WEARABLE MULTI-MODAL SENSOR SYSTEM FOR EMBEDDED AUDIO-HAPTIC FEEDBACK

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ABSTRACT

Wearable sensing technologies give the user the possibility of on-site and real-time measurements, analysis and feedback of movements and postures in everyday behavior, learning and training situations. There are many established motion capturing technologies to support complex movements, but less mobile and wearable systems. One of the key disadvantages of the existing systems is their high complexity, for instance they demand high-speed cameras, multi-channel audio systems or the integration into a special room or laboratory. This paper presents a low cost and easily relocatable sensor-based system for motion capturing and multi-modal real-time feedback. Our system is easy to use, it even allows operation without an external computer. Here we introduce our wearable sensor-setup and outline its applications and benefits in typical everyday training situations in combination with multi-modal feedback and embedded systems including closed loop interactive sonification.

1. INTRODUCTION

This project presents wearable sensing, embedded sonification, and vibrotactiles integrated in one device and first applications. It is a new approach and method for movement and posture measurements in 3D-space. The system provides real-time feedback in an acoustic and tactile form by means of closed-loop interactive sonification according to Hermann [1] and haptic feedback. Information is conveyed acoustically as well as haptically and by useful combinations of both. The presented wearable device is simple and robust and very cheap compared to visual screens, projectors, multi-channel audio systems on the output side or video cameras and microphones on the input side. Furthermore it is easy to use and install. The devices can be cascaded to a complex system e.g. attached to different body parts or more than one person. Sound and haptics in combination are promising real-time feedback methods, without or in addition to visual feedback. In combination with data processing methods, either using external computers or integrated directly into the wearable multi- sensor devices, new possibilities for research in motion capturing, human communication and manual learning are opened that do not demand complicated external cameras or CAVEs. The lightweight and wearability of our system allows unhindered movements in 3D space and enables applications in many fields, such as sports, arts and multi media to name a few. Our technology has been first demonstrated in haptic augmentations and sonifications for applications for musicians by Grosshauser et al. [2] and [3], since it (a) doesn't affect the visual sense, (b) doesn't disturb in bang sensitive situations such as concerts, (c) allows to relate feedback information in the tactile and acoustic medium, so that often neglected but important feedback possibilities are extended and trained supportive. Even more, external instructions from the teacher, trainer and the computer or other users can be transmitted directly and unobtrusively in these channels.

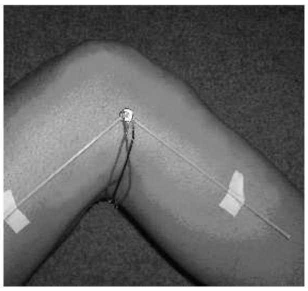

Figure 1: Flexed knee with goniometer

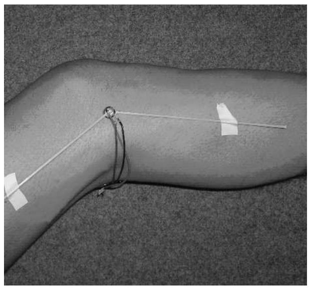

Figure 2: Stretched knee with goniometer

2. DESCRIPTION OF THE SETUP OF THE WEARABLE DEVICES

Our wearable sensor setup in the field of dance is similar to our previous work described in [4] but here the system is not tool-integrated and consists not only of a 5 degrees-of-freedom (DOF) sensor, meaning 3 axis acceleration sensors and 2 axis gyroscopes but also of different goniometers (see fig. 1 and 2), shoe integrated foot switches (see fig. 3) and flex sensors.

2.1. Sensor Setup

Here an easily relocatable flexible sensor based system is presented. Simple usage, with or without the need of an external computer is possible. In this contribution different sensor types will be presented, to show the possibilities and usage in typical everyday training situations. One is a standard 5-Dof board, in combination with foot switches integrated into shoes to scan the contact and weight distribution of the feet and e.g. "losing the contact" while jumping. The other is a wearable flexible goniometer-based sensor system for measuring joint angles and bending sensors to measure flexion. Both systems can be fixed simple and situational on the body of the dancer and adapted to special training situations and problem statements. Due to the higher scanning frequencies of the sensors compared to most visual sensing based approaches, such as for instance fast movements like jumps or even pirouettes can be examined at high accuracy.

Goniometers with a potentiometer are used for joint angle measuring (see fig. 1 and 2). This is a very precise, cheap sensor and easy to fix and install. It can be fixed directly on the body or into the clothing, depending on how precise the measurement has to be.

