# Swimmers in the Loop: sensing moving water masses for an auditory biofeedback system

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***Abstract*—Auditory biofeedback systems in the field of sports are increasingly adopted to provide an online guidance to the people performing actions. This paper concentrates on swimming and on producing auditory feedback intended to enhance the perception of the interaction between a swimmer's body and the surrounding water masses while swimming. The information is related to the concept of 'feel-for-water', that is a key factor to produce an effective propulsion, through a correct perception of the boundary effects of body and water. The presented system is composed of pressure sensors, plastic tubes ending between the swimmer's hand fingers on the dorsal and palmar side, a microcontroller reading the sensors and sending data to a PC for further processing producing the auditory feedback through interactive sonification. We focus on the system setup and present a simple parameter-mapping sonification design as an example, along with possible extensions of the system and other sonification designs. Finally, we present video and audio examples of the system.**

## I. INTRODUCTION

Swimming is an aquatic activity performed with the primary goal of advancing a body through water. To obtain a propulsion, swimmers use their limbs (mainly hands and feet) to interact with the surrounding water. It is commonly believed that propulsion means to "push away" from water, however such a belief is not correct [1]. In fact, an effective swimming is related to the capability of manipulating the water masses we move through.

In this paper we present a system aimed at providing a feedback to the swimmer about how he or she is interacting with the water. In particular we follow the design principle of human feedback systems described in [2]. Through our system we are able to measure the hydrodynamic pressure and convey information, presented in real-time as sound, about the interaction of the hands and the water. An auditory feedback could improve the training and also provide a novel and more profound coach-athlete communication concerning the perception of water. We are currently investigating to what extent swimmers could benefit from such a system during training sessions. In fact, we already used the system described in this paper as a basis to perform experiments reported in [3]. The present work is geared towards describing in detail how the whole system has been designed and developed. Finally, our goal is to stimulate further research into this multidisciplinary field at the boundaries of bio-mechanics, fluid-dynamics, information engineering, sensors and sound design.

The rest of the paper is organized as follows: Section II briefly defines what we mean by swimming in this work, how we can monitor swimming actions and we provide hints about the relevant factors of an efficient propulsion; Section III introduces the concept of biofeedback along with a description of the most notable feedback loops that are involved in our system; Section IV describes the system design and setup, from a sensors, hardware, software and sound design point of view; Section V illustrates how the user interacts with the system and furthermore discusses the overall system; finally Section VI concludes the paper.

## II. SWIMMING

As mentioned before, swimming is a two-body interaction, namely the interaction of human body and water. Effective swimming is about how to best displace water masses using limbs under the cognitive mental control. Good swimmers are typically characterized by an enhanced level of "feel-for-water" perception. "Feel-for-water" is the ability to perceive how water flows as a consequence of pressure gradients. Indeed swimmers experience a self-induced propulsion originated by their actions, and mediated by the water. This means that – with respect to the "push away" from water idea often used by some trainers – it is actually water motion that causes propulsion. More in particular, propulsion is related to how much energy is transferred from limbs to water.

### *A. Related work on monitoring swimming*

Different research and commercial systems exist that focus on monitoring the execution of swimming actions. Some of them focus on body and limb kinematics while others focus on the interaction of body and water.

*1) Kinematics and kinetics of swimmers:* Stamm et al. [4] assessed how accurately the velocity of a swimmer could be estimated exploiting *inertial* sensor measurements, reporting a high accuracy; Lecoutere and Puers [5] monitored lateral and frontal motion using a head-mounted *accelerometer*; Arellano et al. [6] studied how to improve the starting technique of swimmers using a system composed of a force plate mounted on the starting block and a series of above- and under-water *cameras*; Chakravorti et al. [7] described how to integrate different sensors, such as *accelerometers*, *cameras*, *force plates* into a complete embedded system to monitor swimming; and finally, in [8], Magalhaes et al. present a systematic review of the main existing wearable *inertial* measurement systems for monitoring applications.

