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Context Aware Computing
or
the Sense of Context

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A
professo' Borzacchi,
che sei giusto fra i giusti,
limpido, nei gesti come nelle parole.
Grazie.

Vittorio Borzacchi
Professore
Tarquinia

Sommario

I sistemi *ubiquitous* e *pervasivi*, speciali categorie di sistemi embedded (immersi), possono essere utilizzati per rilevare il contesto che li circonda. In particolare, i *sistemi context-aware* sono in grado di alterare il loro stato interno e il loro comportamento in base all'ambiente (context) che percepiscono. Per aiutare le persone nell'espletare le proprie attivitá, tali sistemi possono utilizzare le conoscenze raccolte attorno a loro. Un grande sforzo industriale e di ricerca, orientato all'innovazione dei sensori, processori, sistemi operativi, protocolli di comunicazione, e framework, offre molte tecnologie definibili abilitanti, come le reti di sensori wireless o gli Smartphone. Tuttavia, nonostante tale sforzo significativo, l'adozione di sistemi pervasivi che permettano di migliorare il monitoraggio dello sport, l'allenamento e le tecnologie assistive é ancora piuttosto limitato.

Questa tesi individua due fattori determinanti per questo basso utilizzo delle tecnologie pervasive, principalmente relativi agli utenti. Da un lato il tentativo degli esperti e dei ricercatori dell'informatica di *indurre* l'adozione di soluzioni informatiche, trascurando parzialmente l'interazione *con* gli utenti finali, dall'altro lato una scarsa attenzione all'interazione tra uomo e computer. Il primo fattore puó essere tradotto nella mancanza di attenzione a ció che é *rilevante* nel contesto dei bisogni (speciali) dell'utente. Il secondo é rappresentato dall'utilizzo diffuso di interfacce grafiche di presentazione delle informazioni, che richiede un elevato livello di sforzo cognitivo da parte degli utenti.

Mentre lo studio della letteratura puó fornire conoscenze sul contesto dell'utente, solo il contatto diretto con lui arricchisce la conoscenza di consapevolezza, fornendo una precisa identificazione dei fattori che sono *piú rilevanti* per il destinatario dell'applicazione. Per applicare con successo le tecnologie pervasive al campo dello sport e delle tecnologie assistive, l'identificazione dei fattori rilevanti é una premessa necessaria. Tale processo di identificazione rappresenta l'approccio metodologico

principale utilizzato per questa tesi.

Nella tesi si analizzano diversi sport (canottaggio, nuoto, corsa) e una disabilitá (la cecitá), per mostrare come la metodologia di investigazione e di progettazione proposta venga messa in pratica. Infatti i *fattori rilevanti* sono stati identificati grazie alla stretta collaborazione con gli utenti e gli esperti nei rispettivi campi. Si descrive il processo di identificazione, insieme alle soluzioni elaborate su misura per il particolare campo d'uso.

L'uso della sonificazione, cioé la trasmissione di informazioni attraverso il suono, si propone di affrontare il secondo problema presentato, riguardante le interfacce utente. L'uso della sonificazione puó facilitare la fruizione in tempo reale delle informazioni sulle prestazioni di attivitá sportive, e puó contribuire ad alleviare parzialmente la disabilitá degli utenti non vedenti.

Nel canottaggio, si é identificato nel livello di sincronia del team uno dei *fattori rilevanti* per una propulsione efficace dell'imbarcazione. Il problema di rilevare il livello di sincronia viene analizzato mediante una rete di accelerometri wireless, proponendo due diverse soluzioni. La prima soluzione é basata sull'indice di correlazione di Pearson e la seconda su un approccio emergente chiamato stigmergia. Entrambi gli approcci sono stati testati con successo in laboratorio e sul campo. Inoltre sono state sviluppate due applicazioni, per smartphone e PC, per fornire la telemetria e la sonificazione del moto di una barca a remi.

Nel campo del nuoto é stata condotta una ricerca in letteratura riguardo la convinzione diffusa di considerare la cinematica come il *fattore rilevante* della propulsione efficace dei nuotatori. Questa indagine ha richiamato l'attenzione sull'importanza di studiare il cosiddetto feel-for-water (sensazione-dell'-acqua) percepito dai nuotatori d'alto livello. É stato progettato un innovativo sistema, per rilevare e comunicare gli effetti fluidodinamici causati dallo spostamento delle masse d'acqua intorno alle mani dei nuotatori. Il sistema é in grado di trasformare la pressione dell'acqua, misurata con sonde Piezo intorno alle mani, in un bio-feedback auditivo, pensato per i nuotatori e gli allenatori, come base per un nuovo modo di comunicare la sensazione-dell'-acqua. Il sistema é stato testato con successo nel campo e ha dimostrato di fornire informazioni in tempo reale per il nuotatore e il formatore.

Nello sport della corsa sono stati individuati due parametri *rilevanti*: il tempo di volo e di contatto dei piedi. É stato progettato un sistema innovativo per ottenere questi parametri attraverso un unico accelerometro montato sul tronco del corridore ed é stato implementato su uno smartphone. Per ottenere il risultato voluto é stato necessario progettare e realizzare un sistema per riallineare virtualmente gli assi dell'accelerometro e per estrarre il tempo di volo e di contatto dal segnale dell'accelerometro riallineato. L'applicazione per smartphone completa é stata testata con successo sul campo, confrontando i valori con quelli di attrezzature specializzate, dimostrando la sua idoneitá come ausilio pervasivo all'allenamento di corridori.

Per esplorare le possibilitá della sonificazione usata come una base per tecnologia assistiva, abbiamo iniziato una collaborazione con un gruppo di ricerca presso l'Universitá di Scienze Applicate, Ginevra, in Svizzera. Tale collaborazione si é concentrata su un progetto chiamato SeeColOr (See Color with an Orchestra - vedere i colori con un'orchestra). In particolare, abbiamo avuto l'opportunitá di implementare il sistema SeeColOr su smartphone, al fine di consentire agli utenti non vedenti di utilizzare tale tecnologia su dispositivi leggeri e a basso costo.

Inoltre, la tesi esplora alcune questioni relative al campo del rilevamento ambientale in ambienti estremi, come i ghiacciai, utilizzando la tecnologia delle Wireless Sensor Networks. Considerando che la tecnologia é simile a quella usata in altri contesti presentati, le considerazioni possono facilmente essere riutilizzate. Si sottolinea infatti che i problemi principali sono legati alla elevata difficoltá e scarsa affidabilitá di questa tecnologia innovativa rispetto alle altre soluzioni disponibili in commercio , definite legacy, basate solitamente su dispositivi piú grandi e costosi, chiamati datalogger.

La tesi presenta i problemi esposti e le soluzioni proposte per mostrare l'applicazione dell'approccio progettuale cercato e definito durante lo sviluppo delle attività sperimentali e la ricerca che le ha implementate.

Abstract

Ubiquitous and *pervasive* systems, special categories of embedded systems, can be used to sense the context in their surrounding. In particular, *context-aware* systems are able to alter their internal state and their behaviour based on the context they perceive. To help people in better performing their activities, such systems must use the knowledge gathered about the context. A big research and industrial effort, geared towards the innovation of sensors, processors, operating systems, communication protocols, and frameworks, provides many "enabling" technologies, such as Wireless Sensor Networks or Smartphones. However, despite that significant effort, the adoption of pervasive systems to enhance sports monitoring, training and assistive technologies is still rather small.

This thesis identifies two main issues concerning this low usage of pervasive technologies, both mainly related to users. On one side the attempt of computer science experts and researchers to induce the adoption of information technology based solutions, partially neglecting interaction with end users; on the other side a scarce attention to the interaction between humans and computers. The first can be translated into the lack of attention at what is *relevant* in the context of the user's (special) needs. The second is represented by the widespread usage of graphical user interfaces to present information, requiring a high level of cognitive effort.

While literature studies can provide knowledge about the user's context, only direct contact with users enriches knowledge with awareness, providing a precise identification of the factors that are *more* relevant to the user. To successfully apply pervasive technologies to the field of sports engineering and assistive technology, the identification of relevant factors is an obliged premise, and represents the main methodological approach used throughout this thesis.

This thesis analyses different sports (rowing, swimming, running) and a disability (blindness), to show how the proposed design methodology is put in practice. *Relevant*

factors were identified thanks to the tight collaboration with users and experts in the respective fields. The process of identification is described, together with the proposed application tailored for the special field.

The use of sonification, i.e. conveying information as sound, is proposed to leverage the second presented issue, that regards the user interfaces. The usage of sonification can ease the exploitation of information about performance in real-time for sport activities and can help to partially leverage the disability of blind users.

In rowing, the synchrony level of the team was identified as one of the *relevant* factors for effective propulsion. The problem of detecting the synchrony level is analysed by means of a network of wireless accelerometers, proposing two different solutions. The first solution is based on Pearson's correlation index and the second on an emergent approach called stigmergy. Both approaches were successfully tested in laboratory and in the field. Moreover two applications, for smartphones and PCs, were developed to provide telemetry and sonification of a rowing boat's motion.

In the field of swimming, an investigation about the widespread belief considering kinematics as the *relevant* factor of effective propulsion of swimmers drew attention to the importance of studying the so called "feel-for-water" experienced by elite swimmers. An innovative system was designed to sense and communicate fluid-dynamic effects caused by moving water masses around swimmers hands. The system is able to transform water pressure, measured with Piezo-probes, around hands into an auditive biofeedback, to be used by swimmers and trainers, as the base for a new way of communication about the "feel-for-water". The system was successfully tested in the field and proved to provide real-time information for the swimmer and the trainer.

In running sports two *relevant* parameters are time of flight and contact of feet. An innovative system was designed to obtain these parameters using a single trunk mounted accelerometer and was implemented on a smartphone. To achieve the intended result it was necessary to design and implement a system to virtually realign the axes of the accelerometer and to extract time of flight and time of contact phases from the realigned accelerometer signal. The complete smartphone application was successfully tested in the field with specialized equipment, proving its suitability in enhancing training of runners with a pervasive system.

To explore possibilities of sonification applied as an assistive technology, we started a collaboration with research group from University of Applied Science, Geneva, Switzerland, focused on a project called SeeColOr (See Color with an Orchestra). In particular we had the opportunity to implement the SeeColOr system on smartphones, in order to enable blind users to use that technology on low cost and lightweight devices.

Moreover, the thesis exposes some issues related to a field, environmental sensing in extreme environments, like glaciers, using the innovative Wireless Sensor Networks technology. Considering that the technology is similar to the one used in other presented contexts, learned lessons can easily be reused. It is emphasized that the main problems are related to the high difficulty and low reliability of that innovative technology with respect to other "legacy" commercially available solutions, based on expensive and bigger devices, called dataloggers.

The thesis presents the exposed problems and proposed solutions to show the application of the design approach strived during the development and research.

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Introduction

> Science is but a perversion of itself unless it has as its ultimate goal the betterment of humanity.
>
> Nikola Tesla

The last decades have seen an increased development and availability of cheap, tiny and lightweight sensors, processing units, batteries, energy harvesters. That technologies enabled the diffusion of smartphones, widespread in the consumer market, and of other embedded systems (Arduino, Prototype boards, Wireless Sensor Networks' Motes, ...), mostly used in research and in the Do-It-Yourself (DIY) community. *Pervasive systems* represent one of the most promising opportunities to mix virtual and real world in a seamless and ubiquitous way [194]. The results envisioned by researchers and by industry are promoting the adoption of pervasive technologies to improve quality of life and the development of new tools to help scientists to study man and nature. We successfully designed useful and innovative applicative tools, starting with concrete demands from the domain of sports and sight disabilities, exploiting the available pervasive technology paradigm to improve the existing sport engineering and assistive technologies.

1.1 Background

1.1.1 Ubiquitous and Context-Aware Computing

Ubiquitous computing vision was first described in 1991 by Mark Weiser [194]. Since then the number of ubiquitous computing researchers is increasing, motivated by the shared hypothesis "that enabling devices and applications to automatically adapt to changes in their surrounding physical and electronic environment will lead to an enhancement of the user experience" [58]. Three themes have dominated the research in the ubiquitous computing field: "context-awareness, ambient intelligence and monitoring/tracking. While these avenues of research have been fruitful their accomplishments do not match up anything like Weiser's world [156]".

To represent the context in a computer system, the context needs to be sensed. In fact, to identify and analyse the constituent elements of context, ubiquitous computing research uses a bottom-up approach, starting with sensor data representing aspects of the physical environment [58]. Models of context are used "not only to adapt, but also to try to foresee what is going to take place next and let the application act proactively, guessing what users soon might need to have at hand. In this case questions for system designers are how to adapt to context and how to act proactively in context. Obviously, it is a very hard problem to get all these abstractions, models and inferences right [156, 65]" [72].

The concept of context is tightly bound to the concept of interaction, and context is generally defined as "any information that characterizes a situation related to the interaction between humans, applications, and the surrounding environment [58]". A special type of interaction is described in [72], called Embodied Interaction: "Since the emergence of the research field [...] of Ubiquitous computing, the notion of context has been discussed from different theoretical approaches and in different research traditions. One of these approaches is Embodied Interaction. This theoretical approach has in particular contributed to (i) challenge the view that user context can be meaningfully represented by a computer system, (ii) discuss the notion of context as interaction through the idea that users are always embodied in their interaction with computer systems." Context-aware systems need to interact with the users in order to be useful. For that purpose the systems need to be designed considering the interactions between users and the system from the beginning of the development process.

1.1.2 Interaction Design

The design of human-computer interaction should have the goal of enabling the "[...] user finding herself in a situation of being able to handle all difficulties and not losing focus in her activity [...]" [72]. "Instead of trying to give guidelines for how to design one ultimate design, we need to acknowledge that a design and thereby also the designer is part of this hermeneutic development and that continuous redesigns, done by both designer and user, are necessary for the system to stay relevant to a user" [72]. The designer himself (and the researcher of interactive systems in this case) is part of the design, thus she needs to "become a skilled user in the interaction with [the designed] systems", in order not to waste "one opportunity for design" [72]. Moreover users and designers should respectively understand and design together [42].

The interaction design and context-aware research community exhibit a subtle difference in the way they intend the process of design [72]:

- researchers of *context-aware computing* tend to design systems developing a representation ***of*** the context and force the users to adapt to the representation;
- the approach typically followed by interaction designers on the other hand puts human activity in focus, leading to a design ***for*** context, enhancing the role of users with respect to the system.

Dourish [64] proposes the following six principles for the design (of pervasive applications):

- Computation is a medium;
- Meaning arises on multiple levels;
- Users, not designers, create and communicate meaning;
- Users, not designers, manage coupling;
- Embodied technologies participate in the world they represent;
- Embodied interaction turns action into meaning.

These guidelines have to be considered whenever we, as researchers have to design systems.

1.2 Problems or simply open questions

The time is come to focus "on engaging rather than calming people [156]". Following this statement we analyse some issues related to existing research in the field of Wireless Sensor Networks and Pervasive (Human centered) systems: the focus is often put on monitoring/tracking what happens and far too little considers the involvement and engagement of people.

1.2.1 Context-aware computing research problems

"Context-aware applications promise richer and easier interaction, but the current state of research in this field is still far removed from that vision. This is due to 3 main problems:
(a) the *notion* of context is still ill defined,
(b) there is a lack of *conceptual models* and *methods* to help drive the design of context-aware applications, and
(c) no tools are available to jump-start the development of context-aware applications " [58].

Design

Considering the guidelines of Dourish [64] and the clear classification of the design approach of researchers and interaction designers drawn by Rogers [156], we can infer the lack of a diffuse comprehension of what design and interaction is, among context-aware computing researchers.

Interdisciplinary approach in Ubiquitous and Context aware computing

"Translating ideas between different intellectual domains can be both exceptionally valuable and unexpectedly difficult. One reason is that the ideas need to be understood within the intellectual frames that give them meaning, and we need to be sensitive to the problems of translation between these frames." [63]. Interdisciplinary work needs to be better understood if we want to successfully design useful ubiquitous and context-aware applications.

"Solving real problems does require multiple disciplinary perspectives, but does not always require breaking new ground in those disciplines. It takes a special kind of researcher to accept the compromises of doing multidisciplinary research, and often those researchers must do double duty to both impress the ubicomp [1] community as well as retain credentials with their own, more focused research community. Has this requirement for doing double duty as a researchers helped or hindered the ubicomp community?" [9].

1.2.2 Problems of Wireless Sensor Networks adoption

In the field of pervasive technologies, during the last 15 years, Wireless Sensor Networks (WSNs) have emerged and represented one of the main fields of investigation of researchers, often leading to innovative software architectures, operating systems, communication protocols, and in general enhancements of the technology. Nonetheless adoption of WSNs in the world outside of research projects and academy institutions is still growing [2], and far from possible maximum exploitation [61]. In fact most of existing sensing / controlling applications and systems still rely on *legacy* solutions (characterized by higher prices, higher consumptions, lower number of points of measurements, ..., with respect to what is being promised by WSNs evangelists). What are the key issues? What are the factors motivating such difficulties in the establishment of WSNs as the new paradigm of sensing in the industrial and consumer markets?

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[1] Ubiquitous Computing

[2] Renesas Solutions for Wireless Sensor Networks-Part 1: Overview: `http://web.archive.org/web/20140215174309/http://tw.renesas.com/edge_ol/features/07/index.jsp`, accessed 2014/02/15, stored on `http://web.archive.org`

1.3 Research by doing

Considering that "it can certainly be questioned whether [context-aware] systems will ever succeed outside very specific domains with very limited scope" [72], we chose to research and experiment in the field of context-aware and pervasive computing by heavily interacting with other research communities and with end users. Moreover, research in the field of pervasive systems must not "strive for proactive computing but for proactive people [156]". In this thesis we propose a user-driven and problem-driven research characterized by a deep interdisciplinary approach.

Regarding the problems exposed in Subsection 1.2.1 and in [58], we don't strive to give a better definition of context, but rather to present works related to context-aware and pervasive applications, used in specific fields. There is the lack for enough maturity in the field of research to provide an exhaustive definition, nor we think that there is enough space for conceptual models and methods, as most of pervasive applications cannot be easily (or at all) be generalized.

1.4 Sports engineering problems

The main field of application of pervasive technologies we present in this thesis is related to sports engineering because:

- as a research field it is interesting and inserted within a nice and tiny frame (peculiar to the specific sport), with a good literature and base of knowledge that can be used to develop innovative measurement devices and processing methodologies;
- increasing the participation in physical activities through technologies can enhance the quality of life of people, addressing the problems of a sedentary lifestyle;
- sports engineering can represent a development and testing field for "more serious" applications: assistive and rehabilitation technologies. Sport can represent a controlled and safe test environment where to explore possibilities with exact questions in mind, and developed solutions can be re-used in other near "contexts", like medicine or rehabilitation technologies;
- Sports' Engineering [159] is an emerging and interesting multidisciplinary research topic, where Bio-mechanics, the science of studying the mechanical properties of living tissues [81, 113], and pervasive technologies can effectively work together to achieve new results.