An IDG-300 dual-axis angular rate gyroscope from InvenSense is used. This allows the measurement of the rotation of the x- and y-axis. The ADXL330 acceleration sensor from InvenSense is used, a small, thin, low power, complete x-, y-, and z-axis accelerometer. According to the following description, every axis is important and has it's own defined plane, in which the movement is performed. Thinking in planes and rotations helps to learn complex movements, especially when the movement takes place beside or behind your body and where you can hardly see it. In this case the visual control is replaced or supported by the acoustical control.

Several approaches of sensors in shoes and soles exist, mostly for medical observations and gait analysis like Kong et al. [5], Bamber et al. [6] and Huang et al. [7]. In this paper, two insole soft pad switches in each shoe are used for simple foot position and movement detection. Especially for jumps it is important to know, when the feet leave the floor. This allows e.g. in combination with the knee angle and accelerometer values exact motion sonification and real-time movement synchronization analysis by ear.

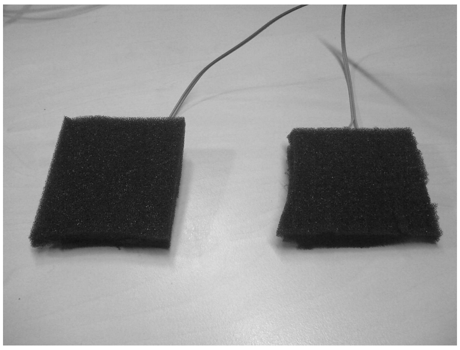

Figure 3: *Insole soft pad switches*

Bending sensors (see fig. 4) are used to detect posture, especially of the back. They can be fixed directly to the skin or integrated into clothing. In our case, it is integrated into a t-shirt.

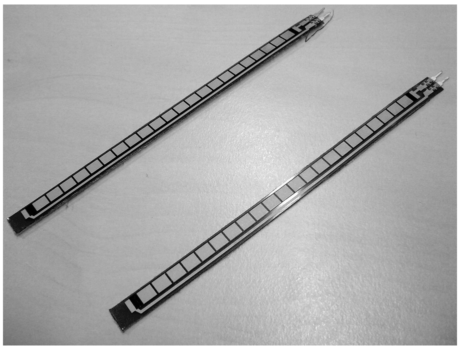

Figure 4: *Bending sensors*

In Sec. 4. we describe two applications to demonstrate the use of the wearable audio-haptic and sonified feedback. Audio-haptic feedback supports the every-day surveillance by significant notifications in real-time and the every-day practicing situations, showing a new way and possibilities of human to machine communication. Besides these scenarios many other possibilities in the area of instrumental music or sports are possible.

2.2. Hardware Setup

The basic setup is realized with an Arduino Nano, fitted with an Atmel Atmega328 micro controller with 14 Digital I/O Pins (of which 6 provide PWM output) and 8 analog Input Pins. The dimension is 0.73" x 1.70", (1,8 X 2,5cm) allows a small form factor and makes wearabilty easy (see fig. 5).

Figure 5: *Wearable PCB with loudspeaker*

2.2.1. Data transfer and Battery

The data from the sensors are transmitted via radio frequency. A small Lithium Polymer (LiPo) battery is directly attached for power supply. The H-Bridge is an integrated electronic circuit, to apply a voltage to the vibration motors and changes the speed. Increased speed implies more urgency and attention of the user, lower speed feels more soft.

2.2.2. Pulse-Width Modulation, digital to analog conversion and amplification

For audio out, the Pulse-Width Modulation (PWM) outs are used (see fig. 6). Pulse-width modulation uses a rectangular pulse wave whose pulse width is modulated resulting in the variation of the average value of the waveform. A standard digital to analog converter circuit from [8] is used to receive the analog voltage. This voltage is amplified with a transistor to drive the loudspeaker

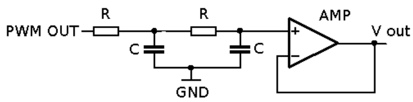

Figure 6: *Digital analog converter with amplifier*

2.2.3. Loudspeakers

One or more small speakers are used for audio out. The frequency range is quite small but the sensitivity of the human ears in the frequency range is high. It means, the sounds are good to hear and easy to locate, but the sound quality is quite bad, caused by the small housing and form factor of the loudspeakers, only 4mm hight and 23mm diameter.

3. CLOSED LOOP FEEDBACK DESIGN

3.1. Sonification and Sound Synthesis

Different sound synthesis models in the area of music technology exist to generate sound and music. Beside the analog sound synthesis, various digital synthesis methods exist. The most common and simple ones are subtractive, additive and frequency modulation synthesis. Further synthesis methods are granular-, wave table-, phase distortion, sample-based and physical modeling synthesis.

