Implementation of the Smartphone Based Biofeedback Application

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Abstract—**Biofeedback applications can prove useful in many areas of human activity. For example, with a system for motion tracking and the use of biofeedback one can be guided to learn the proper movement or informed of its improper execution. This could be especially useful in sports and rehabilitation. In a biofeedback system the feedback information is communicated back to the user, preferably in real time, through one of the human senses: sight, touch, and hearing. The implemented movement tracking biofeedback system requires: inertial sensor(s), a processing device and a biofeedback device. Today smartphones are readily available and more often than not include inertial sensors. The development of a smartphone based biofeedback application is therefore a logical step. The developed application tracks head movements during the execution of the golf swing. Improper head movements are detected and communicated back to the user in real time in a form of audio signals. The user acts on received biofeedback signals trying to correct the improper movement. Extensive measurements and tests were performed to confirm the correct and accurate operation of the application. The usefulness and advantages of real-time biofeedback during the golf swing execution were identified. Golf players with excessive and improper head movements considerably improved their performance after the inclusion of the biofeedback. We believe that such biofeedback systems are applicable to similar examples in sport, fitness, healthcare, and other areas of activity.**

I. Introduction

Biofeedback can be very useful in sports, rehabilitation, and other human activities. In sports and rehabilitation one can learn the proper movements with the help of biofeedback. For instance, the biofeedback can be used to direct or instruct the user to properly perform the movement or alert the user in case of improper movement execution. For the movement analysis a motion tracking system is necessary. A motion tracking system can be based upon different technologies; some examples being: video recordings, optical tracking system, and a system with inertial sensors.

Biofeedback can be applied in real time, during the movement execution, or out of the real time, after the movement has been completed. The example of the latter is the inspection of the recorded video of the performed movement or the post processing of recorded sensor signals as in [3]. The interruptions caused by the non-real-time biofeedback slow down the movement learning process. A better choice is the use of the real-time biofeedback where the feedback information is communicated to the user during the movement execution.

Several channels corresponding to human senses can be used for the biofeedback: visual, tactile, and auditory. The visual channel holds the most information, but it requires high cognitive load and it has relatively high reactive time. The tactile channel has lower reactive time, but it can be irritating or even painful for the user and relatively difficult to implement. The auditory channel has low cognitive load, low reaction time and it is relatively easy to implement.

Nowadays smartphones are readily available, wide-spread technology and in many countries the penetration of smartphones has exceeded 50% in 2014 [1]. The majority of smartphones include inertial sensors that are used for a number of mostly simple applications. We chose smartphone inertial sensors to build a biofeedback system that tracks user movements, detect deviations from the expected positions, and communicate the possible movement errors in real time to the users through the auditory channel.

The use of smartphone inertial sensors for motion tracking is limited due to their relatively low quality which is expressed through the imprecision of sensor signals [4]-[7]. While the position deviation in short-time tracking may be small enough to be neglected, the deviation for long-time tracking is most often too large to be disregarded. One of the motivations for this work is the determination of the usability of inexpensive inertial sensors integrated into today's smartphones for the implementation of a real-time biofeedback application.

The biofeedback application for head movement tracking in golf was developed. Tests on several groups of golf players were conducted. The test show that real-time biofeedback speeds up the correct movement learning process.

This paper is organized as follows. In section II we give the definition of a biofeedback system, explain its building blocks and its functionality. We continue with the demonstration of the biofeedback system operation, the explanation of its versions that are suitable for our application, and the discussion of the most appropriate user interfaces. Section III presents the biofeedback application, its demands, constraints, building blocks, configurations, and user interfaces. In section IV we present the results of application test and biofeedback experiments. We conclude with section V.

II. Biofeedback System

In a *biofeedback* system a person has attached sensors for measuring body functions and parameters (*bio*). Sensors are connected to a computer or any other device

