a neural network with the use of mobile TensorFlow library[4]. This model pairs current user state with tracks' affective score and is then used to propose music based on current mood.

Geographical map of affect HR and GSR signals from BandReader are transformed into Emotional Index [10], a mono-dimensional measure that reflects more positive (> 0) or more negative (< 0) emotions. This information is stored along with current GPS coordinates and then presented for users in aggregated form as a chart of emotions for given area.

Emotion as a context information AWARE[5] [11] is a framework for building context-aware applications. Together with many other possible sources, like GPS position or current battery usage, affective signals may be used as an input. Such a framework, combined with the rule-based language designed for inference on uncertain knowledge [8], gives a reliable base for development of more sophisticated AfC applications.

V. Experimental Evaluation of BandReader

The *Bandreader* application was developed in order to support our practical research in the area of affective computing. We used *BandReader* to record data collected by Empatica E4 and MS Band2 wristbands in a research project regarding the development of affective design patterns in computer games [6]. Thanks to the portabilty of the developed solution, we are further extending it to provide the biofeedback loop. Below we describe the most important results of the evaluation.

i. The Experimental Procedure

The experimental procedure initially comprised of two phases, both performed on a personal computer. In order to analyze the physiological reactions and the stimuli occurences correlation later, the synchronization between the smartphone (with BandReader application running) and the computer was maintaned. During the whole study, the subject was wearing either Empatica E4 or MS Band2 which was paired with BandReader application via Bluetooth. In the first phase the subject is presented with affective pictures [12], one by one, for a fixed amount of time. After each picture, the task is to rate subjectively felt arousal

[4]See: `https://www.tensorflow.org/`.

[5]See `http://www.awareframework.com/`.

in response to the presented stimuli, on a 7-level scale from 1 to 7. The actual experiment is preceded by a short training session with neutral images. The second and last phase involved playing a simple platform game, designed specifically for research purposes [6]. The wristband continued to collect the subject's physiological data throughout the game and the BandReader recorded it for each participant individually. The whole procedure lasted about 22 minutes.

Figure 3: *Empatica E4 wristband (on the left), alongside the eHealth platform and the computer used in one of our studies.*

ii. Summary of Conducted Experiments

So far we conducted two experiments when the procedure involving use of BandReader was applied. The first experiment took place in late April 2017 (Eurokreator lab, Krakow, Poland), with 6 subjects in total. In this attempt though, only the first phase was engaged. The full procedure, consisting of both phases, was held in June 2017. This time, the study group involved 9 persons.

In the studies conducted afterwards, specifically in January 2018 and March 2018, we focused on testing reliablity of data from Empatica E4 and MS Band 2 which was recorded with BandReader. We decided to augment our procedure with two new devices: BITalino and eHealth (see Fig. 3 and 4). This time, BandReader was used in "Multiband recording" mode, which allows to gather data from two devices simultaneously. Both phases of procedure described above were performed, and – what is more – an additional one has been prepared. After playing the game, a relaxing picture was showed to a user, with a very unpleasant sound that followed. This step was applied to acquire data on the strong physiological response to a sudden affective stimuli of the subject. 18 persons participated in the study at that time.

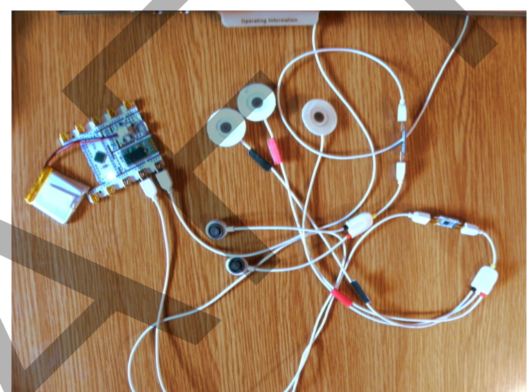

Figure 4: *Bitalino platform, together with GSR and HR electrodes.*

iii. Evaluation Results

As a result of the experiments, several observations can be stated. First of all, *BandReader* proved to be a reliable solution that supported a connection with Empatica E4 and MS Band 2 through provided API. It maintained the connection for the duration of the whole experiment, and generated proper data files (CSV). The main problems that occurred during the experiments were related to the fact that the devices require special configuration, including repeated pairing attempts before the connection takes place. However, these problems are beyond the scope of BandReader, and are related to the API implementation.

Currently *BandReader* effectively implements the core part of the requirements we have formulated (see Sect. IV). The application has modular architecture that can be easily extended (Req. 1). It allows for saving the raw data (Req. 8) from all available sensors (Req. 2) to standard CSV files (Req. 6). These recording may be done in parallel for many devices at once (Req. 3). The application also gives user a possibility to specify the file names by providing identifiers of subjects as well as a possibility to add arbitrary tags to data (Req. 5). It can be then concluded that BandReader is a suitable tool for AfC applications, and our aim – which was to develop a tool for affective physiological data acquisition and storage – seems to be achieved.

VI. Related Research

To date, several other studies involving wearable devices for affective computing applications have been conducted. These regard either general overviews of sensors currently available on the market [13, 14, 15, 16, 17], comparative validation between wearables and medical-quality platforms [18, 19, 20] or actual original experiments involving, for example, emotion detection or recognition [18, 21, 22, 23, 14, 24]. It is notable that some attempts of designing and developing custom measuring devices worn on wrists are made [24, 25, 20].

In this article's context, namely the dedicated data recording software, it seems that not every research group considered this issue, since usually information about this matter is lacking in the respective papers [17, 25, 19, 24, 26, 21, 15]. Often either, official producer's applications are used [13, 23], or custom-developed sensor is followed by custom data collecting software [18, 20]. A notable exception is provided by [14], who used their custom program for real-time signal preview from Empatica E4 Wristband, LG Watch Style and Zephyr Bioharness Module. In the light of our state-of-art analysis, we conclude that our application addresses an important niche and successfully provides reliable tool for data recording and storage from existing off-the-shelf wearable devices. What is more, as our software is an Android application, it finely fits into the current trend of mobile and ubiquitous computing.

VII. Conclusions and Future Work

The objective of this paper was to present a new prototype software application *Bandreader* for affective computing experiments. In our work, we are planning the development of ubiquitous computing systems. As such, we are focusing on the use of mobile devices for data storage and processing and wearable devices for proving practical measurmenets of biomedical signals. In the paper we present an overview of the devices currently available on the market, which allowed us for selecting the ones most suitable for our work. We provided the description of the design and implementation of the application, as well as results of practical evaluation of its operation in our experiments.

As of future work, the application will be extended to support the third device: Scosche Rhythm+ wristband. In addition, implementation of synchronization with the use of Lab Stream Layer is planned. This library provides high accuracy methods for combining the data streams from various devices in local network. It will be primarily used to synchronize the data from variuos recording devices (smartphones, PCs and laptops) in conducted experiments (see also Req. 4). Finally, to support current (see Section iii) and future AfC use cases, broadcasting mechanism will be implemented (see also Req. 7). As a result, BandReader will be considered a middle layer that gathers data from devices and provides the streams to other applications, like music recommendations system mentioned before.

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