In this paper, the embedded synthesizer (see scheme fig. 7) is using granular synthesis similar to [9], which works on the microsound time scale. Granular synthesis is often used sample based and in analog technology. Samples are split in small pieces of around 1 to 50 ms in length. The wearable embedded synthesizer uses oscillators instead of samples and multiple grains of these are layered on top of each other all playing at various speed, phase, volume, and pitch. Most parameters can be influenced with sensor input, so the scope of design is manifold.

The result is no single tone, but a complex sound, that is subject to manipulation with our sensors and switches and the produced sounds are unlike most other synthesis techniques. By varying the waveform, envelope, duration, and density of the grains many different sounds can be produced.

3.2. Wearable Embedded Sonification

Our integrated and wearable devices have at least one built-in loudspeaker. If acoustical feedback occurs, the position in the 3D-space is automatically given through the sound emitted by the device. In result, no complex pointers or 2D or 3D-sound technologies are necessary to point to the relevant position. The spatial hearing of the humans allows exact and fast location of the sound source itself, without having to turn the head or to change any corporal position. Figuratively, every device is a moving sound source, meeting the human habit of hearing and reacting to noises and sounds in everyday life. The directional characteristic of the built in loudspeakers allows even the acoustical recognition of the gyration e.g. of the wrist, which would hardly be possible to simulate in virtual sound environments.

3.3. The Basic Sonification Modes

We discern two different sonification types according to the directness of auditory feedback.

1. Continuous Sonification: This method allows the continuous control of a movement or parts of it in real-time. The "shaping of a figure" is translated directly into a sound feedback. Especially the filter-like sound composition allows manifold sounds.
2. Case-Triggered Sonification: This means, the sound only appears, if a certain problem or deviation appears. The sonification can be changed and turned on and off manually, so the users have permanent control. This allows the individual assignment of a specific sound or sound effect to each sensor or condition, or to group useful sensor combinations.

3.4. Multi Channel versus Direct Dound

Compared to existing standard audio setups, especially multi channel systems, the described wearable device is very simple, but very easy locatable in the 3D listening space. A simple example is, if you try to locate an alarm clock just by hearing the alarm, you know exactly, where it is and from which direction the sound appears. On the other hand, finding the exact position of a sound source in a stereo or multi channel sound field, is much more difficult and dependent of the position of the listener. If there are more than one persons, trying to describe the exact position of the same source, it is already nearly impossible. If you perform this tasks with headphones, it is easier, but usually headphones are not applicable in many situations.

More advanced technologies like 3D Audio, Spatial Audio, and WFS systems improve partly the stability of the sound source, but again, the complexity and form factor of the equipment does not fit into the idea of a new, unobtrusive wearable interface.

The developed device can not only be fitted with more loudspeakers for multi channel audio out, even more than one wearable device itself can be fixed on the body or clothes. In this case, more different sounds from more directions can be provided and produce interesting soundscapes. This multi channel data triggered and 3D spatial information are not only the movement and position of a hand even more the rotation and the distance between two or more loudspeakers and sensor nodes.

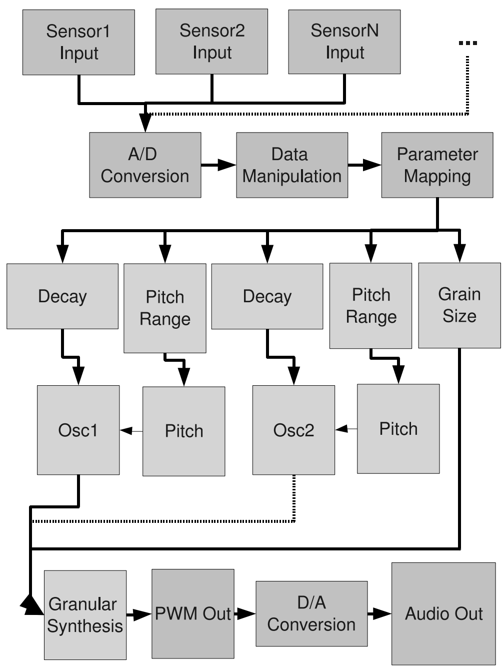

Figure 7: *Synthesizer scheme*

3.5. Vibro-Tactile Feedback

The vibrations are short rhythmic bursts between 40Hz and 800Hz, which is the sensitive range of the mechanoreceptors of the skin. The amplitude and frequency can be varied independently. This allows to evoke more or less attention to specific body parts. The vibration motor with the dimensions 5 x 15mm, lightweight and cylindric shape seemed to be the best compromise. Furthermore, this kind of motor is typically used in mobile phones and is easy available for around 1 euro. Suitable vibration frequencies are around 250 Hz, since fingers and skin are most sensitive to these frequencies, according to Marshall (see [10]).