*2) Interaction of body and water:* *Aquanex* [9] is a system by which palmar-dorsal pressure-on-hands data can be measured and described as virtual flow forces. Due to the closed structure of the system it is not possible to use it to process the data online, but only to record them for afterwards offline analysis, thus impeding to use the system in an interactive real-time application. Moreover, that system only provides the whole pressure difference $p_{\text{palmar}} - p_{\text{dorsal}}$; *Particle Image Velocimetry* (PIV) is a technique to measure water flow: opaque particles are mixed with the water and a plain horizontal laser ray coupled with a high-speed camera acquires photos. By using computer vision to process the subsequent frames it is then possible to obtain a planar structure of the fluid flow. Several studies, among which [10], have used such an approach to effectively study hand-water interaction. However, even though this method enables deeper insights into what happens in water, this approach is not usable in an interactive environment where the swimmer should be free to move in the pool or in open water. Another possibility is demonstrated by the *Vectrino*, which uses a Doppler effect sensor to measure speed and direction of a flow of water, and which has been successfully used to study the optimal swimming velocity of a yellow kingfish [11]. Finally, in recent years, several studies have exploited the possibilities of computer-aided *simulation of fluid-dynamic* systems, among those [12], which focused in particular on studying the optimal spacing of fingers in human swimming.

### *B. Relevant information in swimming*

Sport swimming is about efficient propulsion in covering a distance in minimum time (*end-effect*) under limited energy reservoir conditions. A mere kinematic analysis of body motion does not explain what swimmers perceive through proprioception, nor is it able to completely describe energy expenditure, even though a number of papers report it [13]. The existence of a correlation between accelerometer signals and energy expenditure has been demonstrated. However, even if the accelerations measured in two different motions are the same, based on the actual interaction of the limbs with the water, the energy transfer to water may differ [1].

Indeed, energy transfer between limbs and water can happen at two levels: through friction or through a significant exchange of kinetic energy, through which water is accelerated whilst the limbs pass through it. Through this exchange of energy the body receives an impulse and the water is charged with energy in the form of pressure and velocity. Excellent swimmers can partly regain this energy (similarly to dolphins and other see animals), in order to increase the efficiency of swimming further. In order to be effective and efficient, this transfer should happen at an optimal speed, flow and pressure field. Sensing and understanding of what happens at the level of flow and pressure will enable a more accurate picture of the actual effects of body motion on water. Finally, it has been proven that the formation of flows of fluid (water) is responsible for the most relevant part of the forward locomotion of swimmers [1].

## III. BIO-FEEDBACK

Biofeedback [14] is a way to provide information about an evaluation of actions performed by users to the users themselves. It can be used to guide, to alert, and to inform.

To better describe the feedback, we refer to the loop depicted in Figure 1. These scheme, common to a broad range of fields, e.g., the brain-computer-interface cycle [15], sport feedback systems [16], and rehabilitation scenarios [17] is as follows: The user executes some actions, e.g., moving limbs, whose execution is monitored and measured through some sensors; the data are preprocessed, features are extracted and then, based on these features and an intended goal, a feedback is generated and presented through some sort of stimulating modality, e.g, visual, auditory or haptic, back to the user, thus closing the cycle.

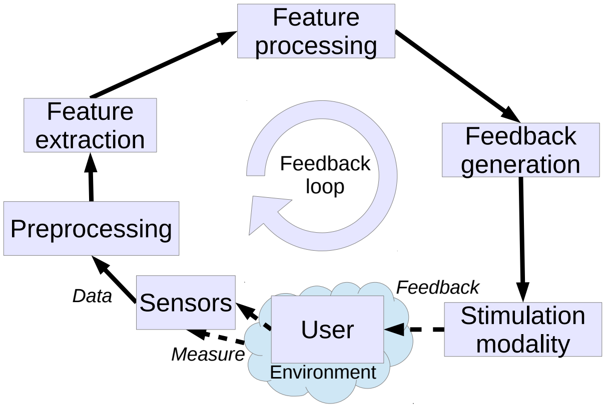


Fig. 1. The feedback loop: the user executes actions that are measured with sensors, these provide data to the preproccesing, feature extraction and feature processing modules, and finally a feedback is generated and provided back to the user through some modality. Adapted from [15].