1.4.1 Rowing and team synchrony

We had the opportunity to start an activity of research in the field of rowing, thanks to the collaboration with rowing coaches. This collaboration has motivated the study of the rowing technique, and an exploration of existing tools used to monitor the performance of athletes. From informal interviews and meetings it emerged that the trainers (a) have to coach heterogeneous groups of athletes; (b) have to train crews for different races. Moreover the trainers asked (c) for systems able to acquire information from the boat; and (d) for tools to help enhance the training level of athletes.

Introduction to rowing

Rowing is an old Olympic water sport, where men use oars to propel a boat [111, 11, 54]. Competitive rowing has the final goal of winning races, through the maximization of the boat speed to cover $2000\ \mathrm{m}$ over water. Muscular energy needs to be transferred to water through the oars, in order to obtain a reacting impulse, causing the forward motion of the boat. Negative effects, slowing (decelerating) the boat, mostly arise from (a) the interaction of the boat's hull with the water; (b) erroneous actions of the oars paddles in water; (c) air - body/hull interaction (friction). Rowing can be performed in a single or multiple men boat. In either case one of the key elements in minimizing negative effects while maximizing forward impulse during drive is the correct synchrony of the production of power on the two sides of the boat [3] and synchrony among different members of the team.

Available technologies

In competitive rowing, several training and testing devices have been used regularly for improving athlete's performance. Feedback systems play an essential role in the training process, but owing to the complexity of most of the systems, their usage has been limited to experts and thus, the systems were not suitable for coaches in daily training. Empirical evidence exists that on-water rowing training benefits from sonification (repeatable acoustic presentation of data) [167, 168, 166]. Systems for online feedback of rower movements do exist, both visual [79] and auditive [167, 68]. The usage of smartphones as sensor platforms in sports is presented by [133, 106], whilst other measures of on-boat dynamics, like foot stretcher forces are presented by [114] . All previous works have concentrated on single parts of a possible complete system. There is no comprehensive, all-inclusive telemetry and auditory training support system.

Synchrony among people is a key parameter when performing tasks related to group activities such as team sports (rowing, synchronized swimming, synchronized diving, ...) [52, 95]. Effective rowing requires high coordination and motor control [110]:

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[3] In order to reduce to possibly 0 the rotation momentum that causes rotation of the hull and thus slows down the boat.

rowers have to coordinate body movements with oars movements while maintaining the balance of the boat. When rowing is done in crews everything becomes more complicated, because every rower has to synchronize his movements with that of other members of the crew. Choosing the right rowing partners (pairs) is a key factor to increase synchrony and power contribution by rowers in a team [19]. The right pairs, exhibiting a high degree of synchrony in the production of power, are typically able to achieve a higher performance, measured in terms of average hull speed, that is the final goal of successful rowing. Moreover "alterations to rower's force-time profiles with different partners indicate the need to better understand interactions between the athletes [19] ", and synchrony of athletes is crucial to develop a higher ability to resist to pain and fatigue [52]. There actually is the lack for instruments able to analyze and help in training synchrony of rowers [52, 95], and a computer-aided approach to improve the training process in rowing is highly desirable [77].

1.4.2 Swimming efficiency

Introduction to swimming

Swimming is a self-induced aquatic activity, aimed at displacing swimmers body, cognitively controlled at limited energy regime, where limb's interaction with displaced water mass changes the energy-density per unit volume in the fluid. The energy-density per unit volume, the pressure, can be perceived and also be measured through sensors. Sonification could be used to map any data-flow measurements as an interactive, functional sound, to be used and presented to users as a feedback carrying information regarding the pressure field around the hand [93]. However even though evidence exists that kinematics alone is not enough to explain flow effects and propulsion in swimming [107], most of the work done until recent years in research of swimming concentrate on kinematics rather than on fluid-dynamics to study efficiency of propulsion.

Feel-for-water

There is the need to communicate the so called *Feel-for-water* of swimmers. This feel-for-water is connected to the most relevant factor in swimming, fluid-dynamics. Typically monitoring of swimming is done by means of direct observation, camera recordings, or measurement systems aimed at analyzing kinematics rather than fluid-dynamics. There is however the lack for systems to monitor underwater fluid-dynamics on a daily basis and for a usable and affordable training aid for water space activities, equipped with auditive biofeedback.

1.4.3 Running performance and gait rehabilitation

Working with national level running trainers and athletes motivated the research of applicability of pervasive technologies to enhance training of running.

Identification of relevant running parameters

Exploration of the possibilities of the use of pervasive technologies to enhance running performance showed a lack of usable wearable devices able to provide information regarding *relevant* running parameters (contact, flight time of feet, energy expenditure, ...). Using systems composed of a single accelerometer, mounted on the waist or trunk [3, 7], reduces the impact on the athletes or patients monitored. However using a single sensor imposes severe limitations to available information about activities, and obliges the research of new ways to gather knowledge from that single sensor.

Realignment of accelerometer signal

Using a single mounted accelerometer, and needing to access information about accelerations along body motion axes and not axes of accelerometer (that can be mounted in a different orientation every time it is put on body), underlines the need for algorithms aimed at realigning the axes of a 3D accelerometer, in order to be coherent with body motion. In fact the knowledge of the center of mass acceleration components is crucial to study human gait [199]. The body reference system consists of the sagittal axis X (antero-posterior direction), the coronal axis Y (mediolateral direction) and the vertical axis Z (aligned with the gravitational vector g). To sample acceleration components, a triaxial accelerometer is usually placed on the lower back of the subject, i.e. near to the center of mass of body. Errors due to the initial and usage misplacement of the device with respect to the body reference system must be corrected. This can be achieved by a virtual rotation of the device's axis (x-, y- and z-axis), in a similar way to the one presented in [139].

1.4.4 Assistive technology for blind and visually impaired

Sonification, precise and repetible transformation of data into sound, can be used to build aids for blind and visually impaired people [152, 8]. The SeeColOr project [24] is aimed at transforming visual information, acquired through a camera, into sound. There actually is the lack for a portable, usable and affordable system implementing the ideas at the base of the SeeColOr technology. The case of Neil Harbisson [91], a color-blind-born American guy, showed how technology can first replace "normal" human senses, and even enhance them over "normal" possibilities: using a camera and an embedded device to hear colors of objects he is pointing at, he became able to develop a particular kind of synesthesia, between auditive and visual senses, leading him to consider himself as the first Cyborg [4].

1.5 Contributions of This Dissertation

In this thesis we propose a working methodology, based on user-driven and user-centric design, to develop innovative pervasive solutions, thought to fit the needs of single classes of users. To demonstrate the validity of the working methodology we present diverse applications, mostly related to the field of sports and human activity monitoring. The diverse applications are considered as design patterns for the application of sensors, processing and feedback systems, in the respective specific *use contexts*. In fact "it can certainly be questioned whether [context-aware] systems will ever succeed outside very specific domains with very limited scope" [72].

The main concern, common to all of the works, is how to find the parameters that are more *relevant* to the performed action (e.g. synchrony for a rowing team, fluid-dynamics for a swimming person, ...), and based on this, develop a solution aimed at analysing, observing and eventually training and/or leverage the effects of that particularly *relevant* phenomenon. A key issue when designing, building, deploying systems, as for training, rehabilitation, is to consider thoroughly how interaction is happening [66], and not only focusing on the sensor systems [177]. Moreover we wish to recall Hartmann et al. [90], that states that "numbers alone are a poor choice for making sense of continuous signals as the relationship between performed action and reported values is not visually apparent". Furthermore the same authors continue affirming that "creating interactive systems is not simply the activity of translating a pre-existing specification into code; there is significant value in the epistemic experience of exploring alternatives [108]".

1.5.1 Rowing

There are two main contributions in the field of rowing training aid tools:

(i) Feedback

a well-documented, ready-to-use and scientifically proven solution for on-water rowing training enhancement through functional audio feedback, usable both on smartphones and on PCs, in order to increase the level of synchrony of the group, leading to a smoother movement of the boat, and thus to a higher average speed;

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[4] `http://www.harbisson.com/`, `http://www.cyborgfoundation.com/`

(ii) Synchrony

the study of methods to recognize and analyze synchrony in a rowing boat: it was necessary to design a system based on accelerometers to detect movement and develop methods and algorithms designed to achieve the goal of detecting the *relevant parameter*, the synchrony of the group of athletes. Several approaches have been tested, starting from the first visual inspections of signals of accelerometers mounted on oars, from cognitivist analysis, based on the study of the trend of correlation between the signals of pairs of athletes, to finally arrive to the definition of a system, called MARS, which through the use of stigmergy, inspired by the communication patterns of some classes of insects by means of pheromones, has allowed to obtain an emergent agent based system for the detection of synchrony of a rowing team.

1.5.2 Running and gait

To analyse running technique, we propose an approach based on a single trunk mounted accelerometer, to measure relevant parameters of running act, flight-contact ratio of feet on ground, medio-lateral symmetry factor. To achieve this goal, specific algorithms were defined, in order to process the accelerometer signal. In order to access information about running parameters from a single accelerometer there is the need to preliminary realign the axes of the measuring accelerometer, as an exact placement of such devices is difficult on human body, and successive placements will exhibit differences in orientation. The realignment of the axes of measure is done using autocorrelation of signal. The extraction of parameters and computation of symmetry is done using ad-hoc algorithms.

1.5.3 Sonification

Starting from SeeColOr [57], we envisioned the possibility to extend it towards mobile platforms and to implement it on OpenSource platforms. Doing so we will provide a bigger number of people the possibility to take advantage of that technology. The new designed application, called SeeColOrMobile, was implemented and tested in laboratory, while on field tests with blind people are being performed during the time of writing this thesis.

1.5.4 Swimming

We started investigating existing literature about swimming training, teaching and performance. We found that most authors do concentrate on kinematics rather than hydrodynamic effects. We believe that this is hindering a better perception of water, and thus also hindering the process of teaching and learning swimming. Thus we proposed, designed, implemented and tested a system able to measure water flow effects in-situ (hands of swimmers) and provide an on-line auditory biofeedback by means of sonification to both swimmers and trainers. Thus we state also that the system is enabling a new way of communication between swimmers and trainers, thanks to the common access to the same information provided over the audio channel.

1.5.5 Wireless Sensor Network adoption

We analysed some reasons still preventing Wireless Sensor Networks to spread in a quicker and easier way inside of communities in which less pervasive computing and information science expertise is present, like Geology and Glaciology. The analysis is done with the goal of providing a base of discussion and consideration to increase the usage of that technology in the world outside of computer science and engineering research communities.

1.5.6 The sense of Context

In this thesis we concentrate on how to transform *relevant* data, sensed on body or in the near field environment of people into meaningful information and on how to transmit, how to communicate it, to users, consumers of that information. Hence instead of concentrating solely on the acquisition and processing per se, we put emphasis on how to make "*sense of the context*" rather than limiting to "*sense the context*" to feed an autonomic and "autistic" computing device. Bellotti et al. [21] state that designers should put more emphasis on the analysis of human-human communication in order to enhance the quality and sense of systems involving the usage of Ubiquitous Computing and tangible interfaces. We give maximum attention to systems and approaches that can be used in real-time by people. The real-timeliness is needed to enable the development of feedback systems, and it motivates the research of the simplest (computationally) possible solutions and algorithms in order to minimize the delay between the point in time of measured events and the consequent output of the "computing" system. Moreover we want to underline that generally "a limited amount of information covering a person's proximate environment is most important for this form of (*Context Aware*) computing since the interesting part of the world around us is what we can see, hear and touch [169]".

1.6 Dissertation Organization

This dissertation is structured into 7 chapters where we deal with the above mentioned problems. In **Chapter 2** we present sonification technology, some background and an assistive technology application called SeeColOrMobile. In **Chapter 3** we present how to monitor rowing activity and provide audio feedback, using pervasive technologies. We present how to produce an auditive biofeedback related to the boat motion using a PC in *Section 3.1* (presented in [40]) and using a smartphone in *Section 3.2* (presented in [39]). We present two innovative approaches to analyze accelerometer data coming from sensors mounted on rowing oars in order to gain information about synchronism of the team, the first, in *Section 3.3*, based on correlation function (presented in [35]), the second, in *Section 3.4*, based on a stigmergic emergent approach (presented in [17]). In **Chapter 4** we deal with the problem of swimming and perception of feel for water, and present a solution to allow sensing and communicating about this "6th sense" using an auditive biofeedback (presented in [185]). In **Chapter 5** we describe how to extract relevant features for running from a back mounted single accelerometer, and how to realign the axes of a 3D accelerometer via software in Section 5.2 (presented in [15]). In **Chapter 6** we present an analysis of some of the reasons behind the slow adoption of Wireless Sensor Networks in the field of environmental sensing (presented in [38]). Finally, **Chapter 7** contains our conclusions about the presented issues.

2

Sonification - introduction and an assistive application

Sound is a wave
like a wave on the ocean

Andrew Bird - Sifters

2.1 Introduction to sonification

Sonification:

> "Sonification is the data-dependent generation of sound, if the transformation is systematic, objective and reproducible, so that it can be used as scientific method."

(Hermann, 2011 [92])

Consider this example: the *bip* emitted by an electric oven's timer carries information about expired time, but nothing more, no information regarding the "state of cooking" of the food. On the other hand the parking sensor (proximity sensors) of modern cars [1] can produce a sound that is directly proportional to the distance from possible obstacles; through this sound the driver obtains information about existence and also of distance to the obstacle in real-time.

Both, timer bell and proximity sensor sound, represent cases of *Auditory Display*, but only in the latter we speak about *Sonification* , as the produced sound depends upon data, carrying information about the distance [160].

---

[1] `http://www.micro-tronik.com/Support/Info/Benz-PTS.htm`,
`http://www.bmw.com/com/en/insights/technology/technology_guide/articles/park_distance_control.html`

Sonification to assist men on a daily basis has already been proposed by FIAT S.p.A. in 1986 with a patent [80]. FIAT proposed a system designed to provide information about the state of the car to the driver.

2.1.1 Sonification techniques

In the context of Sonification we can distinguish four main different sound production techniques:

- *Event-based sonification*: sounds are produced when particular events happen. Alarms and notifications are part of this category.
- *Parameter Mapping Sonification*: any sound can be manipulated changing it's parameters, e.g. frequency, volume, length of a tone. With Parameter Mapping any information that needs to be sonified is *mapped* on a specific sound parameter.
- *Audification*: in case of data series, considered as signals, that are similar to a sound wave (frequency and amplitude), they can be *audified* changing their characteristics to make them audible.
- *Model-based sonification*: this technique differs from all three presented before. Instead of mapping data into sound parameters, data are used as parameters of a model. Interaction with the model, possible by "excitation", putting "energy" into the model, creates a new way of interactively exploring (large) data-sets.

2.1.2 Sport and fun applications

First applications of sonification were mainly concentrated on offline exploration of datasets, with little to zero interaction. During later days, interactive, real-time and online applications of sonification started to become an important part of research effort in the auditory display and sonification community [2].

Sport and fun / game sector represent important sectors of attention in terms of real-time sonification applications:

Paraolympic biathlon

in Paraolympic biathlon blind or visually handicapped athletes use an electronic rifle, endorsed with an acoustic aiming device, that uses real-time sonification of data coming from sensors to provide information about precision of alignment with the target.

Audiogames

A number of games that use sound as a primary means for interacting with the computer, called *Audiogames* were developed.

---

[2] International Community on Auditory Displays - ICAD `http://www.icad.org/`

Matrix Shot is a game with the goal of avoiding a series of virtual bullets fired at the player from a distance. The player is able to determine the position of the bullets thanks to the stereo sound supplied through headphones, in order to avoid being hit, without making use of any visual cues.

One-Player-Blindminton is an *audiogame* that is inspired by badminton, where the player must hit a virtual ball with a racket to bounce it on a virtual wall. Since the ball is virtual, the player can determine the position only by listening to a sound that is produced by six speakers placed around the playing area. This example demonstrates how a sonification consistent information about the location of a ball can completely eliminate the need of a visual contact with the moving object, while not compromising the motor coordination.

2.2 Sonification of colours

2.2.1 Neil Harbisson - the first Cyborg

Neil Harbisson [3], was born with achromatopsia, a condition that only allowed him to see in black and white. He eventually visited schools of fine arts, and started painting, however he only used black and white, and the same way, he only dressed black and white. Before 2003 Neil used to say "I never used colours to paint because I feel completely distant to them. Colours create a mysterious reaction to people that I still don’t quite understand." In 2003 Neil started to work with Adam Montandon, inventing what was then called the *Eye-Borg* (Figure 2.2.1 [4]), a device allowing Neil to perceive colours, acquired through a camera, in the form of sound. Neil Harbisson calls himself the "first cyborg in history". Cyborgism, the enhancement of man with technology means, is considered an important theme of discussion also in the field of philosophy of "Mind-Uploading" [91].

2.2.2 See ColOr

"Following a 2002 survey, the World Health Organisation estimated there were 161 million visually impaired people in the world, of whom 124 million had low vision and 37 million were blind" [146, 57].

---

[3] `https://web.archive.org/web/20140129104056/http://www.newscientist.com/blogs/culturelab/2012/06/cyborg-makes-art-using-seventh-sense.html`

[4] Image under CC license, taken from `http://www.flickr.com/photos/25958224@N02/8122856863`

Figure 2.1. Neil Harbisson with the Eye-Borg device

SeeColOr Project

The SeeColOr (See Colors with an Orchestra) project [5] has the ambitious goal of limiting the effects of visual impairments, providing the information typical of the visual sensory through sound. The transformation of visual information, acquired through sensors or a camera, is done using sonification [10].

The project started in 2005, leaded by Dr. Guido Bologna [6], pursues its goal of:

- *spatialization* of surrounding environment;
- *localization* of objects;
- *detection* of obstacles;
- *detection and recognition* of colors;
- *ability to follow trails of color* in large areas;
- *identification* of the major chromatic components of a static image.

using an Orchestra, to have an intuitive and familiar presentation of visual information.

"The See Color interface transforms a small portion of a coloured video image into sound sources represented by spatialised musical instruments. Basically, the conversion of colours into sounds is achieved by quantisation of the HSL (Hue, Saturation and Luminosity) colour system. The purpose [of See Color] is to provide visually impaired individuals with a capability of perception of the environment in real time." [57].

In fact, during first experiments [7], SeeColOr demonstrated its ability to enable blind users to:

---

[5] University of Geneva and University of Applied Science of Geneva

[6] University of Applied Science, Geneva

[7] `http://www.youtube.com/user/guidobologna`

Figure 2.2. Detection of socks' color using See ColOr [57]

- **detect** a door to enter and exit from a room;
- **walk** along a corridor with the goal of finding a *blue* cabinet;
- **move** in a corridor with the goal to find a *red* shirt;
- **detect** two *red* obstacles and pass between them;
- **avoid** obstacles.

2.2.3 From SeeColOr to SeeColOrMobile

To explore possibilities of sonification applied as an assistive technology, we started a collaboration with the group of Dr. Guido Bologna (University of Applied Science, Geneva, Switzerland). In particular we had the opportunity to study possible uses of the See ColOr system, coupled with mobile technology (smartphones). We chose to explore possibilities of making SeeColOr mobile in order to enable blind users to try that technology with low cost and lightweight devices.