The main goal was the mounting of the sensors, battery, radio frequency transmission module and the vibration motors on the little free areas of the basic platform of the device.

The second important point was the placement of the vibration motors without generating hearable vibrations or distortion. Fixation e. g. near the wrist came up to our expectations of an unobtrusive, everyday usage without influencing the movements, postures and gestures.

3.6. Listening with the Skin

The awareness of tactile feedback on the skin depends on several parameters. The distance between the two motors is big enough for easy identification which one is vibrating. The amplitude and frequency can be varied independently. This allows to evoke more or less attention, increasing and decreasing of the vibration and at least 4 significant combinations between the two motors: (1) both motors on, (2) motor 1 on, motor 2 off, (3) motor 2 on and motor 1 off and (4) both motors off. As described by Bird et al. [11] the touch-sense feedback channel is extended and the awareness of the vibrotactile feedback is increased and trained.

3.7. Recommender System

One challenge is to move the arm in constant speed along a straight line in 3D space. Such a task is enormously complex without any feedback. However, if the hand would be in contact with a wire under tension along the direction, the tactile feedback emitted to the hand would easily enable the hand to move along the line. The tactile feedback provides a guidance along which the hand can orient its movement. Obviously, feedback facilitates greatly the performance under such constraints. For the case of dance, a feedback of similar type can be implemented by triggering haptic feedback whenever a corridor of acceptable behavior is left.

For instance, a tactile burst can be switched on whenever the orientation deviates more than a given threshold, for each direction in space via different tactile feedback frequency or tactile actuator. The corridor could even be adjusted to be at 75% of the standard deviation in performance over the past 5 minutes. In doing so, both the progress is measured, and the system adapts to the performance of the pupil. It could also be quite motivating for a pupil to see such objective progress analysis over time.

4. APPLICATIONS

The idea was to get a 3D audio feedback in the most easy but realistic, precise and useful way. In the end, the user and performer should be able to set up the device alone, without the support of a technician. This will help to increase the acceptance of this new technologies and methods. In the following, two applications are described for dancing and every-day posture recognition and the prevention of slouching.

4.1. Dance, Ballet and Gymnastics

As dancers are used to coordinate to music, sound and rhythm, sonification in this case can depict complex dependencies between action and reaction. Accordingly these dependencies can be understood easier through listening. Examples of dance training and learning scenarios for teacher to student or self assessment and analysis for dance motor skill learning are developed.

4.2. Dance

The device provides feedback, e.g. if a certain point or posture is reached. This means a simple way of controlling the quality of the exercise or the right strength of stretching. The most reliable data in fast motion scenarios and jumps are the goniometer data. The calculated data of the accelerometers and the gyroscopes still have a certain drift and an infeasible repeat accuracy. The professional system of XSense is expensive, too large housings, and not flexible enough, especially if additional sensors are needed. The 6-DOF Board is used for tilt detection and acceleration measurements of jumps.

This measuring method also allows dancers extensive "offline" analysis of their movements, if the sensor data are saved. Sonified variations of body parts and joints, different trails with several changes of certain parameters, positive and negative progress and dependencies between all of them are shown and sonified. Audio feedback of different trials for professional dancers in an auditory form will provide more possibilities in the future.

5. CONCLUSION

The audio-haptic feedback possibilities of our wearable sensor setup promises that changes in movement - here in 3D-space - can be signaled unobtrusively and quite intuitively using combined or discrete haptic and audio signals as indexical and information carrying sign. Even real-time correction or an overdone correction can be shown.

Sonic Interaction Design can not be considered in isolation but needs to address the whole repertoire of interfaces and feedback channels available. For that end we presented a multi-modal audio-haptic integrated embedded wearable sensor/actuator platform to support human activity for many possible applications. The described way of the integration of many sensors and output possibilities are expected to have a positive effect in many learning scenarios and multi-sensorial perception. The feedback helps to understand quite intuitively, how a special and complex movement is executed and trained. Further developments in augmenting both areas, the sensor and the feedback side, will show how learning processes can be improved and adapted to situated demands in everyday life situations. Especially the wrist-mounted device with the multi-modal feedback and multi sensory input is adaptable to different scenarios such as in sports, music and dance, games and many more.

6. ACKNOWLEDGEMENT

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