SONIFICATION OF SCULLER MOVEMENTS, DEVELOPMENT OF PRELIMINARY METHODS

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ABSTRACT

Sonification is a widening field of research with many possibilities for practical applications in various scientific domains. The rapid development of mobile technology capable of efficiently handling numerical information offers new opportunities for interactive auditory display. In this scope, the SONEA project (SONification of Elite Athletes) aims at improving performances of Olympic-level athletes by enhancing their training techniques, taking advantage of both the strong coupling between auditory and sensorimotor systems, and the efficient learning and memorizing abilities pertaining the sense of hearing. An application to rowing is presented in this article. Rough estimates of the position and mean velocity of the craft are given by a GPS receiver embedded in a smartphone taken onboard. An external accelerometer provides boat acceleration data with higher temporal resolution. The development of preliminary methods for sonifying the collected data has been carried out under the specific constraints of a mobile device platform. The sonification is either performed by the phone as a real-time feedback or by a computer using data files as input for an *a posteriori* analysis of the training. In addition, environmental sounds recorded during training can be synchronized with the sonification to perceive the coherence of the sequence of sounds throughout the rowing cycle. First results show that sonification using a parameter-mapping method over few quantities can provide a meaningful sound feedback.

1. INTRODUCTION

Approaching an optimal efficiency in rowing is an important concern for elite athletes and trainers of this sport. This has led the necessity to do the spadework on the path towards an ideal rowing technique. Biomechanical studies account for the most significant part of this research, identifying the influence of particular kinetic quantities (forces, momentums) on the motion of the boat and athletes as well as the most important properties of this motion. These studies provide tools for evaluation of power production and therefore openings for efficiency optimization.

By contrast, few investigations have been conducted concerning the possibilities to influence the athlete's training in order to improve his technique. The rower makes use of different categories of feedback for discriminating between a good and a bad stroke: haptic feedback from oars, foot-stretchers and seat play the most significant role, while visual and auditory input provide useful additional information. Modifying the haptic feedback would be both technically difficult and potentially obtrusive for the athlete. On the other hand, an enhanced training process can easily involve vision and hearing: little attention is required to extract information from a visual display such as the *StrokeCoach System* from Nielsen-Kellerman[1] – an electronic device of widespread use giving the stroke rate, time and stroke count – or by listening to the instructions from the coxswain sitting at the stern of the boat. This project aims at expanding the use of the hearing sense during the training by developing sonification methods of data available from rowing biomechanics measurements. Given that in addition to the strong learning and memorizing abilities associated with the sense of hearing, the perception of complex sport movements can be enhanced by additional auditory information as shown by Effenberg in [1], the potential for the athletes and their coaches to rapidly develop fair analytical skills through interaction with a sonification system seems very promising.

2. BIOMECHANICS OF ROWING

Numerous biomechanical studies of rowing have been carried out since the end of the 19^{th} century and presenting an exhaustive review of the existing literature on this topic goes beyond the limits of this article. However, since the properties of the considered data are of primary importance in any sonification work, an overview of the kinematic and kinetic quantities involved in rowing is presented here. In [2], Kleshnev uses a pragmatic approach to this problem as he connects each reported quantity to the type of sensor used for its measurement. In this way, he sets up a list of measurable quantities which can be considered as available for the analysis. This list includes kinematic quantities related to the boat: velocity, acceleration, 3-dimensional orientation (*i.e.* yaw, pitch and roll), to the oars: position and angles, to the sliding seats and to the athlete himself: position of the trunk. Kinetic quantities are also considered: oar force (as the main factor of propulsion), and forces measured at various places of the boat: foot-stretchers, oarlocks, gates and handles. Various types of sensors – potentiometers, accelerometers, impellers, gauges – can be associated to these biomechanical variables. Environmental parameters such as wind speed and direction, and water temperature round out the set of measurable parameters.