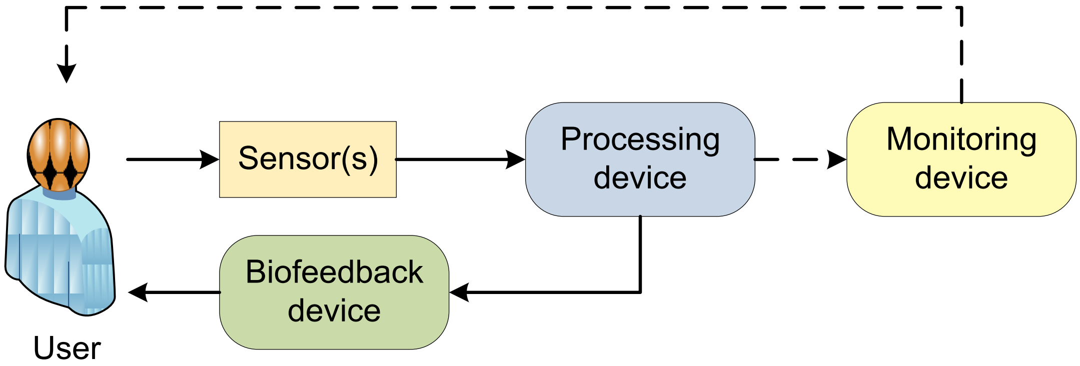

Figure 1. An example of a compact version of the biofeedback system. All system devices are at the user location, therefore the real time operation of the biofeedback loop is not a problem. Monitoring device is not mandatory; it is generally used for reviewing the results.

for analyzing data. Results are communicated back to the person (*feedback*) through one of the human senses (i.e. sight, hearing, touch) [2]. The person tries to act on the received information in order to change the body function or parameter in the desired way. The term biofeedback is frequently described in the connection with physiological processes; in this paper we use it in the connection with the body activity in the sense of physical movement. We use inertial sensors to detect the body movement, processing devices to analyze sensor data, and audio signals for the (bio)feedback.

In general, our biofeedback system consists of several different autonomous devices which are interconnected through wireless communication channels. The primary system tasks are: real-time movement tracking and, in connection with the later, real-time biofeedback.

A. System building blocks

In general a biofeedback system requires: inertial sensor(s), a processing device, biofeedback device(s), a monitoring device (optional), and in the majority of versions also wireless communication channel(s).

Inertial sensors (accelerometers and gyroscopes) are the essential part of the system, which is designed to work with one or multiple autonomous sensor devices. *Processing device* is the core of the system. It receives inertial sensor signals, analyzes them in real time, and when needed, it generates and sends feedback signals to biofeedback devices in real time. *Biofeedback device* employs our senses to communicate feedback information to the user. Commonly used senses are: hearing, sight, and touch. In our system we use audio feedback devices such as loudspeakers and headphones. *Monitoring device* is optional. It is used to monitor sensor signals and analysis results. The monitoring can take place in real time or as a post experimental results analysis. *Communication channels* enable the communication between the system devices. While wireless communication technologies are most commonly used, wired technologies can also be practical; for instance to send a feedback signal from the body-attached processing device (i.e. smartphone) to the nearby headphones.

B. System operation

The generalized operation of the biofeedback system, composed of the above described building blocks, is shown in Fig. 1. Sensor(s) continuously send inertial signals to a processing device for analysis. The activity of the biofeedback device and thus the activity of the feedback loop depend mostly on the analysis results. The basic loop operation modes are:

- *standby*: the processing device is continuously analyzing sensor signals, but a biofeedback signal is not generated; the feedback loop remains open,
- *user guidance*: the biofeedback signal is constantly generated to guide the user to perform a certain movement or to assume a certain position; the loop is constantly closed and the user is expected to react to the biofeedback signal in real time,
- *error detection*: the biofeedback signal is generated only when the system detects an improper movement; the loop is closed for shorter time periods and the user is less likely to be able to react in real time.

C. System versions

Two basic versions of the presented biofeedback system are distinguished: the *compact* version, where all the system devices are attached to the user, and the *distributed* version, where some of the system devices are at a remote location, away from the user. For example, in the distributed version the processing device and the monitoring device from Fig. 1 are at the remote location, sensor(s) and the biofeedback device are at the user. All devices in both locations are typically interconnected through wireless communication channels.

In the compact version of the system the biofeedback loop is located at the user; hence the real-time operation is not compromised due to the communication channel latencies. In the distributed version the biofeedback loop is distributed between the user and the remote location. To assure the real-time operation of the loop, the distributed version of the system must use low-latency communication channels and is essentially bound to the areas of limited extent.

Smartphones can be used in both biofeedback system versions. In the compact version the smartphone is attached to the body of the user and provides functions of all system devices: integrated inertial sensor(s), processing power, monitoring device (screen), and biofeedback device (speakers). In the distributed version the phone’s wireless communication interfaces are used to connect to the remote devices.