2.3 SeeColOrMobile

2.3.1 What are colors

In order to better understand the working principle of SeeColOr and how SeeColOr Mobile has been implemented we next present an introduction to what colours are.

In biophysics *color* is the visual perception generated by nerve signals that the photoreceptors of the retina send to the brain when they absorb electromagnetic radiation of certain wavelengths and intensity in the visible spectrum. The visible light is

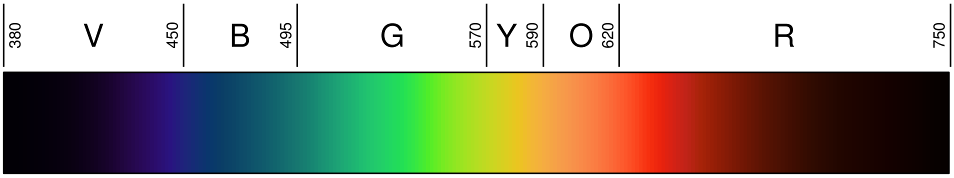

Figure 2.3. Frequency spectrum of visible light

considered white as it is the sum of all the frequencies of the visible spectrum . Each frequency of the visible is associated with a certain color. In particular, the differences in color of objects which do not emit their own light, derives from the fact that a certain body absorbs all the frequencies but the one(s) the human eye perceives.

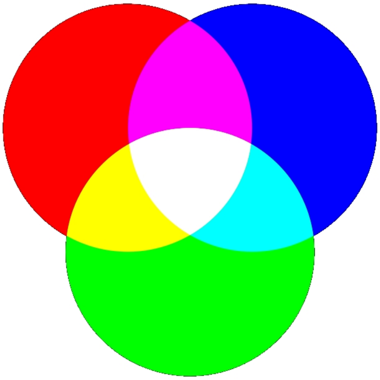

Figure 2.4. RGB addictive model

2.3.2 SeeColOrMobile logical structure

We designed SeeColOrMobile at a logical level as the cooperation of two indipendent modules: **ColorDetection** module, and **DataSonification** module (Figure 2.5) [10]. The first module communicates data to the second, using a simple format, specified later.

ColorDetection module

This module reading the mobile phone camera identifies a sub-area, called **DetectionArea** (Figure 2.6), whose size can be later configured.

DetectionArea is composed of M **VirtualPixels**. Each VirtualPixel (v) is composed of $A * B$ real pixels (r). For each VirtualPixel we identify the main color, coded

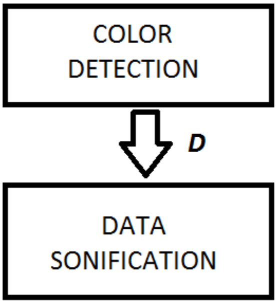

Figure 2.5. SeeColorMobile logical structure

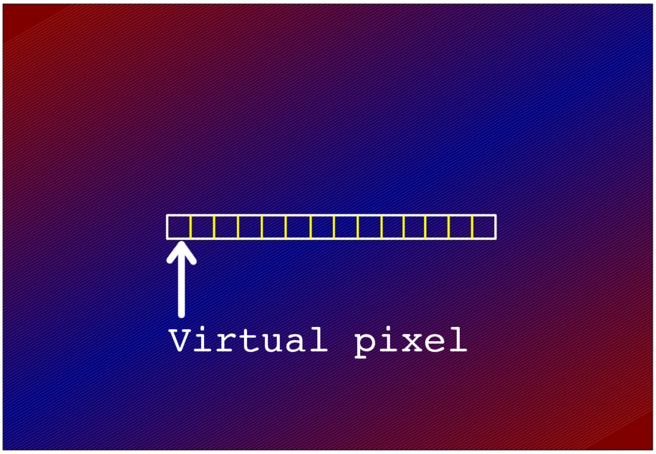

Figure 2.6. AreaDetection

in RGB (Red, Green, Blue) as the average color values of its real pixels, following equation 2.3.2.

$$[R,G,B]_v = [\frac{\sum_{k=1}^{A\cdot B} R_{k_r}}{A\cdot B}, \frac{\sum_{k=1}^{A\cdot B} G_{k_r}}{A\cdot B}, \frac{\sum_{k=1}^{A\cdot B} B_{k_r}}{A\cdot B}]$$

The obtained RGB value of each VirtualPixel is converted into the corresponding HSV (Hue, Saturation, Value) code. Using the HSV code we classify detected colors based on table 2.1. Based on this classification table we derived a simple decision tree, that we here omit for simplicity.

We can classify SeeColOrMobile between the class of ParameterMapping and event-based sonification schemes.

H	S	V	Color	ColorCODE	Intensity
any	any	V < 0,125	Black	4	3
any	S < 0,25	V > 0,5	White	3	3 - (V - 0,5)/0,125
any	S < 0,25	V < 0,5	BLack	4	3 - V/0,125
H < 30 o 330 < H < 360	S > 0,25	V > 0,125	Red	0	S/0,25
30 < H < 90	S > 0,25	V > 0,125	Yellow	5	S/0,25
90 < H < 150	S > 0,25	V > 0,125	Green	1	S/0,25
150 < H < 210	S > 0,25	V > 0,125	Cyan	6	S/0,25
210 < H < 270	S > 0,25	V > 0,125	Blue	2	S/0,25
270 < H < 330	S > 0,25	V > 0,125	Violet	7	S/0,25

Table 2.1. Color parameters

Data format D

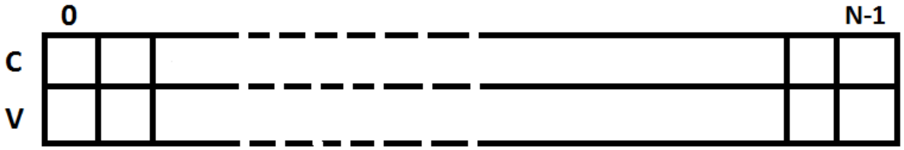

Figure 2.7. Data format

To make the **ColorDetection** and the **DataSonification** module indipendent we designed a simple communication protocol between them, based on a defined *data format* 2.7). The data is represented by a $N * 2$ integer matrix, with N the number of virtual pixels of **DetectionArea**. The first row contains **ColorCode** (C), while the second row contains **Intensity** (V). Each **ColorCode** is an integer $[0, 7]$, corresponding a a particular color. The **Intensity** field is an integer $[0, 3]$.

Color	ColorCODE	Intrument
Red	0	Oboe
Green	1	Flute
Blue	2	Piano
White	3	Voice
Black	4	Alto
Yellow	5	Bass
Cyan	6	Trumpet
Violet	7	Saxophone

Table 2.2. Color-ColorCode-Instrument association

Intensity	Tone
0	Do
1	Sol
2	Si*b*
3	Mi

Table 2.3. Intensity-Tone Association

DataSonification module

This module receives data (Figure 2.7) with colors coded as in table 2.1 from ColorDetection module and is in charge of **sonifying** it. The association between color and musical instrument is provided in Table 2.2. In order to represent spatial information, differently from the original SeeColOr [57] project (that uses Head Related Transfer Function filtering), we used simple stereo panning of audio over L-R speaker / earplug.

2.3.3 Complete application interface on mobile device

SeeColOrMobile uses a simple and intuitive user interface (Figure 2.8), that presents current image from camera of the smartphone, a representation of **DetectionArea** and its VirtualPixels and some information about detected color codes, Frame-to-Frame time and elaboration time (should elabTime be bigger than FtF problems would arise in the application).

```
FtoF=70ms ColorsDetected= W W W W W  ElabTime=12ms
```

Figure 2.8. Main activity of SeeColOrMobile

Other less relevant functionalities that have been incorporated into the application are: Flash Mode (On/Off), VirtualPixelSize (Width and Heigth in terms of RealPixels), AreaDetection (Width and Height, in terms of VirtualPixels).

The complete software SeeColOrMobile has been thoroughly tested, and will soon be published on the app market for Android devices.

2.3.4 SeeLightMobile

Motivated by exchange of experience and thoughts with some blind people, we discovered a new application for the technology developed as SeeColOrMobile. It is a simple and seemingly useless (to non-blind people) application: detect light level in a room. We consider the reason behind this application a good example of "need-for-user-driven-research": the blind people we interacted with explained us that their guide dogs would not sleep with the light turned on. That simple, and astonishingly difficult to think of for someone "normal-sighted" shows the need for deep and continuous interaction between designers, researchers and users.

This new application, called SeeLightMobile [127], based on Android technology and the SeeColOrMobile (presented in Section 2.3) base of code, is specialized into the detection of light level.

SeeLightMobile is designed to detect light levels using either light sensor or on-board camera, using between 2 and 7 levels of light, and presenting the detected light level over sound and over a text that can be converted into speech using Android's *talkback* accessibility function.

The use of the light sensor is clearly possible only if it is present and if the Operating System has access to it:

```
if (packageManager.hasSystemFeature(PackageManager.FEATURE_SENSOR_LIGHT))
        // This device has light sensor
else
        // This device has no light sensor
```

Using light sensor or camera is different, in the sense that the camera is normally subject to automatic white balance, and color correction, that leads to a biased detection of light level. Using the light level detected by the light sensor is done as:

```
// ...
Sensor lightSensor = sensorManager.getDefaultSensor(Sensor.TYPE_LIGHT);
// ...
public void onSensorChanged(SensorEvent event) {
        float currentReading = event.values[0];
        //Classification of light level, reading currentReading
```

```
}
```

On the other hand, using the readings from the camera to detect light level is done in a way similar to the original SeeColOrMobile (Section 2.3) does, calculating the luminance of colors, with the only difference that the *DetectionArea* is composed of a single *VirtualPixel* that has the size of the whole camera view. Moreover, luminance is calculated from the RGB color model as in equation 2.1:

$$Y = 0.2126 * R + 0.7152 * G + 0.0722 * B \tag{2.1}$$

where Y is luminance, the perception of light emitted or reflected by objects, and R, G, and B are the values obtained from the RGB model of the image. The obtained Y value is converted into the light level, and provided to the user as an information in form of sound and text on screen.

2.4 Conclusion

We conclude this chapter with just a few considerations (a) sonification is a promising technology and active investigations regarding its usage in assistive technology applications and environments is currently active in both the research community and in the so-called *maker* community; (b) in other chapters of the thesis we will see other usages of sonification as a communication and a bio-feedback enabling technology.

3

Rowing - measuring synchrony and providing feedback

> Plonger au fond du gouffre, Enfer ou Ciel, qu'importe?
> Au fond de l'Inconnu pour trouver du nouveau!
>
> Charles Baudelaire, Les Fleurs du Mal

Monitoring and measuring elite athletes in their natural training environment is attracting interest in the sporting and engineering research and users community. Complex and cumbersome measurement equipment can influence training and analysis sessions athletes undertake to improve their level of performance, but monitoring is only one of the steps to go along the way of athletic performance improvement. Real-time feedback represents a good way to improve the performance of the athletes, providing direct information about quality and not only quantity of movement. Sound is an effective means to provide a feedback to humans, and sonification is a way to functionally transform information into sound.

In this chapter we present:

- an innovative multiplatform ready-to-use telemetry and sonification solution for PCs for the enhancement of rowing training in Section 3.1;
- a mobile phone based telemetry and sonification solution for enhancement of rowing training in Section 3.2
- a system based on accelerometers and correlation function to extract information about synchronism in real-time from a rowing boat 3.3
- a system based on accelerometers and using an emergent approach based on the stigmergy paradigm to extract information about synchronism in near-real-time from a rowing boat 3.4

3.1 A multiplatform telemetry and sonification solution for rowing

In competitive rowing, several training and testing devices have been used regularly for improving athletes' performance. Feedback systems play an essential role in the training process, but owing to the complexity of most of the systems, their usage has been limited to experts and thus, the systems were not suitable for coaches in daily training. Empirical evidence exists that on-water rowing training benefits from sonification (acoustic presentation of data information) [167, 168, 166]. Accrow is an existing rowing-specific kinematics measurement device (Figure 3.1 [1]). AccrowLive 2.0, implemented to present real-time visual and acoustic feedback during rowing, consists of a multi-platform software solution that provides both real-time telemetry and sonification for smart-phones (iOS) [40] and PCs (Windows, Mac, Linux) connected to Accrow. AccrowLive 2.0 software connects in real-time with Accrow in order to analyze and extract relevant features from the data stream, such as boat acceleration and speed, number of strokes and current boat speed as well as the estimated time over 500m. The acceleration and the speed are represented through a graphical interface plot and through functional sound. The sound presentation follows the principles of sonification of human movements, as presented by [97]. The introduction of a the ready-to-use AccrowLive 2.0 solution will enable more users to take advantage of the sonification technology, in order to achieve a double goal: improve performance for the athletes and develop a deeper and broader understanding of real-time sonification effects on athletes and coaches, thanks to a more widespread adoption of this training technology. Other proposed systems for online feedback of rower movements do exist, both visual [79] and auditive [167, 68].

The usage of an smartphones as sensor platforms in sports is presented by [133] and [106] , whilst other measures of on-boat dynamics, like foot stretcher forces are presented by [114] . All previous initiatives have concentrated on single parts of a possible complete system. There is no comprehensive, “all-inclusive” telemetry and auditory training support system. The main contribution from this innovation is to provide a well-documented, ready-to-use and scientifically proven solution for on-water rowing training enhancement through functional audio feedback. For a throughout description of rowing dynamics refer to [54, 111, 11]. The section is organized as follows: subsection 3.1.1 describes the technology that was needed to build the system; subsection 3.1.2 shows how the pieces of technology are put together to get a complete monitoring, telemetry and feedback system; the system itself is discussed in subsection 3.1.3 ; subsection 3.1.4 concludes the section.

---

[1] Courtesy of BeSB GmbH and University of Hamburg [84]

3.1.1 System description and platform

AccrowLive 2.0 is a solution composed of an Accrow device, the wireless communication channel and one or more analysis/feedback output systems (PCs or mobile devices).

Accrow device/sensors

The Accrow device (BeSB GmbH and University of Hamburg) consists of a MEMS (Micro Electro-Mechanical Systems) Acceleration sensor, sampling at 50 Hz, a 4-Hz-GPS (Global Positioning System) receiver, a microcontroller, a SD (SecureDigital) Card Memory and a WiFi chip. The microcontroller is in charge of executing the task of sampling sensors, elaborate acceleration and speed values by integrating the raw acceleration sensor values and the raw GPS (NMEA protocol) signal, and transmitting the result via WiFi to connected clients (PC and/or iPhone). The microcontroller also saves all sampled data locally on the SD. Using a common web browser it is possible to download the files with all raw data sampled during the training session.

Communication

Data are sampled from Accrow, the external device that has to be put on the boat. In Figure 3.3 the blue arrow represents how Accrow (oriented according to longitudinal boat movements) is placed. The communication with the PC or iOS mobile device, takes place through a Wi-Fi connection (Figure 3.2). The protocol used to transfer the data over the WiFi connection is UDP (User Datagram Protocol). UDP is more suitable for real-time applications than TCP (Transmission Control Protocol) because it does not retransmit lost data, thus saving precious time to provide a lower delay to deliver data. This “real-time quickness” is a crucial aspect in the case of AccrowLive, as the maximum tolerable delay between cause and sound is 100ms in order for humans to experience a multimodal interaction with the system [29].

Output and Analysis device(s)

As an analysis output platform, we use a PC and / or a mobile iOS powered device. PC platform is more usable by coaches than by athletes, whilst the mobile device platform is usable easily by both coaches and athletes in the boat.

Figure 3.1. *Accrow* device

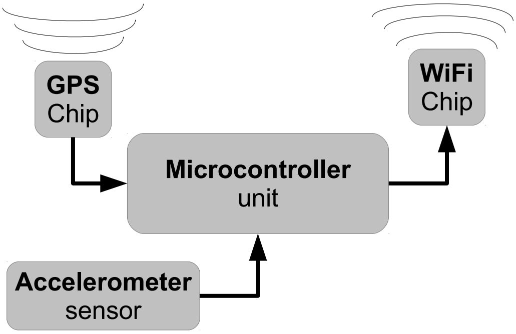

Figure 3.2. *Accrow* internals

Sonification

The sonification scheme implemented in AccrowLive was based on the Sofirow-system (of already empirically proven effectiveness), that had been developed as a rowing specific sonification scheme. It consists of a discrete pitch mapping that converts the acceleration values from Accrow into corresponding sound pitches (frequency modulation).

The sonification consists of a square wave as specified in (1):

(1) $Tone(a) = sgn[Asin(2 * \pi * \nu)]$

where sgn is sign function, A is the amplitude of the signal, sin is the sinus function, and ν is a function of a:

(2) $\nu(a) = 220 * 4^{\lfloor a*12 \rfloor /12}$

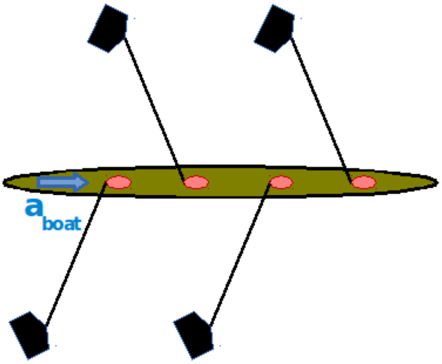

Figure 3.3. Driving direction of boat

Figure 3.4. Complete feedback loop

where ν and a represent respectively the frequency of the wave and the acceleration.

The frequency was mapped as in Figure 3.5 with the function in equation (2), that represents an exponential stepwise function of a. The expressed mapping works as follows: when a is 0g the frequency of the wave is 220 Hz and from 0g to 1g there are 12 different samples of frequency. At a = 1g the frequency is 880Hz and at a = -1g it is at 55Hz. Note that the maximum and minimum accelerations measured on a typical rowing boat in the direction of movement are between +8m/s2 and -8m/s2, that is within the +/- 1g range).

Figure 3.6 represents how to regulate the amplitude A depending on the frequency. This is useful to reduce the perception of loudness. Human perception of loudness depends upon sound frequency (or pitch). To prevent a different perception of the amplitude / loudness of sounds a frequency/amplitude compensation filter

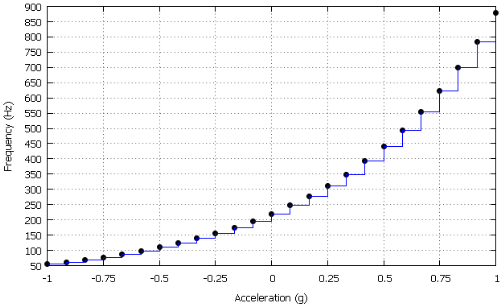

Figure 3.5. Frequency mapping

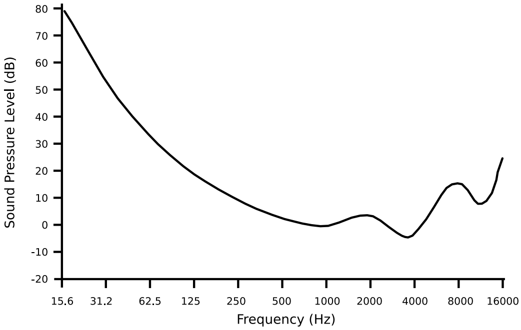

Figure 3.6. Loudness compensation curve for average human hearing

has been implemented, following Figure 3.6, representing the loudness compensation curve usable for average human hearing. The sound designed for AccrowLive 2.0 is called a functional sound. Functional means that the information contained in the data should be reflected meaningfully without losing its inherent information. Creating a more aesthetic sound, as proposed by [68] would probably mean to create a more musical sounding result but that would include multiple overtones (harmonics) and thus it would obliterate differences in the underlying data as changes in tone pitch would be interpreted as changes in the acceleration-trace.