Based on the analysis of some of these parameters, McBride[3] and Soper and Hume[4] provide guidelines to optimize the rowing cycle. In her study, which is intended for athletes and trainers, McBride uses the dissection of a rowing stroke as a starting point to discuss the influence of diverse biomechanical variables on dynamic features of the rowing cycle, in particular those related to the propulsion: oar motion, blade forces, boat velocity. Optimization of efficiency is tackled through the study of force-angle closed curves, the area under which represents the total work produced during a stroke cycle. The author discusses the means to achieve a more efficient shape of the curve – for example with an *"explosive leg drive at the catch"* – and states that the optimal curve is different regarding the position of the rower in the boat in the case of non-single sculler. Furthermore, she studies the way to limit the energy wasting due to dissipation through non-propulsive kinematic quantities, first and foremost through the drag force caused

[1] http://www.nkhome.com/rowing/strokecoach.html

by water friction. An idea introduced to minimize the energy loss due to the water resistance is to limit the variations of the velocity throughout a stroke cycle relatively to the average velocity of the boat, *i.e.* limit the amplitude of the oscillations in the boat velocity. Soper and Hume agree on this particular point as they point out the noticeable difference between top-level and less skilled rowers: according to their observations, athletes of international level tried to maintain the boat velocity constant at the catch while, for less skilled rowers, it tends to decrease until a minimum value before increasing due to the propulsion of the blades.

3. SONIFICATION OF SCULLER MOVEMENTS

Acquiring skills by training results in an improvement of the efficiency of the rowing technique – as claimed in [5] for training on ergometer, and it seems reasonable to extend this observation to effort on a real boat. The aim of this project is to enhance the training process by means of sonification so that it will converge faster and closer towards an optimal rowing technique. Whereas there exist various potential uses of a sonification system as for example synchronization between rowers of a crew, we chose to focus on technique improvement for a single sculler.

3.1. Previous work in sport sonification

Several examples of sonification use in the context of sports are available in the literature, although this field has not been widely exploited until now. Applications include *a posteriori* analysis of the performance, feedback in disable sports, and enhancement of the training process. For example, Van Scoy [6] proposes a way to monitor the evolution of the score during a basketball game in order to evaluate the efficiency of different combination of players. This analysis is intended to be performed once the game is finished, and uses of piano-tone sequences as sound material. These sequences are associated to different combinations of players present on the court and the difference in score obtained by these combinations minute by minute. In disable sports for visually impaired athletes such as torball or blind football, some particular parameters of interest for the game are displayed in the auditory modality, most commonly the location of goals and field limits and the location and motion of the ball. In this context, the sound synthesis is generally assumed by a sounding system attached to the object, *e.g.* by containing small bells. This illustrates how an auditory setup can help a performing athlete while using a meaningful coupling to relevant quantities.

The use of sonification in sports technology appears therefore as a possible field of investigation for optimizing the performances of the athletes. An example of use of sonification of movements in sports is presented by Effenberg in [1], where perceptual aspects and effects on the motor system are highlighted. Hermann *et al.*[7] take advantage of the correlation between sonification and the sensorimotor system for the design of *AcouMotion*, a framework for interactive sonification applied to human body motion. The system runs sensor acquisition, computer simulation of a virtual environment and sonification in parallel. It offers wide possibilities for assisting motor rehabilitation or for designing virtual sport games accessible to visually impaired people. *Blindminton*, for example, is a virtual badminton game without visual display where players make use of the sonification of their own movements to perceive and modify the motion of a virtual shuttlecock on a virtual court. Sonification can also be used in the context of elite athlete training: any Olympic sport involves motion, and the technical part of the training is essentially the learning process towards an optimal motion. In this perspective, Schaffert *et al.* developed a system for the sonification of rowing, introduced in [8]. In their experiments, the acceleration of the boat was directly coupled to a tone of variable frequency, a higher pitch corresponding to a larger acceleration. The tests were followed by a questionnaire which revealed the strong interest and the actual comprehension of the system by coaches and athletes.

3.2. Selection of physical quantities used for the sonification

The main objective to fulfill when looking for the optimal rowing technique is the optimization of the mean velocity of the shell [4]. Velocity was therefore our main concern and was chosen to be displayed as a continuous auditory feedback.

Considering the little space available in a single scull, and with the development of mobile technology, handheld devices are a natural solution for setting up a sonification system to be used in rowing training. Latest generation mobile phones have the functionalities required for setting up such a system, from data acquisition to sound synthesis. Still these systems have limitations with respect to computational power, and designing a complete system running efficiently on a mobile platform represents a real challenge. New types of sensors have also appeared, allowing interactive systems to be aware of their context of use. The sensors we used for the current study were a GPS receiver in a mobile phone and wireless accelerometers. Thus only kinematic quantities could be measured.