D. User interface(s)

Different versions of the system commonly have different user interfaces. For instance, in the distributed versions of the system the interface is divided between the user and the remote location. Since users are performing movements, they generally do not have the possibility to control the operation of the system by using standard interfaces; therefore the operation of the system is best driven by user gestures. Gestures are defined by user's body movements and detected through their characteristic inertial sensors responses. Each biofeedback application has its unique set of gestures that are adapted to its movement patterns. Details about the gesture user interface developed for our application are found later in the text.

III. Real-time Biofeedback Application

Based on the biofeedback system presented above the real-time biofeedback application for golf was developed and implemented. The main functionality of the application is real-time golf swing analysis with real-time audio biofeedback depending on golfer's head movements.

A. Basic application idea

Our basic application idea is to monitor the player's head movements during the golf swing. The idea is grounded on the hypothesis, that wrong movement patterns in the golf swing many times lead to distinct unwanted head movements. Consequently, head movements are very often the indicator of the incorrect golf swing execution. Our hypothesis is backed-up by observing the world's best golf players and their advices [8] and [9]. The majority of them are keeping their heads practically still; hence our biofeedback idea is: "golfers head should stay still during the swing execution". Therefore, the application is developed to detect excessive incorrect head movements and communicate them to the user in real time using the audio feedback.

B. Application demands and constraints

The most important demands are the real-time operation of the biofeedback loop and the implementation of a non-distracting user interface.

One of the constraints faced by the system is the inaccuracy of sensor signals, that primarily limit the time frame of the analysis and puts the movement detection repeatability under question. Typical duration of the golf swing is around 2 seconds [10]. The authors in [11] state that by using the uncompensated sensor signals of the iPhone 4 smartphone the derived angle and position errors are 1 deg/s and 19 cm after the first second respectively.

Apart from the above mentioned demands and constraints that must be met by the application, there are functionalities that are not binding, but may contribute greatly to the overall usability and user experience of the application. Some, but by no means the only such functionalities, are the ease of use (connected to the user interface and the application design) and the possibility of post processing of the data collected by recording of swings.

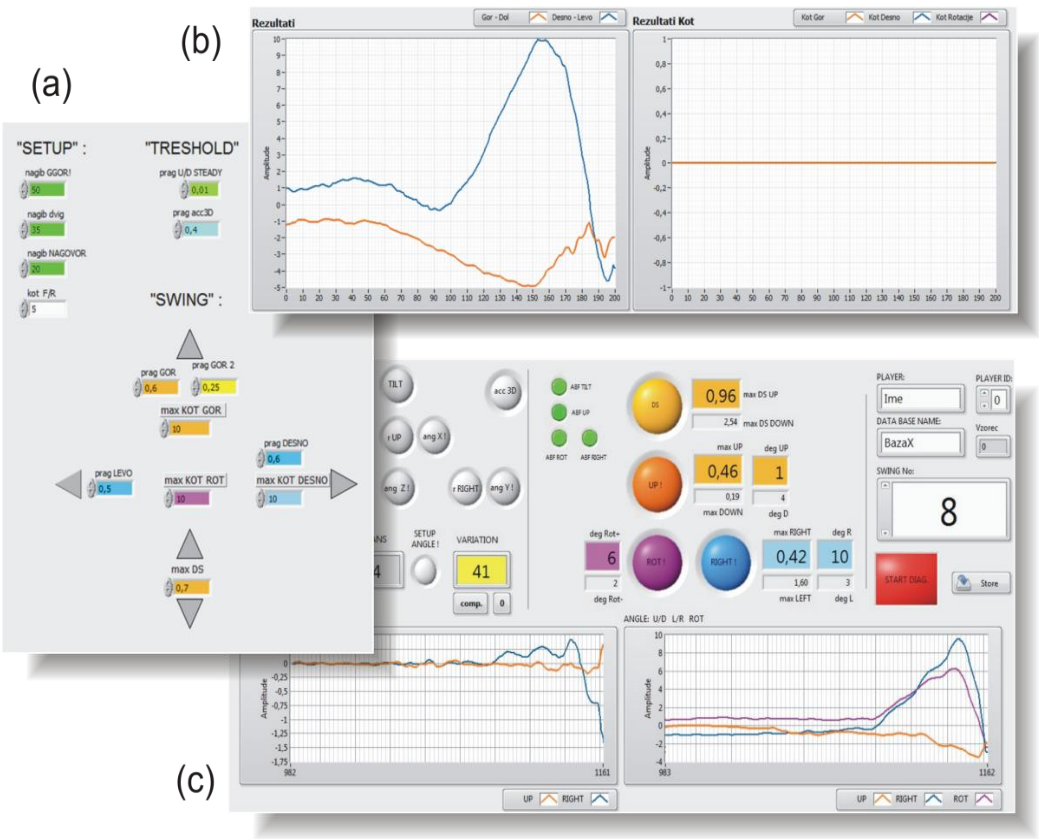

Figure 2. A graphical part of the user interface with keyboard and mouse as input devices. The application is controlled through several windows or tabs such as: (a) settings, (b) swing history, (c) real-time signal monitoring and system states.