3.1.2 Design of the complete system

Activity monitoring (telemetry + presentation)

Telemetry is the ability to measure a system remotely. Sensing is the first step to measure, followed by filtering, calibrating, processing data to extract relevant information with algorithms. Implementing real-time activity monitoring systems, for sports or human safety reasons, using kinematic sensors like accelerometers, gyroscopes, GPSs, asks for the development of robust filters and recognition algorithms [15]. AccrowLive implements the same computationally simple but still robust activity recognition and analysis algorithms, on both mobile and PC platforms. However, the two implementations needed different programming skills, as on the mobile platform the standard iOS development environment was used, taking advantage of native programming, whilst the PC based solution was programmed using SuperCollider, an OpenSource programming environment, language and sound synthesizer. AccrowLive plots the boat acceleration and speed, the number of strokes and displaying the current boat speed as well as the estimated time over 500m.

Monitoring software

AccrowLive was implemented with SuperCollider (SC) on PC systems and using native code for iOS powered devices (iPhones, iPad, iPod). SuperCollider [2] is an Open Source development environment with its own programming language developed and used for real-time audio synthesis. iOS (Apple Inc., CA, USA) is an embedded operating system for mobile devices supporting real-time multimedia applications development. Common characteristics for both PC and mobile versions of the software are presented next. In real time the software represents graphically the acceleration and the speed of the boat. These values are obtained through WiFi from Accrow. Boat speed is calculated by integration of the acceleration values, measured via the MEMS acceleration sensors, and the speed provided by the GPS. Stroke detection is achieved in real-time with a robust algorithm based on the acceleration data. The estimated time over 500m is derived from velocity. The application presents numerical values of relevant rowing parameters: speed, the instantaneous speed of the boat; speed5, the average speed during the last 5 strokes; str, stroke rate, obtained as inverse of last stroke duration; strdist, stroke distance, traveled during the last stroke; and 500m, time the boat would need to travel 500m considering speed during last stroke.

The software plots the data sampled from Accrow as shown in Figure 3.7 and represents the acceleration using functional sonification, as explained in 1.4. The software also allows the data sampled to be saved in a file that can be analyzed after the training session. The coach can interact with the software using the gray part shown in Figure 3.7, choosing which type of analysis to do (Offline using “Load file”, Real Time using “Real Time”), switching the sonification on/off.

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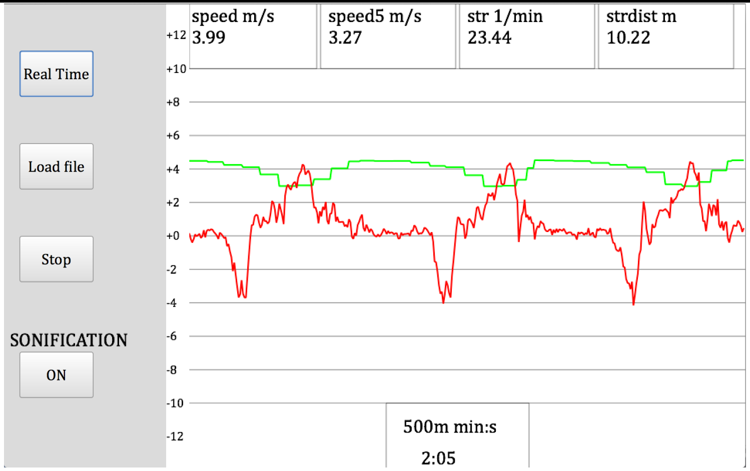
[2] SuperCollider Official site: http://supercollider.sourceforge.net



speed m/s 3.99
speed5 m/s 3.27
str 1/min 23.44
strdist m 10.22
500m min:s 2:05

Figure 3.7. AccrowLive PC GUI

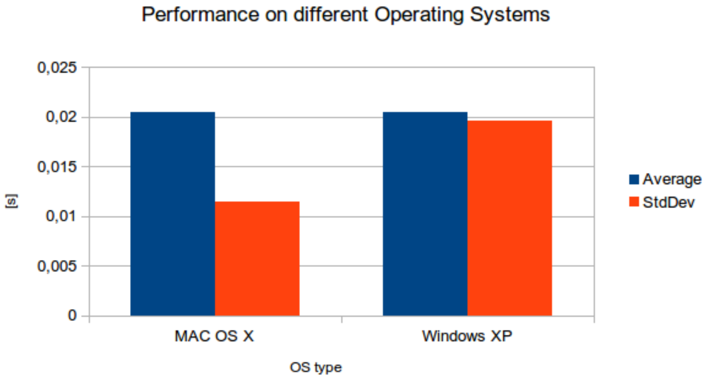


Figure 3.8. Windows vs. Mac OS

3.1.3 System evaluation

In existing literature on sonification, the usage of dedicated devices like Accrow is often described as impractical, looking for solutions based only on easy-to-develop systems (composed of some electronics, a smartphone and some nice sounds). This approach however is only appealing for technology interested readers. Coaches and athletes do need complete systems that can be used just as they take the boat and go on the water. A dedicated, robust, waterproof and simple to mount device like Accrow, coupled with a mobile device or PC system is far more usable than other solutions. This has emerged from preliminary questionnaires some coaches were asked to complete. The whole AccrowLive system is completely wireless except for the battery needed by the Accrow itself, making the preparation of the boat quick and easy.

A comparison of performance of the AccrowLive PC application, running on different Operating Systems is provided in Figure 3.8. The average value reported is almost the same in both systems, and is related to sampling frequency of 50Hz, whilst the standard deviation (StdDev) of the delay between the processed sensor samples is different. A higher value of StdDev indicates for a less stable system. AccrowLive application has also been tested on Linux, but we omit results here for simplicity. On Windows 8 problems connecting Accrow to the PC impeded to successfully perform working tests.

3.1.4 Conclusion and future perspectives

AccrowLive was originally meant to be software designed for coaches to see the acceleration and velocity of the rowing boat during training in real-time. Also the extension of AccrowLive 2.0 with sonification was originally intended only for coaches. Due to the possibility to provide the information on a smartphone it is now thinkable to provide the information from Accrow via the smartphone to the athletes as well, for both kinds of feedback: visual and auditory. But this hasn't been tested up to the present and so, the explanation of how AccrowLive 2.0 can change the training of athletes can only be inferred from those of previous studies [166] as the method doesn't differ in principle. Finally, the sonification platform can be used by coaches during on-water training as well as for a later off-line analysis of athletes' performance. The sonification presented to the coaches aims at assisting their visual observation of the boat motion in daily training by use of sound in order to detect fluctuations that are not visible, and it aims at introducing sonification to more users and into everyday club training including young and older rowers (juniors and masters). As future steps, incorporation of emergent analysis techniques [17] and sonification is planned.

3.2 Smartphone based sonification and telemetry platform for rowing

On water rowing training greatly benefits from sonification. However, no real-time usable smartphone based platform exists for acquisition and sonification of data measured during rowing. We propose the use of a smartphone based system, coupled with an Accrow (BeSB) data acquisition device. The whole system is able to convey the produced sound within 100ms from the movement, thus enabling the presentation of functional real-time feedback to the rowers. The system is thought to be useful for both athletes and coaches. The sonification presented to the athletes is aimed at enhancing their perception for the movement execution with the final aim of synchronizing the crew in a uniform rhythm in order to improve the boat velocity. The sonification presented to the coaches aimed at assisting their visual observation of the boat motion in the daily training routine by listening to the sound in order to detect fluctuations that are not visible. An empirically investigated concept of acoustic feedback that is presented in real-time during on-water rowing training sessions already exists. This section deals with the extension of the technical hardware currently used in high performance rowing training to a smartphone based platform in order to provide the sonification to more users and to everyday club training including young and older rowers (juniors and masters).

3.2.1 Introduction

In this section we present the technical and useful advancements provided by a smartphone-based application with respect to a regular PC-based application in the field of human movement sonification in water sports. Starting from the idea of the existing measurement and information system Sofirow (Sonification in rowing), that was designed as a rowing specific acoustic feedback training device as well as on the hardware-basis of the measurement and analysis system Accrow (both devices were developed from BeSB GmbH Sound and Vibration Engineering Berlin in cooperation with the University of Hamburg), a new convenient system was developed, that combines the two devices. The devices measure the kinematic parameters of the boat motion during rowing: boat acceleration (MEMS- acceleration sensor) and distance travelled (GPS) communicating via WiFi (WLAN). The new system is able to capture kinematic data and transfer it to a smartphone that is configured to run the task specific application, called PERSEO. The boat acceleration-time-trace is sonified (made audible) in real-time (online) by the PERSEO application on the smartphone, without the need to use an additional device, a PC, to perform the sonification. The audio sequence produced by the smartphone can be presented on the rowing boat (for the athletes) and/or on the motor boat (for the coach). The smartphone PERSEO application maps the acceleration data acoustically as direct sound modulation (algorithmic transformation). Put in other words, the measured acceleration data defines the sound sequence. Thus, the sound sequence depends on time and is defined by the movement. The sonification system was developed and field-tested with the German National Rowing Team [163] . With the sonification of the boat acceleration, an acoustic feedback system (Sofirow) was developed for high performance rowing and its effectiveness was tested with athletes from the German Rowing Association (DRV). Statistically significant improvements in the mean boat velocity as well as in different characteristics within the boat acceleration-time-trace were achieved using the sonification in on-water training. The results found demonstrate the potential of the sonification concept in principle, providing feedback about the movement execution via the sense of hearing and thus, also invisible details of the movement are subtly controlled. The sonification concept was already implemented into the technique training of elite athletes as an innovative approach to training, exhibiting a high effectiveness. The PERSEO mobile application is an improvement of the already existing Sofirow PC based sonification solution. The most important advantage of using a mobile phone, compared to a PC-based solution, is its convenient, compact size, readily and inexpensively protected from water, enabling easy, daily usage of the system. The new system makes use of an existing device called Accrow to perform measurements in rowing, The measuring and analysis system Accrow was designed for on-water training and rowing races in cooperation with BeSB GmbH Berlin Sound and Vibration and the University of Hamburg. The Accrow device measures boat motion data: velocity with GPS and boat acceleration with a MEMS-acceleration sensor during the rowing trip. In the previous system, the data were stored on a SD-card and transferred via WiFi (WLAN) to a notebook for online and/or off-line analysis. The offline-analysis is performed using a specific software, called Regatta, that performs different rowing specific routines, like load analysis, race analysis (alternatively for 2000m, 1000m or 500m rowing races), race start sequence analysis.

Related work

[180] introduce an Inertial Measurement Unit- based Sensor Network (SN) aimed at continuously monitoring rowing technique on the water. They show the great potential offered by SN in serving as monitoring equipment in on-field training, but stop at the point of evaluating acquired data, without any mention to training. They introduce an interesting concept of rowing technique optimization loop, but give no information about how to interact with the rower. [73] improved the running technique of

runners using interactive sonification. They produce sounds based on the vertical displacement of the center of mass, with the goal of making the running action more economic. Such kinds of work do confirm the idea of pervasive systems, aimed at enhancing athletes performances, in a broad range of fields. Remote introduced by [122] presents a work in which a couple of accelerometers, configured in a precise geometrical structure, enable the calculation of rotational speeds of rowing oars on water. We think that such an approach, aimed at simplifying the complexity of sensors needed to carry out measurements goes in a promising direction. However the work stops at the point of on-water tests of the system setup, without any further usage of acquired measured data. RowingInMotion is an application for iOS based smartphones. It allows the user to use the sensors that are embedded in smartphones to measure kinematic values (speed and acceleration), and visualize them, save them to file, transmit them to another device [158] . It is however lacking the possibility to use an external device, like Accrow. Thalos Rowing is an Android based Open Source application, that visualizes data coming from kinematic internal sensors of a smartphone and performs sport specific algorithms, like stroke detection, peak speed detection, and permits the data to be saved or transmitted to other Android devices [157] . By use of the Accrow device, a precise analysis and optimization of on-water training as well as an analysis of a rowing race profile becomes possible. Through the acquired kinematic data it is possible to calculate the essential details of the external training load (boat velocity, stroke frequency, propulsion per stroke), volume (distance travelled, number of rowing strokes) and time duration (driving time per section) [130] . With respect to the existing mobile phone based solutions we propose a system taking advantage of a dedicated embedded industrial grade sensing device coupled with an Off-The-Shelf smartphone. As the Accrow device has already been tested and proved to be accurate, measurements carried out using it are more scientifically relevant than others carried out using acceleration sensors, and GPS devices found on board of smartphones. Accrow-Live [162] is an application for a Windows-based PC, that provides live visualization of the data acquired with Accrow. The mobile phone application, PERSEO, incorporates both functionalities of Accrow-Live and Sofirow, providing a portable real-time telemetry and sonification solution.

3.2.2 Sonification scheme

The sonification scheme that was used is rather simple: parameter-mapping, with acceleration magnitude mapped to sound pitch. The mapping was obtained implementing on iPhone all needed code, to produce the sound. We decided not to use any existing sonification software in order to explore the potentiality of the platform before starting to use something more complicated. Moreover, libraries like libpd would require to jailbreak the mobile device in order to adjust settings, which was not a viable solution in this case. The sonification was implemented using the following formula to map acceleration values to corresponding frequencies:

$$Tone(\sigma) = Asin(2 * \pi * \nu), \nu = 220 * 2^{\lfloor \sigma * 12 \rfloor / 12} \tag{3.1}$$

In equation 3.1 σ and ν represent respectively acceleration and frequency in radians/s. A0 denotes amplitude. Consideration was given to determining A0 in the sonification scheme, but it can be manually altered through the volume button on the smartphone. In doing so, a 12-tone scale for the acceleration values was chosen, with values from 0 to 1. At constant conditions (0g), sound frequency = 220Hz, at an acceleration of 1g, tone frequency = 440Hz, and an acceleration of -1g (meaning deceleration) tone frequency = 110Hz. The 12-tones between 220Hz and 440Hz are thus simply obtained, without any need to involve external sonification software.

Figure 3.9 illustrates the functional mapping between the kinematic acceleration magnitude and the frequency (i.e. tone).

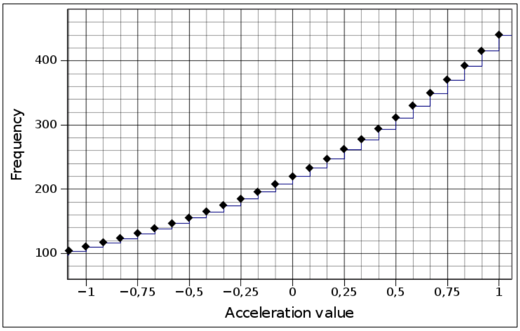


Figure 3.9. Discrete semi-tone scale.

To clarify the mapping, the following acceleration sequence was considered which is displayed in figure 3.10.

In figure 3.11(a) , continuous and discrete sonification schemes are displayed to illustrate how the use of discrete values obtained with equation (1) for tone data input creates a tonal scheme. The figure shows on the left (figure 3.11(a)) the continuous scheme in action, whilst on the right (figure 3.11(b)) a discretized output domain, corresponding to the discretized input domain is displayed.

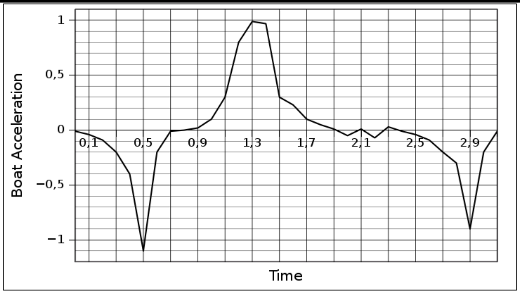
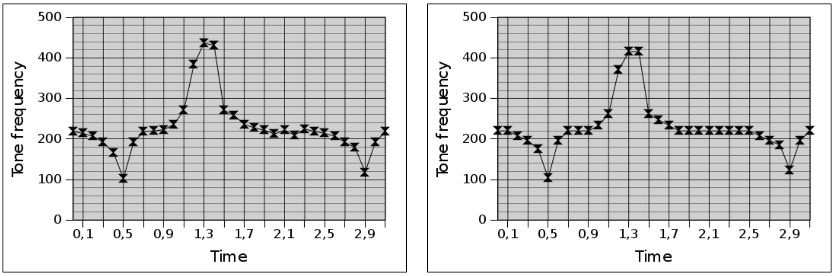


Figure 3.10. Boat-acceleration-time sequence



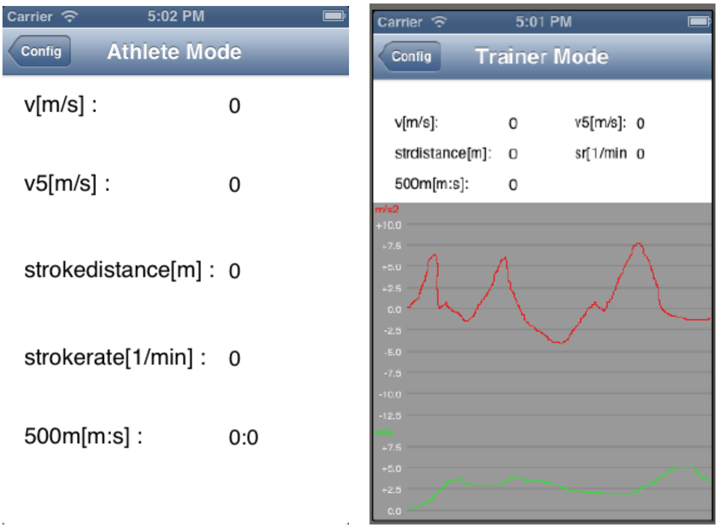
(a) Continuous sonification

(b) Discrete sonification

Figure 3.11. Continuous vs discrete sonification scheme of the boat-acceleration-time sequence.

3.2.3 Modes of operation

The application (app) on the smartphone is configured to offer a choice between two different modes of operation, both using the same sonification code, but presenting different visual information; the athlete mode presents only basic numberic data about speed, acceleration, strokes per minute; whilst the trainer mode shows two graphs, representing speed and acceleration of the boat. The application carries out two main tasks: receiving data from the WiFi connection and processing it to present the dual visual/audio display. Received data is also saved to the internal memory of the smartphone for later post-training analysis carried out using the Regatta rowing specific software, and offline sonification for the purpose of exploring new sonification schemes with the same data. To use the system, the user has to turn the device on and to start the application on the smartphone. In the screen display, preferences can be set to alter the behavior of the application, such as the possibility of switching between the sonification of the boat acceleration or its speed and the possibility of using the application in trainer 3.12(b) or athlete mode 3.12(a).



v[m/s] : 0

v5[m/s] : 0

strokedistance[m] : 0

strokerate[1/min] : 0

500m[m:s] : 0:0

v[m/s]: 0 v5[m/s]: 0

strdistance[m]: 0 sr[1/min 0

500m[m:s]: 0

(a) Athlete (b) Trainer

Figure 3.12. Modes of operation of PERSEO app.