Human *actions* are responsible for, and can be related to, kinematic changes of their limbs, that on the other hand *cause* intermediate effects, which *influence* the end effects of the actions. Figure 2 describes the three perception loops that are coupled to the three aforementioned levels, namely the *proprioception*, the *perception* and the *evaluation*. An auditory feedback of kinematics, such as the one proposed by Schmitz et al. [18] to study the interrelation of audio and visual stimuli at a neurological level, can be considered as an *immediate effect* level feedback. In contrast, a registration of the time needed to cover a given distance and the production of a feedback for that is associated with the overall *end effect*. On the other hand, by considering flow pressure rather than solely kinematics, the feedback has to be considered as an *intermediate effects* level, because the energy transfer from limbs to water is happening exactly at this intermediate level [19].

In the context of this paper we will specifically exploit mainly auditory feedback at an intermediate effect level. To

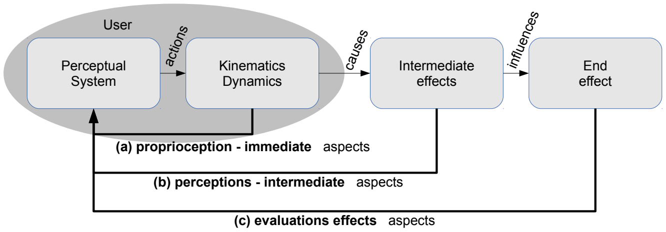


Fig. 2. Different event levels on the route to self-induced locomotion in aquatic space (adapted from [2]).

systematically produce informative sounds we refer to an established technique, namely sonification [20].

## IV. System Design

Considering that we want to focus on the *intermediate*, perceptual effects we will concentrate on fluid dynamic effects for which we need to define the system setup, that will be presented next, while the employed sonification schemes are described in the following subsection.

### *A. Setup*

In order to obtain a system able to measure pressure and to transform that information into sound, we need to find appropriate sensors, choose appropriate components to perform the acquisition of the data from the sensors, and then the equipment needed to produce the real-time feedback for the user. These system's components will be presented next.

*1) Sensors:* To sense the static pressure component of water we use the "piezo-probe" method, which is basically an open hole on a wall over which fluid can flow, as opposed to a "pitot-probe" that is generally used to measure the speed of a flow of fluid, as for instance known from the tube on the nose of air planes to measure the speed relative to air. Figure 3 shows the main difference between these two configurations of pressure probes. Note that the same sensor/transducer could be used to measure either the pressure from the piezo and from the pitot probe. This underlines the importance not only of choosing the transducer, but also, and even more importantly, the choice of the location, type and relative position and orientation of probes with respect to the measured phenomena.

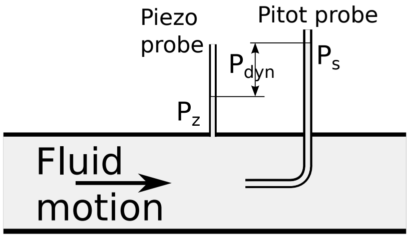
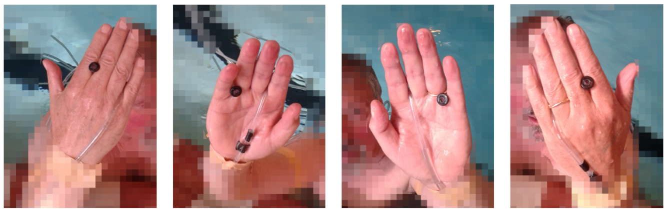


Fig. 3. Piezo and pitot probe principle of working. $\mathrm{P_z}$ is hydro-dynamic pressure, $\mathrm{P_s}$ is stagnation pressure, and $\mathrm{P_{dyn}}$ is dynamic pressure.

To obtain electronic values we use a set of 4 differential pressure transducers, the Freescale MPX5010DP, each attached to a tube with an open end. The open ends are placed as "piezo-probes" between the fingers of the two hands of the swimmers as depicted in Figure 4.



(a) Right dorsal (b) Right palmar (c) Left palmar (d) Left dorsal

Fig. 4. Positioning of the probes on the two hands.