C. *Application building blocks and configuration*

For practicality, we first developed a distributed version of the biofeedback system (see section II.C). In this version the biofeedback loop is distributed between the user and the remote location. Inertial sensors and the biofeedback device are attached to the user's head, the processing and monitoring devices are at the remote location. The devices on both locations are connected through low-latency wireless channels.

The application uses the inertial sensors integrated into the iPhone 4 smartphone, which is attached to the head of the golf player. With the appropriate attachment of the smartphone to the head of the golf player we achieve very good repeatability of detection of different 3D head movement measured from the static start position at the swing setup.

A laptop is used for the processing device. The laptop must be on the location which is in the range of a local wireless network used for the transfer of sensor data from the smartphone to the laptop. The application is designed in the LabVIEW™ development environment and is able to run on any compatible MS Windows operating system.

Headphones are used for the audio biofeedback device. They are wirelessly connected to the laptop. The audio feedback signal is generated by the laptop and sent to the headphones over the RF-ISM channel.

D. *User interface*

Our application implements a hybrid user interface comprised of a graphic user interface for controlling the application on the laptop and a gesture user interface for controlling the application during the execution of the swing. Both interfaces work simultaneously.

The graphical user interface runs on the laptop and allows the complete access and control of the application and its functionality at all times. Fig. 2 shows the graphical user interface and some application windows.

The gesture driven user interface greatly eases the application usage; it allows the user to fully concentrate on the swing itself, and not on controlling the operation of the application. The application and its gesture user interface (GeUI) are able to detect different golf shot stages and swing phases. For instance; gesture user interface helps users to take the correct swing setup position.

The indispensible parts of the user interface are the characteristic audio signals. They give the user the information about the application states and transitions between them, they inform the user that the application is ready for the swing; they signal errors to the user, etc.

E. *Real-time signal analysis*

During the golf swing training, the user should be focused primarily on the swing execution and the possible acoustic feedback signals. To alleviate the user's interaction with the application at the times of training the GeUI was developed. The application also includes a window with abundant data and information about the swing, which are simultaneously shown in numerous diagrams, error indicators, peak value detectors as shown in Fig. 2. The user can review them after the swing. If needed, the user can modify the application parameters between each swing.

IV. Results of Application Test and Biofeedback Experiment

We present the most significant results of numerous measurements and experiments aimed at:

- testing the correct and precise application operation,
- usability of real-time biofeedback for the correction of errors during the performance of a golf swing.

A. *Application test*

During the application test we focused primarily on: (a) correct detection of application states and transitions between them, and (b) precision of sensor signals and the derived analysis results.

The application test stage includes the recording of golf swings performed by a professional golf player with a very consistent swing execution in terms of movement repeatability. We have recorded all of the performed swings without any selection. The results are shown in Fig. 3 and they confirm the following:

- The correct detection of application states and the transitions between them. This is evident from the time alignment of the signal peaks.
- The sufficient precision of sensor signals. This is evident from almost perfect alignment of curves representing the swings and their identical shape. We can observe that all the curves begin (takeaway swing phase) precisely at rotation angle zero and deviate for less than a few degrees throughout the swing.

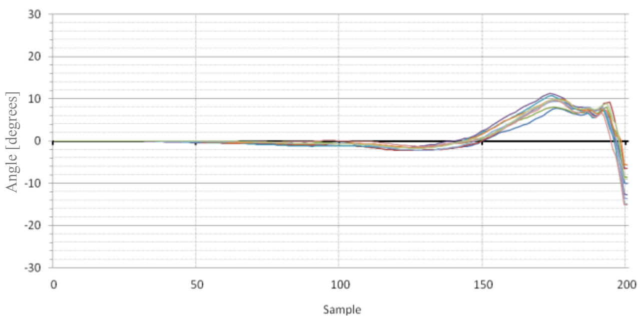

Figure 3. Series of swings performed by a professional golf player. Curves shows head rotation angle in degrees in the Left/Right (+/-) direction for the last 200 samples of the swing. The sample frequency is 60 Hz, head rotation to the left yields positive angle values. We observe that the head movement is very consistent for all executed swings

From the results in Fig 3. it can be concluded that the application works correctly and that the precision of the sensor signals is high enough for the analysis of the required quality. The acquired records of the professional golf player also serve as the source and model for setting the threshold values for triggering and state signals used by the application.