3.2.4 System Setup

Figure 3.13. Overview of the complete system and its process operation

The system uses a WiFi (WLAN) connection to communicate between the Accrow device and the smartphone. Even though other possible options would have been available (Bluetooth, Zigbee, Proprietary RF stacks) WiFi was chosen because it is a rather stable wireless transmission standard, and moreover all smartphones incorporate WiFi transceivers.

Data between the Accrow device and the smartphone is transferred through a UDP stream, without any retransmission of lost packets. Retransmission is not required, as the sonification is consuming data in real-time, and packets out of sequence would generate incorrect sounds, whilst a longer wait time to correct the sequence of packets would mean the introduction of time lags, or a buffer time, that finally would translate into a longer delay between movement and sound, reducing its causality. Figure 3.13 shows how the complete system is placed in the loop with the rowing team.

Mobile application software design

The design of the software running on the mobile platform was done having in mind simplicity and minimalism, in order to ease the task of modifying it in future and to have a modular and reusable code. To tackle with a complex problem like real-time stream processing and audio generation the use of an existing design pattern was chosen: the Model View Controller (MVC) design pattern [82] . A simplified representation of basic MVC is shown in figure 3.14 Using the MVC pattern enables a quick modification of the application, in order to incorporate it in the future to new data sources (acting on the Model) like other sensors, and to extend the output part of the application, acting on the View.

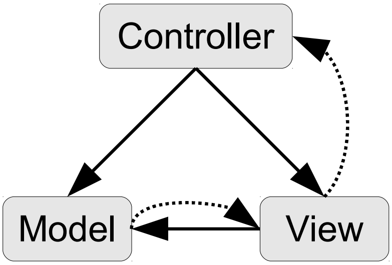


Figure 3.14. Model View Controller design pattern.

Using the MVC pattern it is quite easy to deal with the different forms of visualization (graphic, or audio). We successfully used the same pattern also on an Android system on which other sensors where tested. In MVC the application is analysed into 3 parts: Model, that in a sensor application can be considered the data source (the part of the application that reads values from sensors), the Controller is managing the "intelligent" part of the application, taking care of the data read, applying some filtering where needed (low pass filter, windowed FIR filter [15]), and the View that represents the "output" of the application. The first step in the development of the application has been to implement a graphic only view, and later add an additional audio View.

Figure 3.15 gives an overview of the complete layout of the application design.

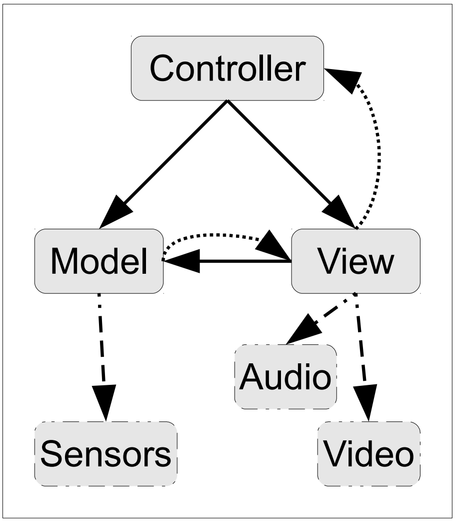


Figure 3.15. Design of the mobile application using the MVC pattern

In the future, the mobile application can be easily extended, simply acquiring new signals, or carrying out signal processing to generate new signals to produce other sounds.

3.2.5 Experiments

We first tested the system in the laboratory, to measure action- to-sound delay. The tests were repeated and the results show an average delay between 50 and 90ms that is within the 100ms- time-limit for causality of action-feedback in sonification. Experiments with the newly developed system will be carried out in Italy and Germany in several local rowing clubs. The experiments will focus on the usability of the system. As the transmission range of the device is in the order of magnitude of tenths of meters, coaches can be in a distance of the athletes' boat, thus providing a usable, simple and affordable mobile telemetry system. The on-boat sonification has already been proved to be important to athletes [85] . In near future we plan to start using the device on a more regular basis, carrying out experimentation that allow to acquire more knowledge about the short and long time effects of a regular usage of the system.

3.2.6 Conclusions

The developed system consisting of an Accrow wireless sensing device and a mobile phone and the PERSEO application enables real-time sensing and sonification of rowing training. As a future work it could be possible to add a sonification library, like SuperCollider or PureData to the application. PureData has actually been discarded as on newer versions of iPhone (starting from version iOS 3), it seems to be no longer supported.

3.2.7 Conclusion for rowing sonification

The sonification of rowing boat has proven to be effective in providing information to athletes and trainers about quality of movement of boat. In the preceding two Sections 3.1 and 3.2 we provided evidence for how a smartphone based and a PC based solution for telemetry and sonification of on-water rowing training can be build.

3.3 Rowers' synchrony and Pearson's correlation

Movements synchronism is a key parameter for various human activities such as team sports (rowing, synchronized swimming, etc.). In this section, we investigate methods to determine whether human movements are synchronous or asynchronous. We develop a system that acquires signals through accelerometers and compares those signals using correlation. All system components are chosen and tuned to reduce the overall delay between the moment in which the human action occurs and the moment in which the system produces the output. As a proof of concept, we present an application used as an aid to train synchronized movements and we test it on elite rowing athletes boats. The results show that the system is able to generate the output within 500 ms from the moment in which the athletes moved.

3.3.1 Introduction

Pervasive computing is a key enabler of innovative monitoring and training technologies in sports [48]. Among the most promising pervasive technologies are Wireless Sensor Networks, that have already been used to monitor sport activity, like rowing technique analysis [180]. Kinematics of a moving body is represented by acceleration, that can be measured along 3 orthogonal directions using 3D accelerometers. Cheap and tiny accelerometers, like MEMS (Micro Electro-Mechanical Systems) based accelerometers, enable the development of lightweight systems, that only marginally interfere with the monitored activity. However MEMS devices exhibit a non-negligible noise level that needs to be considered when developing applications that use them.

Synchrony among people is a key parameter when performing tasks related to group activities such as team sports (rowing, synchronized swimming, synchronized diving, ...) [52, 95]. To study how athletes in a team interact with each other, we use kinematic wireless sensors to track their movements, a computing device to analyse the measured signals and to provide an aid for the trainer and a feedback to the athletes. We show how to monitor movements in real-time and recognize if they are synchronized using a cheap and non-intrusive sensor network of 3D accelerometers, placed on body or technical equipment (arms, rowing oars, ...). The approach is using algorithms that can be executed on computationally constrained devices, like smart phones or nodes of a wireless sensor network and that are robust with respect to noise-to-signal level of sensors. The system we present in this work is using correlation of acquired signals to calculate a score of synchronism between athletes performing the same activity (rowing). Correlation is a measure of linear dependence between signals. The correlation of signals can be computed on constrained devices.

Moreover our tests show that the correlation method is usable in real-time to monitor group activities.

The rest of the section is organized as follows: we describe background in section 3.3.2, possible synchrony detection approaches in section 3.3.3, and the analysis method in section 3.3.4. We present proof-of-concept experiments in section 3.3.5, and conclude in section 3.3.6.

3.3.2 Background and application fields

We omit a detailed description of rowing for simplicity and length of the text suggesting [11] to the interested reader. Effective rowing requires high coordination and motor control [110]: rowers have to coordinate body movements with oars movements while maintaining the balance of the boat. When rowing is done in crews everything becomes more complicated, because every rower has to synchronise his movements with that of other members of the crew.

Choosing the right rowing partners (pairs) is a key factor to increase synchrony and power contribution by rowers in a team [19]. The right pairs, exhibiting a high degree of synchrony in the production of power, are typically able to achieve a higher performance, measured in terms of average hull speed, that is the final goal of successful rowing. Moreover "alterations to rower's force-time profiles with different partners indicate the need to better understand interactions between the athletes [19] ", and synchronism of athletes is crucial to develop a higher ability to resist to pain and fatigue [52]. For these reasons we are interested into measuring and studying synchrony of rowers to get insights about performance and to provide a tool to increase it during training.

A crucial point when developing training aids is the Human-Computer-Interaction. Using visual and tactile feedback about coordination between a rower and a virtual rower is possible on a rowing simulator [75], however to train on an indoor simulator is not the same as to train with a real hull on-water. Considering also that synchronization is considered to be the art of becoming one with the other and with music [178], we suggest to apply sonification, as sonification of motor behaviour impacts on listeners and on their coordination performing rhythmic activities [181], and an audio feedback related to the behaviour of each player of an handball team helps training play tactics [96]. Sonification of the whole boat acceleration enhances human senses correlated with movements altering the behaviour of rowers, leading to a higher overall performance [165, 68].

3.3.3 Synchrony detection approaches

Interactive applications need to handle data streams and informations in real-time. It is possible to use cheap and small MEMS accelerometers to work in the frequency range we consider relevant $(0 - 128\ \mathrm{Hz})$ for human activities as the results obtained using this kind of devices do not differ *significantly* from high end devices [120], as long as the used analysis methods do not include any integration of signals, as this would lead to drift errors.

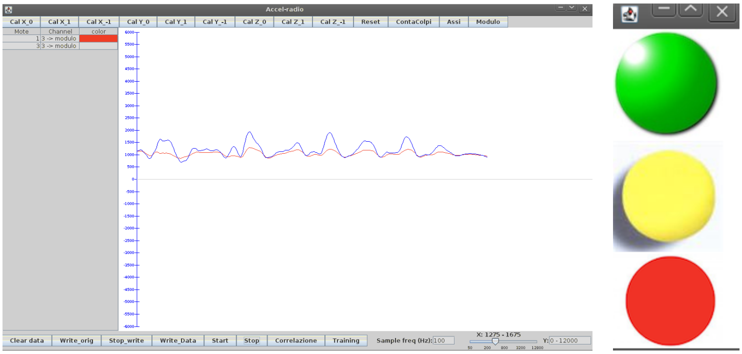
To detect signal synchronism, different approaches are possible: frequency analysis, Artificial Intelligence algorithms, ad-hoc algorithms, or statistic analysis.

Frequency analysis: the inspiring work "Are you with me?" [120] describes a way to determine whether two devices are worn by the same person, using the coherence function (a frequency analysis technique). Limitations of frequency analysis are that a precise estimation of time synchronization would require the inspection of both the amplitude and phase components of the transformed signal (this would be difficult in real-time on limited embedded devices). FFT analysis is a widespread signal processing approach, however not only FFT spectrum computation is CPU intensive but with FFT analysis it is also difficult to understand whether two movements happen at same time, as FFT calculation gives as output values a magnitude and phase values of the transformation. Wavelet analysis is an analysis method which can extract frequency and time informations from signals. It is generally computationally more lightweight than FFT, as it does not require spectrum calculation. Also in terms of synchrony detection wavelet seems more promising than FFT, as it calculates coefficients that are localized both in frequency and in time domain [86]. We intend to investigate the usage of wavelets in future, but omit to present it here because of lack of time. *Artificial Intelligence* approaches like Artificial Neural Networks generally require relevant training and validation data-sets. Moreover it is generally more computationally intensive to use AI approaches than classical ones. We do not investigate the usage of *Ad-hoc algorithms* like pattern recognition in time, because using a standardized and existing methodology would ease the understanding of the calculated quantities. *Statistic approach*: Correlation between series of values represents the most interesting approach to be implemented on limited devices, providing an easy to understand score of linear dependence of the analysed signals.

3.3.4 Matherials and methods

Pervasive system hardware and software

Our *pervasive system* is composed of Shimmer2R [125] Wireless Wearable Sensor nodes, connected as a Wireless Sensor Network (WSN) using 802.15.4 with a PC.



Mote	Channel	color
1	3 -> modulo	🟥
3	3 -> modulo	

Sample freq (Hz): 100

X: 1275 - 1675

Y: 0 - 12000

(a) Graphical Interface.

(b) Visual feedback

Figure 3.16. Graphical Interface of Java program and Visual 3-state feedback

Shimmer2R nodes are composed of an MSP430 MCU, a Bluetooth and 802.15.4 radio, the Freescale MMA7361 accelerometer, a lithium battery. The motes are programmed using the TinyOS operating system and the NesC language. The PC is working as the base station of the WSN using a Shimmer node as the gateway and a Java program to manage data streams, perform signal analysis and provide the real-time processing facility (Figure 3.16(a)). During preliminary phases some python scripts are used to perform offline analysis of acquired signals and develop first offline prototypes of the algorithms, later incorporated into the main Java program [119]. The Java program also provides a basic visual feedback component(Figure 3.16(b)).

Pearson correlation index

Accelerometer data acquired on different people can be analysed to assess whether that people are pairwise performing similar actions [195], using correlation of signals [74]. Pearson correlation index [149] is a widely used approach to the calculation of correlation of signal pairs, in terms of linear dependence between that pairs. Considering the definition of variance $\sigma_x = var(X) = \frac{\sum(X_i - X_{med})^2}{N}$ and of covariance σ_{xy} between variables x and y as $\sigma_{xy} = cov(X,Y) = \frac{\sum(X_i - X_{med})(Y_i - Y_{med})}{N}$, Pearson's correlation index (or coefficient), is calculated between two aleatory variables as a measure of linear dependence of their covariance σ_{xy} and the product of their respective standard deviations σ_x and σ_y:

$$\rho_{xy} = \frac{cov(X,Y)}{\sqrt{var(X)var(Y)}} = \frac{\sigma_{xy}}{\sigma_x \sigma_y} \tag{3.2}$$

According to Pearson's theory $-1 \leq \rho_{xy} \leq 1$ and more in particular: $\rho_{xy} > 0$, sequences x and y are directly correlated, or positively correlated; $\rho_{xy} = 0$, sequences x and y are said to be uncorrelated; $\rho_{xy} < 0$, sequences x and y are inversely correlated, or negatively correlated.

Considering a simple algorithm implementing Pearson's index, the minimal computational complexity is O(n), in particular for a window of n samples, it needs a total of $4n\ \mathrm{ADD} + (3n+5)\ \mathrm{MUL}$ operations (ADD is addition operation, MUL is multiply operation).

Applying Pearson to rowing signals

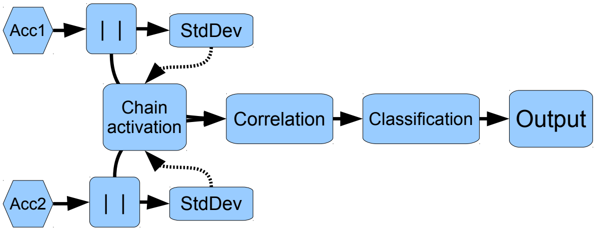


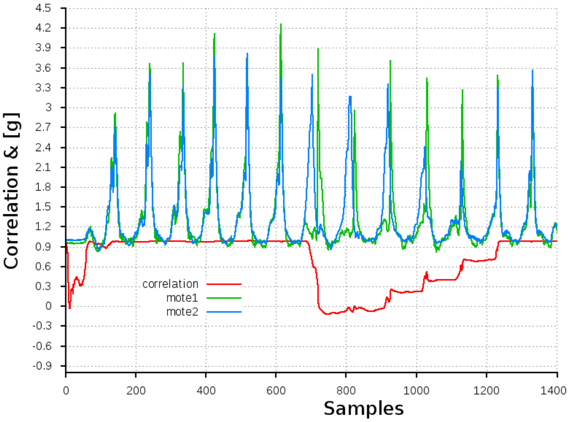
Figure 3.17. The activity recognition chain for a pair of accelerometers

To measure how much two different objects (people) are experiencing (performing) similar movements, we use accelerometers placed on the objects (or body parts) we want to measure. Considering that 99.65% of energy of typical human movements is located below $25\ \mathrm{Hz}$ frequency range [15] the sensors are sampled at $50\ \mathrm{Hz}$. Acquired data is analysed and processed using an activity recognition chain [180], depicted in Figure 3.17. All analysis are performed on the module of the measured 3D acceleration vector (components x, y, z), $n_i = sqrt(x_i^2 + y_i^2 + z_i^2)$, in order to be robust with respect to the placement and orientation of the sensors [15].

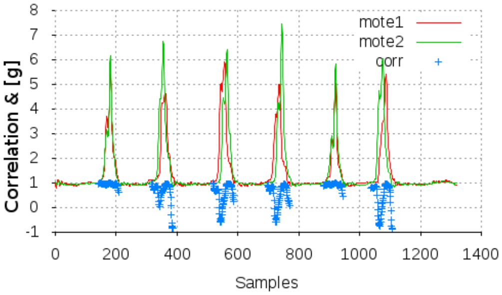
The first step of the analysis is the recognition of activity or inactivity, done applying standard deviation (StdDev) calculation on a $200\ \mathrm{ms}$ sliding window of the raw acceleration module for each accelerometer, and classifying $\mathrm{StdDev} \leq 0.2$ as inactivity and $\mathrm{StdDev} > 0.2$ as activity. The activity in case of accelerometers mounted on rowing oars handles (near the hands of athletes) is represented by strokes, that can be used to divide the signal into segments. Once the signal has been segmented we calculate correlation of absolute values of acceleration from a pair of accelerometers on a $500\ \mathrm{ms}$ sliding window. The size of the window on which correlation is calculated affects also the value of correlation, so this is one of the most important design choices, represented by a trade-off between accuracy and reactivity to changes in signals. The calculated *Correlation index* value is divided into three configurable classes. The configuration allows to adjust the correlation value of *high synchrony*, *medium synchrony* and *low synchrony* classes.

The total computational load of the algorithms is causing a negligible delay on the calculation of the correlation and synchrony score, thus the total delay between the moment in time in which actions are performed and the instant in time in which the related output is generated by the system is bound by the size of the Sliding Window, that in this work is $500\ \mathrm{ms}$, is $500\ \mathrm{ms}$.

Laboratory tests



(a) Signals and correlation values for the arms movement test in laboratory



(b) Signals and correlation values with a windowed approach

Figure 3.18. Signals and correlation values for the arms movement test in laboratory and Signals and correlation values with a windowed approach

Table 3.1. Classification of correlation values

Correlation index	Synchrony Class
$0.8 \leq \rho_{xy} \leq 1.0$	High
$0.6 \leq \rho_{xy} < 0.8$	Medium
$-1.0 \leq \rho_{xy} < 0.6$	Low

To test feasibility of Pearson correlation index to detect synchronism we perform preliminary laboratory tests, in which movements of the hands of a test person are acquired through wireless accelerometers and data analysed offline. Figure 3.18(a) depicts acceleration module values for two accelerometers and the corresponding correlation index, obtained on a sliding window of $500\ \mathrm{ms}$ of data. In Figure 3.18(a) at the beginning of the test correlation index is low, even though both accelerometers are not moving. This low value (below 0.5) of correlation is caused by noise of accelerometers (thermal, micro-vibration, ...) and not by actual actions. We notice that there is the need to filter out all situations in which the calculated correlation index is not relevant. This is done by adding the *Chain activation* to the system. The Chain activation component uses the StdDev of acceleration module to determine whether relevant actions are happening or not, and in affirmative case it enables correlation calculation and output of the system, otherwise turning it off. In Figure 3.18(b) we can see how the *Chain activation* component acts, disabling correlation calculation and output when the StdDev of the two signals is below the 0.2 value.