As described in Section 4.2, an estimation of the absolute value of the boat velocity was extracted from the GPS measurements. In addition, short-term variations of the velocity were integrated from the raw data from the accelerometers. Finally, the raw acceleration was used for detecting the stroke rate in real-time.

3.3. Specification of the type of interaction

One of the objectives for the rower is to learn how to reproduce the movements corresponding to what is assessed as a “good stroke” – either by the coach or the athlete himself, *e.g.* through the usual haptic perception – with help from an auditory display. The main aim of our sonification system is therefore to help the rower getting a live perception of the motion of the boat. In this way, he will be able to hear in real-time the effects of his own movements and the changes in his strategy. In this perspective, having a reasonably short latency is necessary in order to maintain the perceptual association within the action-feedback chain.

An *a posteriori* analysis can also be conducted buy means of sonification and can be useful for both coach and athlete. The auditory display computed from logs of training sessions can be generated with an accelerated timestamp in order to divide the time of analysis. This method is commonly used in various domains using auditory display of large sets of data, which is illustrated by Hayward with the audification of seismograms [9]: the analysis of the data, which can cover several hours of recordings, can be performed with a time-compression factor of 200. In a similar way, a long training session can be skimmed through rapidly, provided that the listener has received a training beforehand to be able to extract relevant information from the display.

3.4. Sonification methods

In [10], Hermann introduces a taxonomy for sonification and enumerates the different types of existing sonification methods: Audification, Earcons, Auditory Icons, Parameter-Mapping Sonification and Model-Based Sonification. Referring to Hermann’s work, we chose to use the Parameter-Mapping Sonification method for the quantities for which a continuous feedback was required. This includes the absolute velocity provided by GPS measurements with a low update frequency and the velocity variations relative to the mean velocity of the shell provided by the accelerometer at a much higher time resolution. In the second sonification system (Section 4.3.2), additional Earcons are used to give a feedback concerning the time-lag with respect to the intended stroke rate chosen at the beginning of the experiment.

Since the context of use of such a sonification system is an outdoor, on-water training in a rather noisy environment, sound level variations were chosen not to be part of the design. On the other hand, pitch variations are much more easily perceived in this type of environment. Thus the association between pitch and boat velocity was chosen as the main point of the Parameter-Mapping Sonification.

4. EXPERIMENT

In this section, we present equipment and acquisition methods used for collecting sculler movement data. Finally we present how these data were sonified, and we discuss preliminary results as well as limitations of our system.

4.1. Equipment

Figure 1: *Equipment: the rower carries a smartphone that receives GPS and accelerometer data used for the sonification.*

The equipment used for the on-water experiments consisted in a Nokia N95 mobile phone running Symbian S60 operative system, the GPS receiver present in the phone, and a couple of wireless Witilt v3.0 accelerometers from SparkFun Electronics. These accelerometers were preferred to the built-in ones, since they have a higher resolution and a wider range ($\pm$6g). The accelerometers were sending 3-dimensional acceleration data to the mobile phone via a Bluetooth protocol at a frequency of 120Hz while the sample frequency of the GPS was 0.5 Hz. A MiniDisc player was used to record the environmental sounds during the training session.

4.2. Acquisition process

The mean velocity between two GPS samples was computed using the great-circle distance formula to obtain the distance covered by the boat:

$$d = R \arccos\left[\,\cos(l_1)\cos(l_2)\cos(L_2 - L_1) + \sin(l_1)\sin(l_2)\right] \quad (1)$$

where R is the Earth radius, l_1 and l_2 the latitudes and L_1 and L_2 the longitudes of the two successive samples.
An internal function giving an approximated value for the average velocity between two samples is available on the GPS receiver but the refreshing rate seems to be very low and the results seem very approximate and hardly useable, as shown in Figure 2. The values for the velocity obtained using the distance computed according to Equation 1 roughly meet the ones given by the internal function, with a higher temporal resolution corresponding to the GPS sample frequency.