*2) Hardware:* An Arduino Duemilanove board, composed of an Atmel ATMega328 microcontroller, running at $8\ \mathrm{MHz}$, with a specifically self-written firmware, acquires the voltage of the output of the analog transducers Freescale MXP5010. This transducers have been chosen based on their operation range: between $0$ and $10\ \mathrm{kPa}$, equivalent to approximately $0 - 1000\ \mathrm{mm}\ \mathrm{H_2O}$. In fact, the hand will normally go no deeper than $1000\ \mathrm{mm}$ in water. It should be noted that the Freescale MXP5010 sensors are meant for air and gases, and not for liquids. However, water will never get in contact with the membrane of the sensors, thanks to the fact that they reside in a waterproof box, hanging above water level. The overall system architecture is depicted in Figure 5.

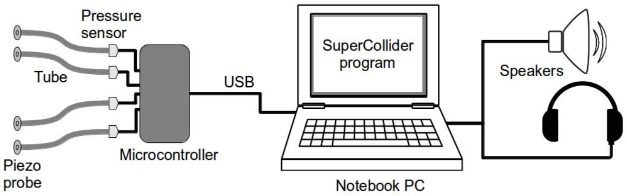


Fig. 5. Scheme of the complete system: probes, tubes, transducers, microcontroller, PC, loudspeakers.

*3) Software:* Converted voltage values are processed and then sent to a PC for the real-time sonification procedure. The firmware of the microcontroller acquires data from the A/D converter input pins at a frequency of 640 Hz. Moreover the firmware executes a simple 10:1 averaging filter, thus providing to the application that computes the sonification on the PC a filtered data stream with a sampling rate of 64 Hz. The Arduino and the PC are connected via a USB cable over which we use a serial virtual connection with a simple ASCII protocol. The stream is decoded on the PC using a SuperCollider program which is also responsible for the real-time sound synthesis.

*4) System's operation:* The overall system is attached to a fishing pole in order to keep the hardware outside the water. Only the plastic tubes reach to the hands of the swimmer. Moreover a waterproof pair of earphones provides the audio signal via a long audio cable back to the swimmer.

Raw data quality is high, i.e. the signal-to-noise ratio is with $34\ \mathrm{dB}$ pretty high as a result of the averaging filter implemented on the microcontroller. The data is qualitatively and numerically comparable to data reported in existing literature [21]. Figure 6 shows a plot of the signals for all 4 probes acquired with our sensing setup for a total of 3 breast swimming cycles. We show other plots of data acquired with our system in the following figures. In particular, in Figure 7 we show 3 cycles of crawl style.

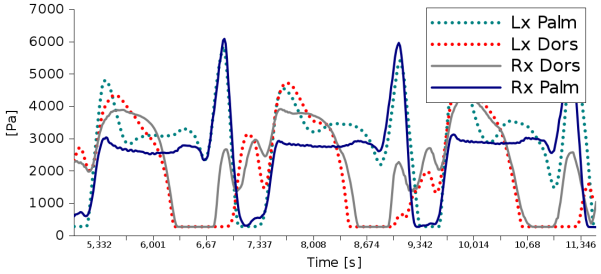


Fig. 6. Plot for the 4 pressure time series for 3 breaststroke cycles.

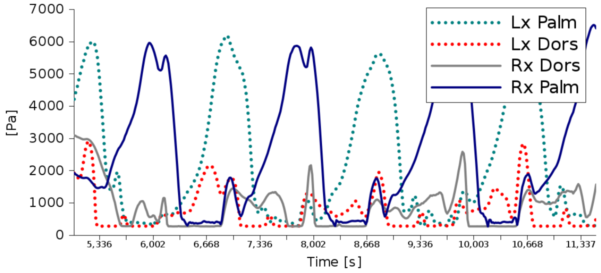


Fig. 7. Plot for the 4 pressure time series for 3 crawl cycles.

In Figure 8 we depict the phases of a single "gliding-variant" breaststroke cycle (propulsive and gliding phase), and in Figure 9 we emphasize the phases of a single crawl cycle (left hand in water, left hand out of water).

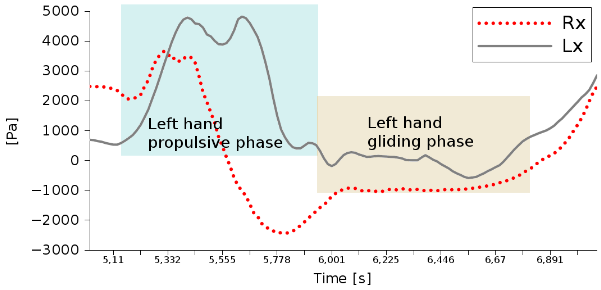


Fig. 8. Plot for a single cycle of breaststroke, Palmar-Dorsal pressure for Left and Right hand.