3.3.5 Rowing experiments

During our first experiments we use the Shimmer2R wireless devices connected to a portable computer to collect acceleration values from the members of a rowing team training on water. Collected data is analysed and processed using Python scripts in order to define the most appropriate threshold values for the *Synchrony Class*. Following empiric observations and with the help of trainers we define the classes, and in further validation experiments we configured the correlation classes as reported in Table 3.1.

The testing of the system on rowing athletes is divided into an indoor and an outdoor-on-water test. The indoor setup is shown in Figure 3.19(a), where each mote is attached the handle of an ergometer. This indoor ergometer test is carried out in order to assess whether the two rowers are rowing in synchrony or not, placing the wireless sensors on their respective ergometer handle. Setup used during one of the on-water tests is depicted in Figure 3.19(b), with one mote on each oar of a single sculling boat. This single rower is being studied to monitor and measure the symmetry of bilateral movements. The experiments prove that our system, configured with the reported Synchrony Classes is well suited to analyse in real-time synchronism of movements and help the trainer in the process of following the training behaviour of the athletes.

(a) The test setup on the ergometer.

(b) The test setup on the boat

Figure 3.19. The test setup on the ergometer and The test setup on the boat

The overall tests performed indoor and outdoor confirm the validity of the approach, and chosen thresholds for the algorithms (StdDev 0.2 as the threshold between activity and inactivity, and the Synchrony Classes reported in Table 3.1) are coherent with the ones tested in the lab. During the tests carried out on water with rowing athletes we see that the measured accelerations are smaller than the assumed values, thought to be similar to the values on the ergometer. This can be related to an overall higher degree of attention during the performance of movements, to be as smooth as possible. However as all thresholds are set on statistic variables, and not on raw values, the system is completely independent from minimum / maximum acceleration values.

Other practical tests, performed in a rowing gym, employing the complete software solution (composed of analysis and audio-visual feedback), show that further development and investigations are needed in order to build a system that will help

Table 3.2. Synchrony of strokes during an on-water training

Low	Medium	High
37.8%	28.9%	33.3%

athletes and trainers on a daily basis to achieve respectively a higher degree of synchronism and to better form the best possible rowing pairs. Synchrony values are not always at maximum level (see Table 3.2) , even when elite athletes are explicitly asked to concentrate on the synchrony as much as possible. This is a good reason to further improve the measurement system and to investigate the effects of the complete feedback system on training, both short term effects and long term learning effects.

3.3.6 Conclusions and future work

This section presents a system designed to assess synchronism, based on a statistic method, Pearson correlation, implemented on a Wireless Sensor Network, and tested on-field are actually able to give this information. The system is configurable, to be general and adaptable for different levels of expertise of athletes and types of training. The system is tested in collaboration with high level rowing trainers and athletes, and proves to be able to assess in real-time if two parts (body or oars) are moving at same time, in synchrony. Active work is on the realization of a mobile equipment supported on-field usable system. The mobile system is based on an Android phone running the Spine [20] middleware coupled with wireless motes running the Spine firmware. In future we will investigate how the system providing real-time sonic feedback of the level of synchrony alters the way athletes perceive actions of other team members, to understand whether it will lead them to change their own actions to actually increase overall synchronism.

3.4 Assessing Rowers' coordination via motion-based Stigmergy

3.4.1 Background and motivations

The primary goal in competitive rowing is to achieve a better control of velocity during the whole race. Such a goal requires a highly efficient rowing, which depends on many dynamically interacting factors. Variables such as interpersonal coordination, seat acceleration, boat balancing and feathering should be perceived by the rower to avoid checking the boat and wasting energy. In practice, this task is extremely difficult to perform, as it requires continuous coordination between two to eight rowers and a coxswain [19].

Conventional coaching layout in rowing consists of a coxswain in the stern and a coach in a motorboat, offering advice based on what they see and feel, based on few empirical data. With the naked eye, they can only acquire aggregate data such as the speed of the boat, or individual data such as the stroke rate of each rower. Suggestions are seldom precise enough to correct flaws in individual performance. For this reason, novice rowers are often taught the basics of rowing through endless hours of practice aimed at coalesce them into a team. On the other hand, professional rowing races are typically decided by the order of tenths of seconds. Hence, a computer-aided approach to improve the training process in rowing is highly desirable [77].

The classical way a rower can evaluate his individual performance is by indoor rowing machines equipped with a software system [53]. Several studies on monitoring of rowing have reported on the factors influencing performance. As a general remark, most studies and systems concerned with the recording of rowing biomechanics provide only some basic measurement and simple statistical analysis tools to assist the coach and the athletes on the training phase [140, 51, 109].

In the last decade, wearable sensors and wireless sensor networks (WSNs) have been applied to monitor human movements [200, 7, 3, 78, 148] and, more specifically, to obtain high-resolution real-time parameters on rowing performance [153]. Most of the initial efforts have been concentrated on data acquisition and integration [122, 22]. Recently, some experimental studies have started to address the problem of providing real-time feedback and on-water analysis of the biomechanics indexes of the athletes during training. In practice, monitoring the crew performance in real-time requires choosing a trade-off between what to monitor and how to present it [69]. Indeed, there are many possible parameters, and their tracking should be related to the specific training practice, according to a process-oriented approach. Actually, many efforts in the field have been aimed at supporting system-oriented analyses based on complex mathematical models of the rowing performance. One of the most important lessons learnt from these efforts is that the algorithms used to perform the parametric aggregation must use a limited amount of state, be highly flexible, and be able to handle noise. Indeed, much work still has to be done before such systems can be used on a regular basis for monitoring crew team performance [140].

A novel perspective can be gained by considering a different design paradigm. It has been argued that any explicit modeling of a collective behavior effectively biases the system, and constrains it within an idealized description that is dependent on the *cognitive* requirements of the designer [192]. Typically, this approach deploys an arsenal of techniques, including machine learning and probabilistic modeling, in the attempt of dealing with the inherently uncertainness, time-varying, and incomplete nature of sensory data. However, this does not alter the fact that the representation of a functional structure is still predicated on the descriptions of the designers. In contrast, with an *emergent* approach collective perception is concerned with the augmentation of sensory data in order to enable local action. It is not a process whereby the observation of an external observer is abstracted and represented in a more or less symbolic manner, i.e., the so-called *cognitivist* approach [192]. Emergent paradigms are based on the principle of self-organization [94], which means that a functional structure appears and keeps spontaneously at runtime. The control needed to achieve results is distributed over all participating entities. In the literature, the mechanisms used to organize these types of systems and the collective behavior that emerges from them are known as *swarm intelligence*, i.e. a loosely structured collection of interacting entities [18].

The fact that simple individual behaviors can lead to a complex emergent behavior has been known for decades. More recently, it has been noted that this type of emergent collective behavior is a desirable property in pervasive computing [18, 50]. Biological paradigms have inspired significant research, not only in robotics and communication networks, but also in pattern detection and classification [18]. For example, in [154], a swarming agent architecture for distributed patterns detection and classification is presented, providing robustness, scalability and fast convergence.

According to the *stigmergy* paradigm [190, 173], agents do not communicate with each other, but indirectly interact by changing their environment. In the literature, various types of stigmergy have been distinguished. *Sign-based* stigmergy occurs when markers are left in the environment to influence the subsequent behavior (choice and parameters) of entities. In *quantitative* stigmergy, the mark varies in a quantitative manner. In a stigmergic computing scheme, the environment acts as a shared medium through which agents communicate. Each agent is able to sense and change the state of a part of the environment. These changes need to persist long enough to affect the subsequent behavior of other agents. Hence, the environment acts as a common shared service for all entities enabling a robust and self-coordinating mechanism [105, 33].

This section describes and discusses how an emergent approach can be used for measuring both the overall crew asynchrony and the individual rower asynchrony towards the crew. Based on this approach, a prototype of a tool for assisting the coach in perceiving the crew's coordination in real-time has been implemented and demonstrated experimentally. The results of this in situ experiment are presented and discussed. The approach and the prototype are referred to as MARS (Multi-agent system for Assessing Rowers' coordination via motion-based Stigmergy). Agents of the system use stigmergy as coordination mechanism.

The section is organized as follows. Subsection 3.4.2 covers the related work on performance analysis in rowing. In Subsection 3.4.3 we introduce the architecture of the MARS system. Subsection 3.4.4 is devoted to the multi-agent model of processing with its related stigmergic paradigm. Subsection 3.4.5 describes the deployment of the MARS system architecture. In Subsection 3.4.6, we discuss experimental results. Subsection 3.4.7 draws some conclusion and suggests future work to be undertaken.

3.4.2 On-water rowing monitoring: related work

To the best of our knowledge, no work has been done in the field of rowers' asynchrony processing using an emergent approach and wireless sensors. However, there are a number of projects that measure raw biomechanical parameters of rowing and perform analysis using a cognitivist approach. In this section, we intend to present such projects with the aim of providing a landscape of the current methodologies. Moreover, the comparison presented in this section does not take into account hardware settings (e.g. number and types of sensors) and performance indicators.

In [77] an experience of application of WSN for rowing performance is presented. The system was able to monitor boat speed and set, and the synchrony of the rowers based on their seat acceleration. Since acceleration data contains a high noise ratio, with a cognitivist approach only a few data points are of practical interest, namely, maximum acceleration during stroke and maximum deceleration during finish. The local computation is then mainly devoted to extract and report critical points, and to calculate some aggregation, e.g., frequency of oscillation. Such extracted data are then sent to a display. To cope with the highly variable and noisy character of such data, the authors employ some dynamic calibration algorithm in the parameters setting. However, the authors claim that such algorithm is not sensitive enough and might be fine-tuned for a use on regular basis.

In [122] the authors have applied WSN to the oars and boat for monitoring boat movement, boat balancing, and trajectory of the stroke. The novelty of the approach consists in the usage of a couple of accelerometers placed on each oar in order to calculate its angular velocity. Three different tests are performed: an early calibration in laboratory, an indoor experiment with an ergo-meter, and on boat trials. The resulting data is stored in a file. Subsequent analysis of such data is not performed, as the authors have performed this test and data collection only as a proof-of-concept of their technology.

In [130], the authors present a coaching device for rowing and an analysis software, called Accrow and Regatta, respectively. Accrow employs an accelerometer and a GPS receiver to measure the boat acceleration and velocity, respectively. Regatta analysis provides boat velocity, stroke rate, propulsion per stroke, distance traveled by the boat and the required running times. The coach receives such performance data at the end of the on-water training unit. The system made of Accrow and Regatta can be used to analyze the effects of different rowing techniques or different stroke rates on the boat velocity.

Geospatial data has been used by [140] for measuring rowing performance in terms of boat velocity and acceleration variation of a single stroke cycle. In particular, the study provides a classification of physical parameters in four categories depending on their source, and a conceptual approach for monitoring and evaluating rowing. Some preliminary testing are discussed, focusing on the potential of mobile mapping technology, on the various data types, the sensors, their level of integration and limitations. The testing is carried out with a data acquisition system made of an acceleration sensor and a GPS receiver. However, the system is focused on stroke cycle characterization in terms of acceleration and speed.

In [22] an integrated data acquisition system for rowing performance analysis is presented. The analysis is carried out by means of a post-processing. The authors point out that a great deal of effort is necessary for the in-field calibration procedure, which is supported by an *ad hoc* software directly interfaced with the tool used to handle the signals. The Section describes the design, calibration and evaluation of a broad range of sensing devices displaced on the boat. The study is focused on designing innovative rowing shells meeting the specific requirements of a crew.

In [180] a WSN-based approach to improve rowing performance is presented. The authors describe the design of the system and some real-world experiments. They investigate how to integrate inertial measurement units into the process of rowing technique optimization. The study is focused on possibilities offered by the sensors and employs conventional signal processing techniques, giving some insights about the type of sensors to be used. The system has been experimented in both training and racing conditions, showing its ability to measure rowing technique indicators such as stroke length and stroke rate for both amateurs and world-class rowers.

In [164] the authors present an evaluation of online sonification as an aid for visually impaired rowing athletes. The approach allows athletes to better follow the movements of the rest of the rowing team. The system, called Sofirow, is implemented on a device that samples accelerations and speed of the boat and produces a parametric sound, directly proportional to the linear acceleration of the boat. Thus, perception of the boat run by the athletes is enhanced as the single rowing cycle can be perceived as a short sound sequence.

In [69] a quantitative evaluation of four different sonification schemes for rowers is presented. The study is considered more extensive than the work carried out in [164], as a broad range of sonification models are used, i.e., wind, pure tone, musical instruments, and car engine. Questions about characteristics of the sound stimuli are also posed in order to assess the ability of the participants to extract information from the sonification models.

3.4.3 The overall architecture

In this section, we first provide an ontology-driven conceptual modeling, so as to sufficiently capture the most important requirements and tasks to be performed; then, we detail the main modules of the system.

An ontological view of the proposed approach

An ontological view of the MARS system is represented in Fig. 3.20, where base concepts, enclosed in gray ovals, are connected by properties, represented by black directed edges. The core properties are *Athlete is in Asynchrony* and *Crew is in Asynchrony*. As these properties cannot be directly sensed (i.e., instantiated) by the system, they are *abstract* properties, shown by dotted edges. The overall system is aimed at indirectly discovering them, by observing the collective strokes of the rowers starting from data provided by wireless sensors.

More formally, let us consider a *Crew* of N *Athletes*, each of them rowing with *SensoredEquipment*. As a specific sensored equipment we considered the *Oar* (in figure, specific properties are shown with white ovals and are connected by white directed edges). A *SensoredEquipment* constantly provides *Samples* and related *Time*, which are taken by a *MarkingAgent*. As a specific sample we considered the *Acceleration*. Each *MarkingAgent* leaves *Marks*, which are located in the *SensingSpace*. For each *SensoredEquipment* there is a *MarkingAgent*. *Marks* are aggregated in the *SensingSpace* generating *CollectiveMarks*. For each *Crew*, a *SimilarityAgent* observes *Marks* and *CollectiveMarks* in order to produce a *Similarity* measure of them with respect to optimal marks, these correspond to the marks produced under a desired

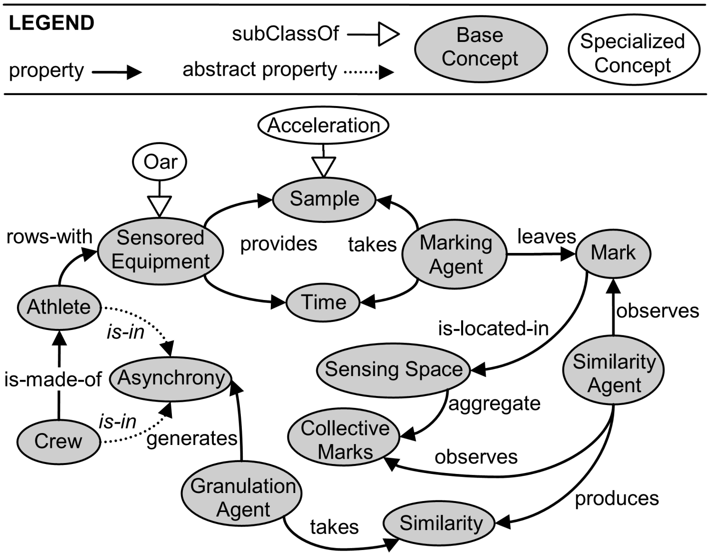


Figure 3.20. An ontological view of the emergent approach for measuring asynchrony in rowing

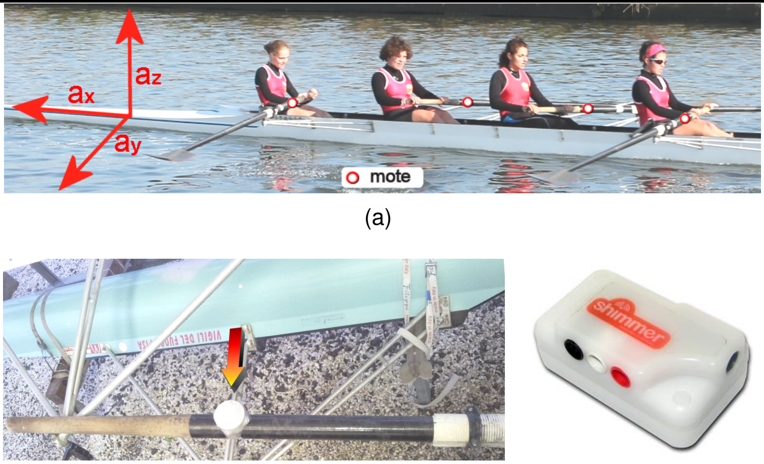
level of synchrony. Finally, a *GranulationAgent* takes as input the *Similarity*, and generates a level of *Asynchrony*.

The main modules of the MARS system

The MARS system is made of four main subsystems: (i) a sensing subsystem, i.e., wireless sensor nodes (motes) placed on oars to allow local sensing of the strokes; (ii) a tracking subsystem which collects the sensed data; (iii) a processing subsystem which computes the performance indexes; (iv) a displaying subsystem, which provides the performance indexes to the coach. In terms of hardware components, the setting of the sensing subsystem employs accelerometers, whereas the other subsystems run on a conventional laptop.

The sensor placement and a sensored oar are shown in Fig. 3.21. To allow noise reduction in the data produced by sensors, motes have been placed on the inboard segment of the oar, between the handle bottom and the oarlock. To improve accuracy, simple techniques may be used to virtually align the motes with respect to a reference system [15]. In Fig. 3.21(b), the oar and a waterproof enclosure endowing the mote are shown. Fig. 3.21(c) shows one mote used for the experiment, a COTS device sold by Shimmer research, running the TinyOS an embedded OS.

Fig. 3.21(a) also shows a tri-axial reference system for acceleration, a_x, a_y, and a_z, parallel to the longitudinal, horizontal and vertical axes of the boat, respectively. The asynchrony of rowers can be measured based on two phases, which are both



(a)

(b)

(c)

Figure 3.21. (a) Position of the motes on the boat; (b) a sensor-ed oar (c) a mote.

carried out along the vertical axis: (i) the placing of the oar blade in the water; (ii) the removal of the blade out of the water. For this reason, we will consider only the vertical axis a_z, referred to as a for brevity. This mono-dimensional input signal will also allow us a simple and effective presentation of the method.

The main modules of the MARS system are represented in Fig. 3.22, by means of a communication diagram. Here, an interaction organized around the users (shown as sticky figures) and the parts of the system (shown as rectangles) is represented. In particular, synchronous and asynchronous messages are shown with filled and stick arrowheads, respectively. Finally, a comment is shown as a rectangle with bent upper-right corner. The interaction starts with the *Rower* who interacts with the *SensingUnit* by means of the sensored oar (1). The *SensingUnit* periodically sends data (e.g., acceleration and timestamp) to the *TrackingUnit* (2), which is responsible for tracking all sensed data (3). The *ProcessingUnit* periodically takes from the *TrackingUnit* (a) a batch of sensed data (b), and provides the *DisplayingUnit* with asynchrony measures (c). The *DisplayingUnit* provides such asynchrony measures to the *Coach* (d). When needed, the *Coach* looks at the *DisplayingUnit* (i) and advises the *Rowers* (ii) who correct their rowing activity accordingly, and so on.