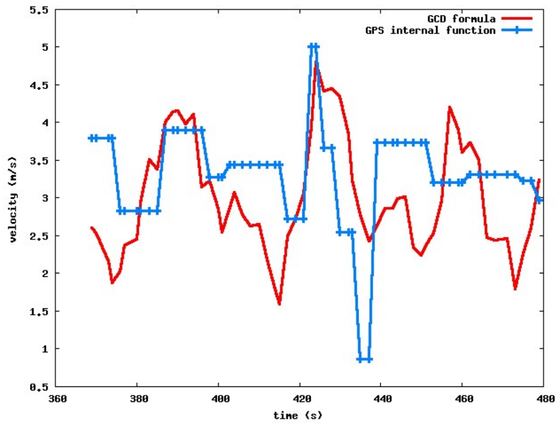

Figure 2: *Velocity from GPS measurements: internal function and great-circle distance formula.*

One accelerometer was attached to the boat and sent the acceleration in the three spatial dimensions X, Y, and Z to the mobile phone. For the present work, only the direction of the propulsion of the boat was taken into account.

If values for the velocity were directly integrated from this raw data, they would be completely unrealistic due to the accelerometer's unpredictable drift. As the deviation due to this phenomenon seemed to be somewhat linear with respect to time, the actual data used for the sonification was the difference between this value and a locally averaged velocity computed by a moving average filter. In this way, the deviation was reduced to a constant offset corresponding to the drift accumulated along the filter window, which was discarded at a later stage of the sonification. In order to get a smooth curve for the averaged velocity cleared of velocity variations inherent to the rowing cycle (see Figure 3), the filter window length was set approximately to the duration of a couple of cycles.

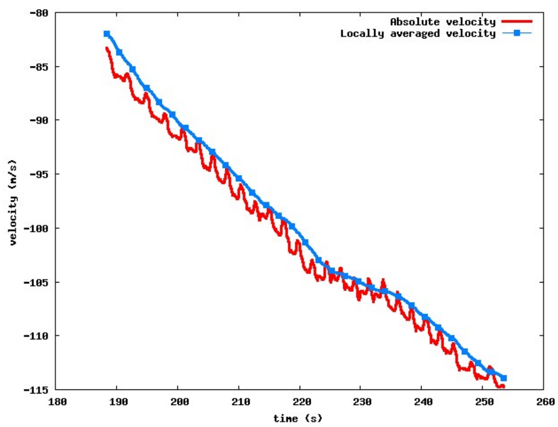

Figure 3: *Computed velocity and moving average.*

After a light low-pass filtering, peak detection was performed on the acceleration data in order to compute and update the stroke rate in real-time.

A microphone was taped on an outrigger and connected to a MiniDisc player placed inside a waterproof storage compartment in order to record the environmental sounds usually heard by the athlete while training.

Data were collected during a training camp on the artificial flatwater course in Račice, Czech Republic, with athletes from the Swedish national rowing team.

4.3. Sonification

In this section we present the first two interactive sonifications which we designed for representing single sculler velocity.

4.3.1. Pure tone with gliding frequency

The sound material used as a first draft of the sonification of sculler movement was a pure tone of variable frequency. The sonified data are short-term variations of the boat velocity as introduced in Section 3.4: the frequency was coupled to the data using the following mapping:

$$f(t) = \alpha \exp(\beta(v(t) - \bar{v}(t))) \quad (2)$$

where v is the velocity integrated from acceleration data, $\bar{v}$ is the moving average of the velocity, and α and β are positive parameters kept constant throughout the experiment which are required for keeping the frequency band within the audible range. The exponential mapping function follows the representation of the pitch in the human auditory system, which is proportional to the logarithm of the frequency.

4.3.2. Musical sounds

The second sonification system made use of the MIDI[2] synthesizer built in the mobile phone to generate musical sounds. This has several advantages: polyphonic capabilities allow to associate the existing data sets to different instruments, musical sounds are much more friendly to the human ear than sinusoidal tones and having a controller directly incorporated into the device in charge of the data acquisition saves computational resources associated to data transfer. The pattern of the generated sound was a "trill" of constant bandwidth[3] played by pizzicato strings, and we used the same mapping formula than for the previous sonification to determine the pitch range of its centre frequency. In order to accentuate the expressivity of the trill and to reinforce the perception of a greater speed for a higher pitch, the intertone duration was determined by a hyperbolic tangent-shaped function yielding values between 20 and 220 ms.