## B. Sonification

As explained before, we collect as raw (digital) data the pressure values from 4 probes $P_{\mathrm{rp}}(t), P_{\mathrm{rd}}(t), P_{\mathrm{lp}}(t), P_{\mathrm{ld}}(t)$ ($r$: right hand / $l$: left hand, each $p$: palmar / $d$: dorsal side of the hand) at a frame rate of 64 Hz. The variables are scalar pressure values in Pascal.

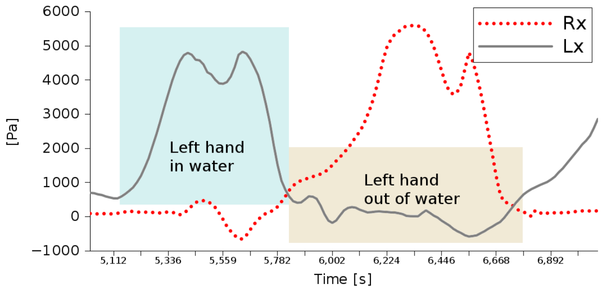


Fig. 9. Plot for a single cycle of crawl, Palmar-Dorsal pressure for Left and Right hand.

The aim of the sonification is to create an awareness of the changes due to interaction of hands and water, and thus, to provide the swimmer (and coach) with a propulsion-relevant stream of information. To omit the influence of the depth-dependent hydrostatic pressure (lowering the hand below the surface results in increasing pressure values even without any movement at all) on the flow-dependent static pressure, to selectively use information about the net energy transfer, the pressures of the palmar and dorsal are subtracted. This difference remains zero at a hand in resting water, independent of the depth in water. When the hand is in motion the value represents the flow effects. So we derive our sonification designs from the two differences

$$
\begin{aligned}
P_{\mathrm{r}}(t) &= P_{\mathrm{rp}}(t) - P_{\mathrm{rd}}(t) \\
P_{\mathrm{l}}(t) &= P_{\mathrm{lp}}(t) - P_{\mathrm{ld}}(t)
\end{aligned}
$$

for the right and left hand, respectively.

The sonification designs that we describe here have been already presented in another paper [22]. However we report here a short overview of the main concepts of one of them for completeness and as an exemplification of how that process it performed.

*1) Direct Mapping:* The direct mapping sonification is a kind of baseline for sonification, using the rather most basic standard pitch-mapping to represent pressure values as continuous tones. This mapping has already been used in rowing, mapping a boat's linear acceleration to pitch by one of the authors [16]. We apply a mapping to continuous frequencies, that is a time-analogue and value-analogue mapping, considering a linear mapping of $P_{\mathrm{r}}(t)$ to "pitch, so that $P_{\mathrm{r}}(t) = 0$ Pa is mapped to 349.2 Hz (corresponding to MIDI note 65) and $P_{\mathrm{r}}(t) = 5000$ Pa is mapped to 1396.9 Hz (corresponding to MIDI note 89) for each time $t$. The same mapping is applied for $P_{\mathrm{l}}(t)$ and $\mathrm{freq}_l$. The parameters $\mathrm{freq}_r$ and $\mathrm{freq}_l$ are used in two simultaneously running independent synthesizers presenting sound on the right and left earphone channel, respectively.

*2) Other mappings:* We developed also a task-specific mapping for a set of experiments dealing with the question "Can swimmers use real-time sonification to gain symmetry of pressure changes while swimming breaststroke?" As a preliminary step we had to define symmetry of pressure changes at both hands, respectively. We adopted a definition of asymmetry, instead of symmetry, for the ease of later processing, as $\mathrm{asym}(t) = P_{\mathrm{r}}(t) - P_{\mathrm{l}}(t)$. Finally the task-oriented mapping exploits the obtained feature of asymmetry to modulate a complex sound in terms of formant filters.