In the following section, we provide a more detailed view of the peripheral units. The core of the system is represented by the *ProcessingUnit*, which is described and analysed in Section 4.

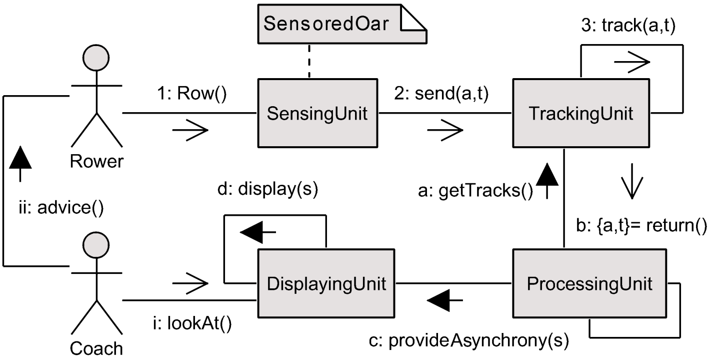


Figure 3.22. Communication diagram of the main modules of the MARS system

The *SensingUnit* module

parameters A sensing unit is made of a Shimmer mote attached to the oar. Each mote (size 53x32x25mm) is composed of a micro-controller, a rechargeable battery, a 3-Axis accelerometer, a Bluetooth transceiver and other components not relevant to this work. The mote runs a program written in NesC[3] over TinyOS[4], an open source, event-driven operating system designed for networked embedded sensor systems. The mote has been programmed so as to be managed with minimum power consumption. More specifically, it cyclically samples the accelerometer at a given frequency and sends the sampled data to the tracking unit. The sampling frequency can be set wireless, by using a simple two way protocol. The mote can also be reset and synchronized upon commands sent using a wireless transceiver. We experienced that, with this management program, the average battery life is three hours, thus allowing us to perform long lasting on-field tests. A limit of such motes is the relatively short transmission range of their on-board Bluetooth transceiver, which is roughly $20\,\mathrm{m}$.

The *TrackingUnit* module

The tracking unit is made of a laptop equipped with a Bluetooth receiver. The logic of the unit is developed in Java. The unit is responsible for the wireless interactions with the motes, i.e., reset mote, set sampling frequency, and synchronize mote. At the physical level, the unit works as a Bluetooth master to the motes. At the application level, when the application starts, the unit forces a preliminary synchronization of the motes, through a simple three-way handshake protocol. While the system is running some clock drifts on the motes may occur. Hence, timestamps provided by motes

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[3] http://nescc.sourceforge.net

[4] http://www.tinyos.net

may not be synchronized with respect to the tracking unit. To overcome this issue, timestamps are adjusted on the tracking unit, considering the sampling period and the inter-arrival time of samples.

The *DisplayingUnit* module

The MARS system supplies the coach with both visual and aural [131] displays. The visual channel provides quantitative values of asynchrony, whereas the aural channel is designed for providing qualitative information. The aural channel is more immediate and has the advantage of leaving the coach free from watching the asynchrony data continuously. This allows him to follow the evolution of the whole team or the performance of a single rower with respect to the team in an easier and more effective way.

Using our system the coach is able to perceive the evolution of the crew and to communicate via voice in real-time, providing the crew valuable information to enhance the collective performance. Possible use cases of the coach are the following: (i) listen to the individual asynchrony; (ii) watch the individual asynchrony; (iii) listen to the collective asynchrony; (iv) watch the collective asynchrony. During a training session, the coach, who is normally tuned via the aural channel, looks at the visual content only occasionally. At the end of the training session, he can examine the visual plot of individual and collective asynchrony, in order to establish a performance improvement initiative for the next session.

3.4.4 The *ProcessingUnit* module

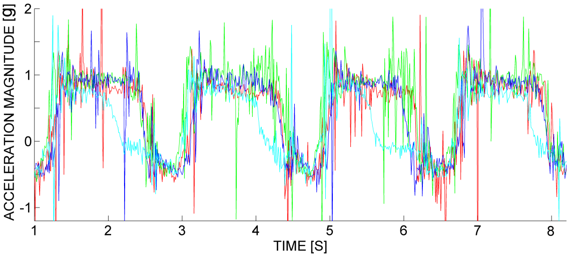
In this section, we first introduce some definitions to formalize our method, then we describe the different processing phases.

The static pre-filtering

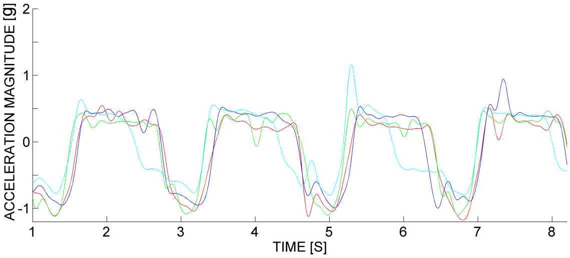
Let us consider an equipment of N wireless accelerometers, one for each rower, releasing an acceleration magnitude vector sample $\mathbf{a}^{(i)} = (a_1^{(i)}, ..., a_N^{(i)})$ every T_S seconds, where $a_j^{(i)} \in \mathbb{R}$, $j = 1, ..., N$ and $i \in \mathbb{N}$. Fig. 3.23 depicts a pilot scenario of vertical acceleration magnitude (normalized to gravity g) against time, for $N = 4$ rowers (each j-th channel represented with a different color).

More specifically, Fig. 3.23 (a) depicts raw signals, containing some electro-mechanical noise caused by micro-scale effects that are independent from human activity. To remove the electro-mechanical noise, a static filtering is first performed.

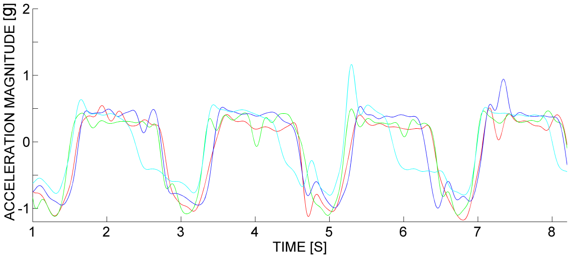
The static filtering is made of a moving-average filtering plus a subsequent conventional low-pass filtering. The former replaces each sample with the average of the previous samples within the span. We employed a span of 5 for the former, and a cutoff frequency of $20\,\mathrm{Hz}$ for the latter. With these parameters, the filtering causes a delay of a few tenths of a second, which is negligible for the application domain. We also made the signal zero-mean by removing the average, which is irrelevant for detecting the rowing stroke. Fig. 3.23 (b) and (c) show the effect of the static filtering of the raw samples in the pilot scenario.



(a)



(b)



(c)

Figure 3.23. A pilot scenario of vertical acceleration magnitude against time, with 4 sensored oars: (a) raw samples; (b) after a moving average filter with a span of 5; (c) after a low-pass filtering with a cutoff frequency of $20\,\mathrm{Hz}$.

The marking processing level

While the j-th athlete is rowing, for each sample $a_j^{(i)}$ released at the i-th step, the marking agent related to the athlete's oar deposits a mark in the sensing space. Fig. 3.24 shows a triangular mark (with solid line), which is characterized by a central (maximum) intensity I_{MAX}, an extension (or spatial decay) ε, and a temporal decay θ, with $\varepsilon > 0$, and $0 < \theta < 1$. The mark intensity spatially decreases from the maximum, corresponding with the acceleration value of $a_j^{(i)}$, up to zero, corresponding with the acceleration value of $a_j^{(i)} \pm \varepsilon$. Further, all the intensity released has a temporal decay, of a percentage θ per step, as represented with dashed line. Hence, after a certain decay time, the single mark in practice disappears. The decay time is longer than the period T_S by which the marking agent leaves marks. Thus, if the athlete holds an approximately constant acceleration, at the end of each period a new mark will superimpose on the old marks, creating an accumulated mark whose intensity will reach a stationary level. In contrast, if the marking agent moves to other accelerations, the mark intensities will decrease with the time without being reinforced.

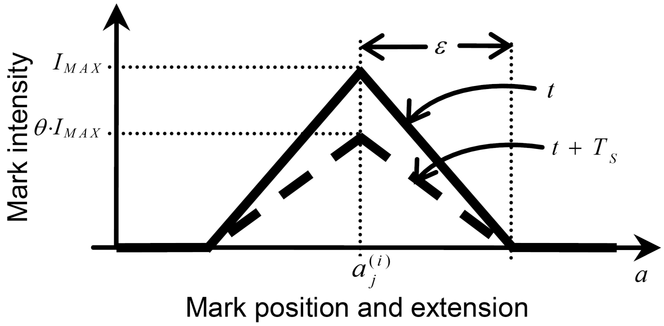


Figure 3.24. A single triangular mark released in the sensing space by a marking agent (solid line), together with the same mark after a step of decay (dashed line).

More formally, at the i-th instant $t^{(i)} = i \cdot T_S$, the j-th marking agent leaves in the sensing space a mark of intensity $I_j(a, t^{(i)}) \equiv I_j^{(i)}(a)$ defined as:

$$I_j^{(i)}(a) = \max\left(0, I_{MAX} \cdot \left[1 - \varepsilon^{-1} \cdot \left|a - a_j^{(i)}\right|\right]\right). \tag{3.3}$$

Every T_s seconds the intensity of the mark released at the i-th instant automatically decays of a percentage θ of its current value, that is,

$$I_j^{(i)}(a, t) = u(t - i \cdot T_S) \cdot I_j^{(i)}(a) \cdot \theta^{\frac{t - i \cdot T_S}{T_S}}, \tag{3.4}$$

where $u(t)$ is the unit step function, i.e., a discontinuous function whose value is zero for negative argument and one for positive argument.

In order to assess whether the superimposition of marks yields the maximum intensity level to converge to a stationary level, let us consider a theoretical scenario which produces the utmost possible intensity level. In such scenario, the j-th marking agent keeps its value of acceleration $\bar{a}_j^{(i)}$ constant and releases an infinite series of identical marks, with a temporal period of T_S seconds. Hence, the current intensity level $I_j(a,t)$ of the accumulated mark is obtained as the sum of the intensities of the marks left by the j-th marking agent, that is, from formula (2),

$$I_j(a,t) = \sum_{i=0}^{Z=\lfloor t/T_S \rfloor} u(t - i \cdot T_S) \cdot I_j^{(i)}(a) \cdot \theta^{Z-i}, \tag{3.5}$$

Then, from formula (3) we can deduce that after $Z \cdot T_S$ seconds,

$$I_j(a,t) = I_j^{(0)}(a) \cdot \theta^{Z} + I_j^{(1)}(a) \cdot \theta^{Z-1} + ... + I_j^{(Z)}(a). \tag{3.6}$$

Since $a_j^{(i)} = \bar{a}_j^{(i)}$ is constant, from formula (1) it follows that $I_j^{(0)}(a) = I_j^{(1)}(a) = ... = I_j^{(Z)}(a)$. As a consequence, formula (4) becomes the sum of the first $Z+1$ terms of a geometric series, and it follows that

$$I_j(a,t) = I_j^{(0)}(a) \cdot \frac{1-\theta^{Z+1}}{1-\theta}. \tag{3.7}$$

If $Z \gg 1$, then

$$I_j(a,t) \to I_j^{(0)}(a) \cdot \frac{1}{1-\theta}. \tag{3.8}$$

For instance, with $\theta = 0.75$ the stationary level of the maximum is equal to $4 \cdot I_{MAX}$.

Analogously, when superimposing identical marks of N rowers we can easily deduce that the intensity of the collective mark grows with the passage of time, achieving a collective stationary level equal to N times the level of formula (6). Fig. 3.25 shows an example of four accumulated marks (colored lines) and of the collective mark (black line) created in the sensing space at the instant $t = 3.22\,\mathrm{s}$ by the filtered signal of Fig. 3.23 (c), with $I_{MAX} = 10$, $\varepsilon = 0.3$ and $\theta = 0.75$. It is worth noting that the accumulated marks have a triangular shape, with their maximum value close to $I_{MAX}/(1-\theta) = 4 \cdot I_{MAX}$. It can be deduced that in the recent past the acceleration was almost stationary for all rowers. As a consequence, also the collective mark has a shape close to the triangular one.

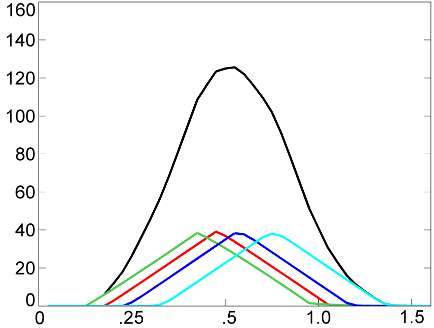


Figure 3.25. An example of four accumulated marks (colored lines) and of collective mark (black line) created in the sensing space at the instant t=3.22 s by the signal of Fig. 3.23 (c)(pilot scenario), with $I_{MAX} = 10$, $\varepsilon = 0.3$ and $\theta = 0.75$

The similarity processing level

The first important observation from the marking processing level is that an accumulated mark takes a triangular shape when acceleration does not vary sensibly within the last steps. We suppose here that any rowing stroke produces a signal whose acceleration pattern strongly depends on a number of factors. In our approach, we do not need to establish which phases of the rowing stroke correspond to a stable acceleration. We only assume that in synchronized rowers these phases might be close. A second observation is that the collective mark contains a short-term memory concerning the overall closeness of the stroke accelerations of the rowers. Here, we can associate some semantics to the parameters of a mark. Small spatial and temporal decay may generate a Boolean processing: only almost identical rowing strokes can produce collective marking. Larger spatial and temporal decay allows distinguishing different rowing strokes, up to a limit which may cause growing collective marks with no stationary level.

Exploiting these observations, in the following we discuss how a different type of agent can recognize coordination of rowing strokes: the similarity agent. Basically, the similarity agent is responsible for assessing the similarity of accumulated and collective marks with respect to corresponding optimal marks. Let us first identify the optimal marks. Fig. 3.26 shows an example of close-to-optimal marks, belonging to the pilot scenario ($N = 4$), taken at $t = 3.84\,\mathrm{s}$, $I_{MAX} = 10$, $\varepsilon = 0.3$ and $\theta = 0.75$. Indeed, from formula (5) we can deduce that the optimal accumulated and collective marks are triangular marks with height equals to $I_{MAX}/(1-\theta) = 40$, and $N \cdot I_{MAX}/(1-\theta) = 160$, respectively. Fig. 3.27 shows an example of marks produced by poorly synchronized rowing strokes, which has been taken at $t = 5.31\,\mathrm{s}$ from the pilot scenario. Here, marks are not stationary, because their shape is very far from the triangular one.

Here, the optimal (say, reference) accumulated and collective marks can be defined as triangular marks with the centers placed at the barycenter of the current collective mark. In the figure, optimal accumulated and collective marks are also shown, with dashed line.

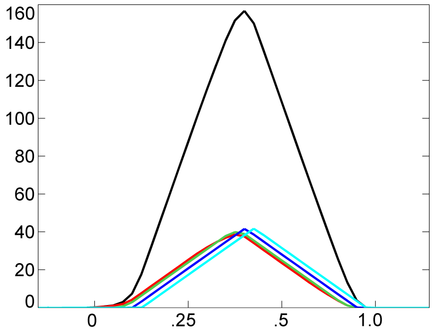


Figure 3.26. An example of close-to-optimal accumulated and collective marks, belonging to the pilot scenario, taken at $t = 3.84\,\mathrm{s}$, $I_{MAX} = 10$, $\varepsilon = 0.3$ and $\theta = 0.75$

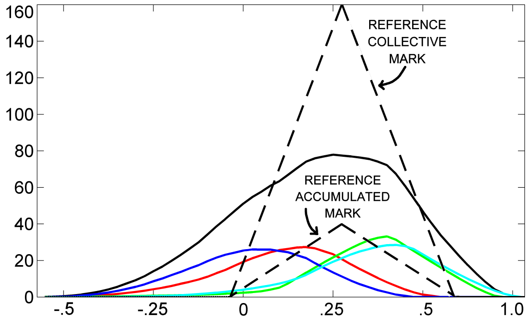


Figure 3.27. An example of marks produced by poorly synchronized rowing strokes (solid lines) with the reference marks (dashed lines)

More formally, Fig. 3.28 shows the similarity logic of the agent. Given a reference mark A and the current mark B, their similarity is a real value calculated as the area covered by their intersection (colored dark gray in the figure) divided by the area covered by the union of them (colored light and dark gray). The lowest similarity is zero, i.e., for marks with no intersection, the highest is 1, i.e., for identical marks. It is worth noting that accumulated and collective marks have not, in general, triangular shape. In conclusion, given N distinct accumulated marks, the similarity agent computes N individual similarities between each of the accumulated marks and the reference mark,

Table 3.3. Basic definitions for assessing the similarity of marks

Definition	Name and properties
(i) $\lvert I(a)\rvert = \int_{-\infty}^{\infty} I(a)\,da$	Cardinality of a mark $I(a)$: a real number.
(ii) $a* = \frac{\int_{-\infty}^{\infty} I(a)\cdot a\ da}{\int_{-\infty}^{\infty} I(a)\,da}$	Barycentre of a mark $I(a)$: a real number.
(iii) $I_A(a) \cap I_B(a) = \min\left(I_A(a), I_B(a)\right)$	Intersection of two marks $I_A(a)$ and $I_B(a)$: a mark.
(iv) $I_A(a) \cup I_B(a) = \max\left(I_A(a), I_B(a)\right)$	Union of two marks $I_A(a)$ and $I_B(a)$: a mark.
(v) $\mathbb{S}\left[I_A(a), I_B(a)\right] = \frac{\lvert I_A(a)\cap I_B(a)\rvert}{\lvert I_A(a)\cup I_B(a)\rvert}$	Similarity of two marks $I_A(a)$ and $I_B(a)$: a real number.
(vi) $\mathbb{D}\left[I_A(a), I_B(a)\right] = 1 - \mathbb{S}\left[I_A(a), I_B(a)\right]$	Dissimilarity, complement of Similarity: a real number.

and a collective similarity between the collective mark and the reference collective mark.