Data sent by the GPS receiver was represented using a linear mapping to the MIDI note number of a continuous trombone tone updated at every incoming sample.

A peak detection algorithm was applied to the raw acceleration data in order to determine and render the time-lag of the current stroke with respect to the intended stroke rate, chosen by the athlete at the beginning of the training. We used the sound of two different percussive instruments for providing this information to the rower in form of an earcon. The choice of percussive sounds was motivated by the natural ability for humans to follow rhythmical patterns displayed in the auditory modality in synchronization tasks [11].

4.4. Current limitations

In addition to having a low sample frequency, the GPS data seemed to have a significant uncertainty and only the use of an external GPS receiver of better quality could offer perspectives for a more elaborated sonification based on these measurements. For this reason, a continuous and immediate sound feedback must be generated from the data provided by the accelerometers.

In both sonification strategies, the drift offset assumed constant in Section 4.2 is absorbed by the mapping. This makes the mapping parameters dependent on the drift, which varies from a training session to another and which also depends on the sensor, hence it is very difficult to predict general values for these parameters. For this reason, the online sonification could not be implemented in a satisfactory manner for the on-water tests. However all the experimental data were logged, looked through to determine suitable mapping parameters and used to generate the sound, which was later presented to the rowers. This remains a major issue and different options are currently being considered to sort it out.

Furthermore, the mean to communicate the auditory display to the athletes is still under investigation: a loudspeaker setup would require devices small enough to be placed inside the boat and powerful enough to override the environmental sounds and to be heard by the rower. On the other hand, using headphones would allow for louder feedback but this could mask environmental sounds, which are informative for the rower.

4.5. Preliminary results

In order to get a good perception of the correspondence between sonification results and sequences of the rowing cycle, we synchronized outcomes generated in an offline context with environmental sounds recorded during the collection of kinematic data.

The possibilities of the system were illustrated by the difference in the properties of the sound generated by a novice and by an international rower: independently of the stroke rate, the latter clearly showed a more dynamic movement pattern as one could hear a much steeper increase of pitch (for further information please listen to sound examples A and B[4]). It is important here to note that the minimization of the velocity variations addressed in Section 2 obviously does not apply in such an extreme case, as this concern only relates to a finer level of comparison than the one induced by such a skill gap. Its evaluation could help improving a personal technique by comparing either successive performances or techniques of rowers belonging to the same category, whereas the present example only gives an overview of the power expenditure involved.

Rowers and trainers, who listened to our sonifications, showed great interest and good understanding of the system as the sounds were presented to them. However, it appeared clearly that the auditory display did not meet the aesthetic requirements for a final version of a sonification system. This was expected for this first prototype, which was not intended to be used for training, as listening for a long time to a pure tone would not be a pleasant experience. Also for this reason, we reconsidered the auditory display for the second sonification: although being more ear-friendly, musical sounds are rather repetitive and can become quite annoying considering that a training run usually lasts longer than 10 minutes. To address this problem, a threshold could be used to trigger the sonification, such that it would be displayed only if the relative variations of the velocity exceed a certain value. Introducing other types of sounds could be another solution, for example through physics-based models for sound generation or by binding the playback speed of a music file to relevant physical quantities.

[2] Musical Instrument Digital Interface

[3] Hence not a musical trill *stricto sensu*.

[4] Sound examples are available at `http://www.speech.kth.se/~dubus/ISon2010/rowing`

5. FUTURE WORK

The work presented in this paper is at an early stage. In our future work efforts, first priority shall be given to resolve the current limitations detailed in Section 4.4, especially the drift issue preventing to perform satisfying tests in the actual conditions of a training, having the sonification system interacting in real-time with the rower. The aesthetics of any sonification intended to be tested in these conditions should be considered very seriously as a displeasing auditory feedback could raise the risk of unwillingness from the athletes. Listening tests will be carried out with coaches and rowers in order to establish the perception of the sound attributes and their coherence with the actual characteristics of the training session.

We will consider alternative sensors which could be involved in the acquisition process, and provide information about other kinematic or kinetic quantities relative to other parts of the boat and to the rower. Furthermore, additional Earcons, Model-Based Sonification, and new types of sounds could be implemented to dispose of a wider range of options that the athletes could select depending on their preferences.

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