## V. EVALUATION OF THE SYSTEM AND DISCUSSION

This section presents a few interaction examples, for which additional multimedia material is provided on a separate website, and a brief discussion about the system and on the main development issues we faced over time.

### *A. Interaction with the system*

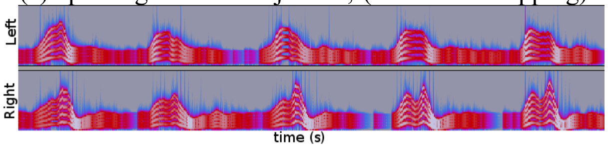
The usage of the whole system from the point of view of the swimmer is limited to wearing the plastic tubes on the arms holding the probes between the hand fingers, as shown before in Figure 4, while the researcher or trainers walks on the pool-side carrying a fishing pole on which the acquisition devices are mounted and which also holds the audio cable that brings the sounds to the swimmers earphones. The video provided as supplementary material for this paper (see http://pub.uni-bielefeld.de/publication/2718036) makes evident how unobtrusive the system is, and gives a perception of the meaning of the concurrency of actions and sounds. Note that the sound is exactly the same that the swimmer perceived at the time of recording.

Moreover two audio snippets, referring to two different swimmers, called *M* and *T* for anonymity here, can also be found on the same page as the video [23]. Both swimmers, *M* and *T*, were swimming a breaststroke gliding variant, while listening to the presented direct parameter-mapping sonification. Spectrograms of the audio signals are shown in Figure 10. Comparing the sounds and the related spectrograms of respectively *M* and *T* we notice that subject M tends to anticipate actions on the left side with respect to the right hand. On the other hand we notice that for subject T the sound presents two peaks per cycle, possibly representing a strange movement, causing an interruption of the water flow and a consequent pressure drop.

### *B. Discussion and System Evaluation*

The presented direct mapping offers a ways of using interactive sonification in human physical activities, that is an unbiased representation of the pressure changes to sound. From the audio playback particular moments in time during which particular actions are performed by the swimmers, can be perceived. The comparison between the two different swimmers' sounds reveals that the even simple mapping is able to communicate to the swimmer and the trainer that listens to the same sounds from outside the water, how the hand-water interaction is taking place.

(a) spectrogram for subject M, (S1: direct mapping)



(b) spectrogram for subject T, (S1: direct mapping)

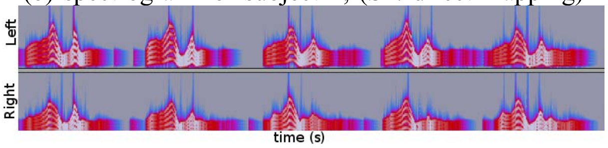


Fig. 10. Comparing sonifications for two different swimmers using the direct sonification.

The past and ongoing research we are conducting about human aquatic activities and interactive sonification is placed in a broader field of interest, spanning from high-level elite athletes training, to people interested in learning or improving their aquatic propulsion efficiency, and to people needing to perform some kind of therapy, like general motor-rehabilitation or even behavioral rehabilitation processes. During the coming year we will perform experiments with athletes and will present the system to the aquatic therapy community in some specialized conferences.

## VI. CONCLUSION AND OUTLOOK

We presented a system for the recording and real-time sonification of hydrodynamic pressure while swimming in water. As opposed to other approaches which exploit inertial wearable systems and are thus geared towards kinematics, we instead focused on hydrodynamic pressure because it represents an *intermediate effect* between body actions and the final effect of speed and thus time needed to cover a given distance. The presented system is able (i) to acquire pressure at the swimmer's hands, by means of piezo-probes and electronic pressure sensors, (ii) to process it (filter/condition) online, and (iii) to transform the signals into real-time auditory biofeedback. The sound is presented to swimmers using in-ear underwater earphones, while swimming.

We have already conducted a set of preliminary experiments with the goal of further understanding to which extent our system could improve or change the established way of teaching and training swimming. As our next steps we plan first, tests to further assess the correlation between energy transfer (from limbs to water as measured with our system) with $O_2$ consumption, and secondly, extensive on-field tests and experimentation of the complete sensing and feedback system with the participation of athletes from a European country's national team.

## VII. ACKNOWLEDGEMENT

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