B. *Biofeedback experiment*

In the biofeedback experiment we close the biofeedback loop by activating the biofeedback signals. Head movements exceeding defined thresholds are treated as errors and are communicated to the user in real time, during the entire execution of the swing. The biofeedback signal in the application is a binary acoustic signal (beep).

When users are aware of the cause of their swing errors, they can easily understand the biofeedback signals and consequently act on them. The application allows that the biofeedback is triggered at different combinations of available head movement signals. To prove this concept we conducted a series of experiments that would show that using the real-time audio biofeedback could help golf players with inconsistent swing correct their unwanted excessive head movements and hence improve their swing consistency and performance.

Fig 4. shows the results for the beginner player that excessively moves the head during the execution of the swing. The curves represent the average head rotation speed in the left/right direction calculated from the series of twenty swings. The dashed line represents the average for swings without the (audio) biofeedback, meaning that the player performed the swings without the notifications about the detected errors. The head rotation speed error threshold was set to the signal value ±0.15 rad/s. It can be noticed that the player considerably exceeds the set thresholds. After switching the biofeedback signals on, the player performed another series of twenty swings. Their average is represented by the solid line. It is evident that the biofeedback considerably helped the player. The left/right head movement has been almost eliminated.

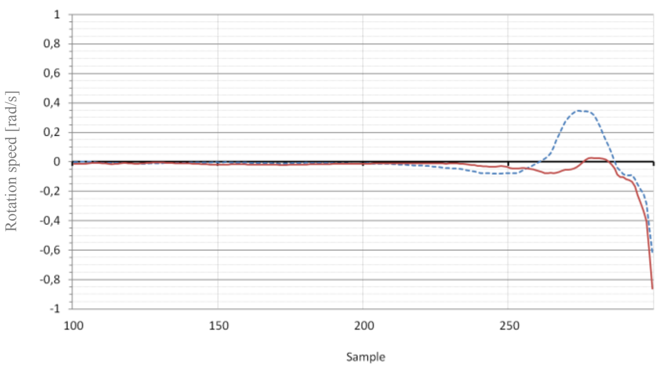

Figure 4. The benefit of biofeedback for a beginner golf player. The graph shows the comparison of player's head rotation speed [rad/s] in the Left/Right (+/-) direction without the biofeedback (dashed line) and with the biofeedback (solid line). Curves represent the averages calculated from twenty swings performed without the biofeedback and twenty swings performed with the biofeedback.

We must emphasize that the above are only the preliminary results of biofeedback experiments conducted on a limited population. The results were primarily gathered for the purpose of application test and the test of the biofeedback loop operation. More extensive experiments are required to prove the usability of such systems in sports, rehabilitation and other possible areas of use. What surprised us is the fact that the learning process was even faster than anticipated. At this point we do not wish to speculate about the movement learning process or corrections mechanisms with the aid of biofeedback. To prove the usefulness and benefits of biofeedback more extensive experiments and analysis are required, which will incorporate both: the objective measures (signals) and subjective measures (user opinion).

V. Conclusion

This work shows that the existing smartphones with their built-in inertial sensors can be used for short-time movement analysis in real-time biofeedback systems.

For the implementation of the test biofeedback system we chose golf. We developed the application that uses audio feedback for the correction of golf swing in real time. We also developed a hands free gesture user interface for the user. We are convinced that the gesture user interface is an indispensable element of the biofeedback system, because it alleviates user's interaction with the system.

Field experiments show that our application is an efficient tool for the correction of the head movement errors, especially for beginner players having problems with swing consistency.

The next challenge and the logical step forward is the implementation of the compact version of the biofeedback system. The compact version runs entirely on the smartphone without the need for a separate external processing device and without the need of wireless communication channels.

While we have tested our biofeedback application on the golf swing example, we believe that such biofeedback systems are applicable to similar examples in sport, fitness, healthcare, and other areas.

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