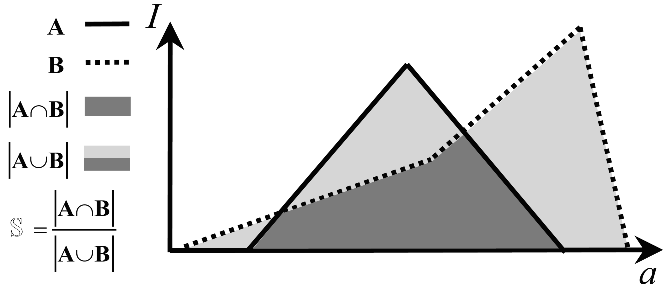
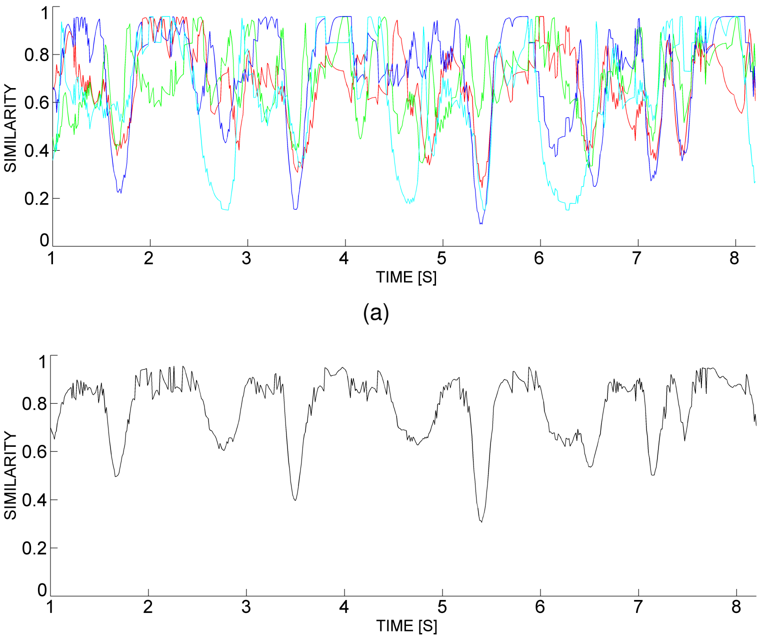


Figure 3.28. A visual representation of the Similarity between two marks

Table 3.3 shows the basic definitions that the agent uses for assessing the similarity of marks. For instance, the similarity in the examples of Fig. 3.26 and Fig. 3.27 is 0.950 and 0.556, respectively. As a result, Fig. 3.29 (a) and fig. 3.29 (b) show the similarity of accumulated and collective marks for the pilot scenario. Finally, the dissimilarity is calculated as the complement of similarity, according to the formula (vi) in Table 3.3.

The granulation processing level

In this section, an attempt is made to establish some general transformation process that produces a human readable asynchrony starting from dissimilarity. In fact, dissimilarity signal produced so far cannot be provided to the coach for an easy interpretation. In order to achieve accessibility, relevant information should be presented for actively supporting the decision process of the coach. More specifically, we focus on the concept of *information granulation* of time series.



(a)

(b)

Figure 3.29. Similarity of the accumulated marks (a) and collective mark (b) with their references, in the pilot scenario

The process of information granulation is a vehicle of abstraction leading to the emergence of high-level concepts. More specifically, information can be granulated over predefined time intervals, giving rise to temporal granulation, but also over the sensing variable (i.e., acceleration), giving rise to sensing granulation. Information granules need to be *stable* meaning that they have to retain their identity in spite of some small fluctuations occurring within the experimental data, as any judgment of an experienced coach. Further, information granules need to be *distinguishable*, meaning that their identities should be distinct enough from each other.

In user-oriented granulation, the user (i.e., the coach) identifies the parameters of the information granules, according to his supervisory process. Proceeding with a given window of granulation, we propose some basic transformation. The interested reader may refer to [150] for a detailed study. More specifically, our objective is to construct crew and rower asynchrony descriptors that can be legitimized by direct experience of a coach. The problem can be posed in the following way; given is a collection of numeric dissimilarity data, let us say $\mathbf{D} = d_j^{(i)} \in \mathbb{R}^{(N+1)\times T}$, where $d_0^{(i)}$ and $d_j^{(i)}$ are the collective and the (j-th) individual dissimilarity at the i-th instant of time. A granulation process provides a collection of asynchrony data suitable for a specific *Performance Improvement Initiative* (PII) taken by the coach during a training process. Let us say: $\mathit{\Gamma}(\mathbf{D})_{PII} = \{\sigma_j^{(i)}\} \in \mathbb{R}^{(N+1)\times T}$, where $\sigma_0^{(i)}$ and $\sigma_j^{(i)}$ are the collective and the (j-th) individual asynchrony at the i-th instant. Hence, $\mathit{\Gamma}(\mathbf{D})$ is a *performance indicator* with an intuitive interpretation based on experimental evidence of an experienced coach.

In the following, we consider both local (online) and global (offline) PPIs, in order to monitor rowing performance within temporal windows of different scales. For this purpose, the process of granulation is established by determining the window of granulation and its numeric representative as a descriptor. A basic descriptor that can be considered is the simple moving average (SMA), i.e., the unweighed mean of the previous $\mathit{\Delta}$ samples:

$$\mathit{\Gamma}(\mathbf{D}) = \{\sigma_j^{(i)}\} = \begin{cases} \text{undefined} & \text{if } i \leqslant \mathit{\Delta} \\ \frac{1}{\mathit{\Delta}} \sum_{k=0}^{\mathit{\Delta}-1} d_j^{(i-k)} & \text{if } i \geqslant \mathit{\Delta} \end{cases} \tag{3.9}$$

where $\mathit{\Delta}$ is the temporal window. We use formula (7) with two different scales of granulation, i.e., a *macro-granulation* for a global (offline) PPI, and a *micro-granulation*, for a local (online) PPI.

Fig. 3.30 shows a scenario 40 seconds long, with individual (in color) and collective (in black) asynchrony, as a result of a macro-granulation process with $\mathit{\Delta}$=2000. Here, we involved a crew of four rowers, named *Cyan*(C), *Red* (R), *Blue* (B), and *Green* (G). The following considerations can be easily made: (i) rowers C and G have the worst performance; (ii) rowers C and R sensibly diminished their performance in the second half of the scenario; (iii) the collective performance sensibly diminished in the second half of the scenario.

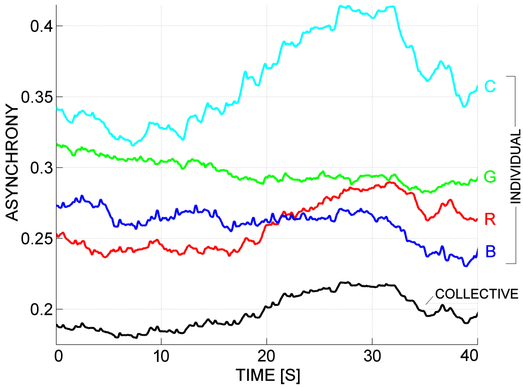
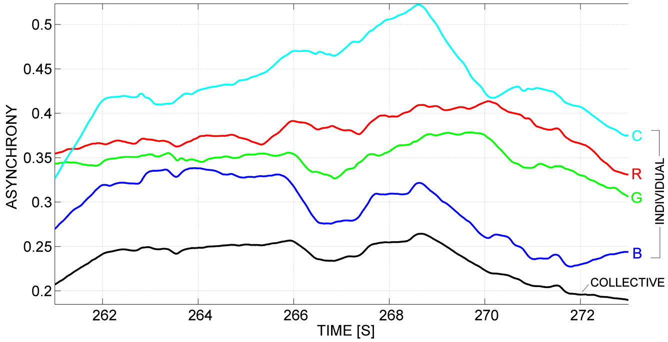


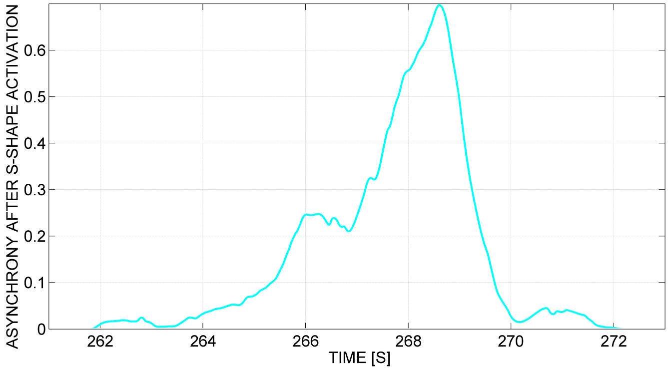
Figure 3.30. A scenario 40 seconds long, with individual (in color) and collective (in black) asynchrony, as a result of a macro-granulation with $\mathit{\Delta}$=2000.

Fig. 3.31 (a) shows another scenario of asynchrony, resulting from a micro-granulation process with $\varDelta$=800. In order to achieve a better distinction of the critical phenomena, a further sensing granulation has been performed, by applying an s-shape activation function (Fig. 3.32) with α=0.4 and β=0.6 considering the following definition:

$$f(x;\alpha,\beta)=\begin{cases} 0 & \text{if } x \leqslant \alpha \\ 2\cdot\frac{(x-\alpha)^2}{(\beta-\alpha)^2} & \text{if } \alpha \leqslant x \leqslant \frac{\alpha+\beta}{2} \\ 1-2\cdot\frac{(x-\beta)^2}{(\beta-\alpha)^2} & \text{if } \frac{\alpha+\beta}{2} \leqslant x \leqslant \beta \\ 1 & \text{if } x \geqslant \beta \end{cases} \tag{3.10}$$



(a)



(b)

Figure 3.31. (a) A scenario of approximately 12 seconds, with individual (in color) and collective (in black) asynchrony, as a result of a micro-granulation with $\varDelta$=800. (b) The same scenario after s-shape activation with $\alpha = 0.4$ and $\beta = 0.6$

Fig. 3.31 (b) shows the resulting signal. As an effect of the sensing granulation, low values are further decreased, whereas higher values are further amplified, in order to evidence major discrepancies from crew. Here, for example, the following considerations can be made: rower C increasingly loses their synchrony with respect to the group, starting from about the 264-th second and up to about the 269-th second, and subsequently regains synchrony.

In order to be provided to the aural display, the asynchrony signal has been also sonificated [62]. In particular, our sonification scheme is aimed at producing a pure tone with fixed amplitude, and whose frequency is related to the asynchrony signal. More specifically, the frequency is calculated so as to produce musical notes of the diatonic scale. For this purpose, the input value is quantized on 12 values, ranging from $220\mathrm{Hz}$ to $440\mathrm{Hz}$, corresponding to the musical notes *A3* and *A4*, respectively. More formally:

$$Sonification(\sigma) = C_0 \sin(2\pi\nu),\ \ \nu = 220 \cdot 2^{\lfloor \sigma \cdot 12 \rfloor / 12} \tag{3.11}$$

where C_0 is an amplitude constant, and σ is the current asynchrony value. In order to perform a qualitative assessment of this sonification schema, an excerpt of sonification of the signal in Fig. 3.31 (b) can be downloaded and listened to from the following web address: http://tweb.ing.unipi.it/sonification.mp3.

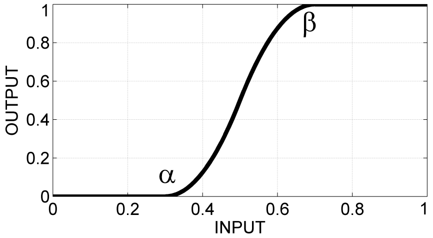


Figure 3.32. An s-shape activation function, with $\alpha = 0.3$ and $\beta = 0.7$.

3.4.5 The deployment of the MARS system architecture

Fig. 3.33 shows a UML deployment diagram of the MARS system architecture. Here, there are two device categories, i.e., *Mote* and *Netbook*, which reside on the boat and the motorboat, respectively. There are many motes taking part of a sensing unit, each managed via the *TinyOS* operating system as an autonomous execution environment. There is a single netbook managed via the *Windows OS*, which hosts the tracking, processing and displaying units. On the boat, each *Rower* interacts indirectly with the

Physical Sensor of a mote via his *Oar*. In the mote, the *Time-Acceleration Sampler* processes and records time and acceleration data from the physical sensor, whereas the *Sample Transmitter* component sends data to the Tracking Unit. On the motorboat, the coach is provided with asynchrony measures via the *Visual and Auditory Display* component, i.e., the netbook display and the headphone, respectively. On the tracking unit, the *Sample Receiver* (a Java-based component) is provided with the data coming from motes. Such data are stored in the *Sample Log*. The processing unit is entirely based on the Java-based *Multi-Agent Systems Manager*, which hosts the various agents and the *Marks Repository* implementing the marks properties. The Multi-Agent Systems Manager is based on Repast Simphony[5], a Java-based modeling system supporting the development of interacting agents. It can be used as a GUI-based (user driven) simulation environment, as well as an execution engine run from another Java application. As a final outcome, the processing unit provides the *Asynchrony Log*, which is the input for the *Visual and Auditory Display*. A single netbook can support many motes, via a wireless communication protocol based on Bluetooth. In particular, we used a total of 4 motes, one for each rower (as in the experiment rowers used one oar each).

3.4.6 Experimental studies

In this section, we report on experiments carried out to perform a check of the accuracy and repeatability of the MARS system. For such experiments, we involved a crew of four rowers: a novice, named *Cyan*(C), and three intermediate-level rowers, named *Red* (R), *Blue* (B), and *Green* (G). For each considered run, we made an acquisition session, involving the use of the MARS system and a parallel video recording of the session, respectively. In all sessions, the sampling frequency has been set to $100\,\mathrm{Hz}$. Table 3.4 shows the main features of the considered runs. Different types of runs have been considered, in order to test the system on a variety of conditions. Each session is divided into observation slices. An observation slice is a temporal window of some seconds in which the coach expresses a level of asynchrony by observing rowers with the naked eye, namely, watching the video (possibly in slow motion) without using the MARS system. There are three possible levels of asynchrony that can be expressed: *Low* (L), *Medium* (M) and *High* (H).

For each session, the local (online) asynchrony has been processed, by using Δ = 2000. During the first session (A, the tuning session), the parameters for the activation function have also been set, according to the PPI established by the coach, who was focused on the novice rower, Cyan. Once the coach finished his assessment

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[5] http://repast.sourceforge.net

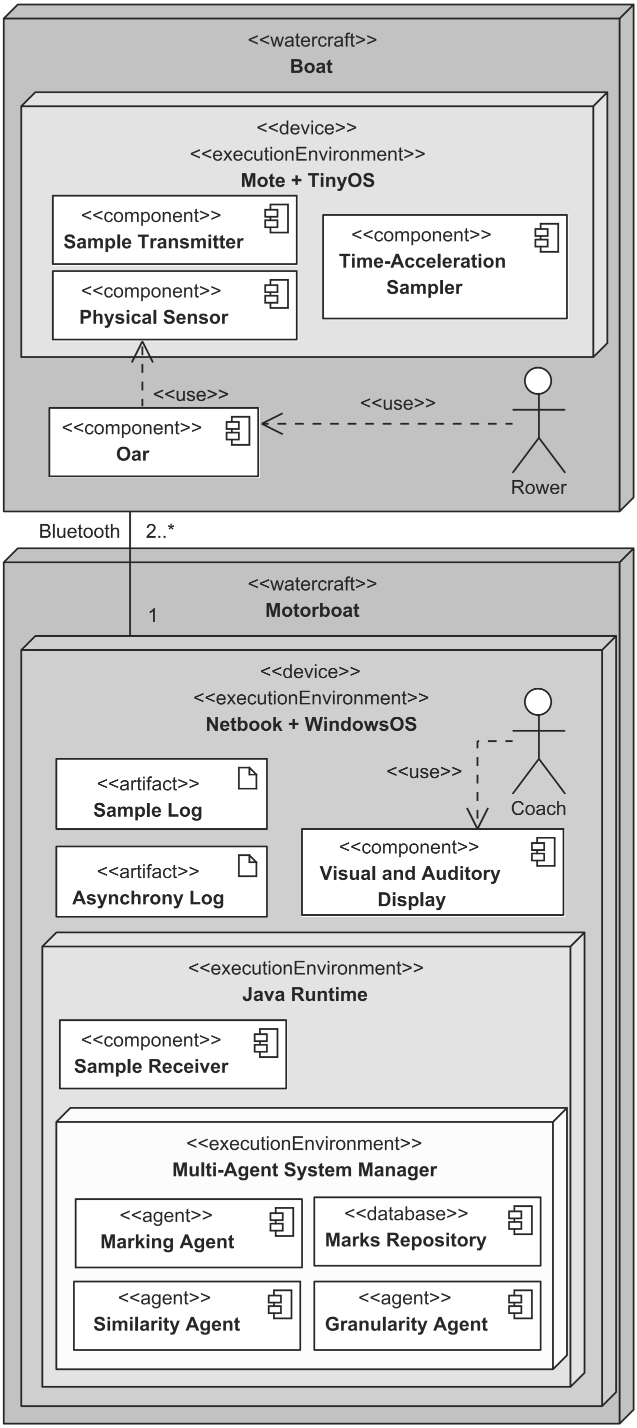


Figure 3.33. MARS, overall system architecture

Table 3.4. Runs and their main features

Run (session)	Total samples	Average strokes per minute (SPM)	Number of observation slices	Type of run
A	6500	33.4	13	inner-club competition
B	8000	15.4	8	training
C	4500	32.0	9	inner-club competition
D	5000	31.2	10	inner-club competition
E	8000	15.0	8	recovery

of run A, the activation function parameters have been set in order to produce the corresponding outcome via the MARS system. In this process, α and β were set to 0.3 and 0.5, respectively. The setting of the two parameters is simple: starting from standard values, which can be easily adjusted with a very few trials so as to pursue the reference values provided by an experienced coach. Table 3.5 shows the comparison between the coach and the system opinions. The coach was asked to perform the analysis using a video playback. The asynchrony values presented quantify the timing across the rowers. The numerical results provided by the MARS system can be located into corresponding classes used by the coach, using the following mapping: $[0, 0.2] \rightarrow L$, $(0.2, 0.5] \rightarrow M$ and $(0.5, 1.0] \rightarrow H$. As a result of the tuning session, the asynchrony produced by the system has become totally compliant with the coach classification.

Tables 3.6, 3.7, 3.8, and 3.9 show the results for the other sessions, by using the same parameters established in the tuning session, it can be noticed that in the testing sessions the asynchrony values produced by the system are totally compliant with the corresponding coach opinions, thus confirming the effectiveness of the system.

First, it should be noted that the variability of asynchrony is almost entirely expressed by the novice (Cyan) rower, according to the PPI of the coach. More specifically, in session A the Cyan (C) rower loses his synchrony at the start of the observation slice (first five seconds) and close to its end, with a peak between the 40^{th} and the 50^{th} second. In session B, at the 31^{th} second both Green and Cyan rowers lose their synchrony. It is worth nothing that the coach is not able to measure the difference between the two rowers, whereas the MARS system is able to assess that the Cyan performance is worse (0.40) with respect to the Green rower (0.22). In addition, at the 50^{th} second, the Cyan rower loses his synchrony again. In session C, the Cyan rower is the unique rower who appreciably loses his synchrony with three peaks, between the 5^{th} and the 10^{th} second, between the 20^{th} and the 25^{th} second and between the 40^{th} and the 45^{th} second. A similar behavior can be observed in session D, where a relevant asynchrony is detected in the first five seconds. Finally, in session E is the Red rower who, together with the Cyan rower, shows some performance drop be-

Table 3.5. Session *A*, Coach and System assessment

Time	Coach				MARS System			
(sec.)	R	G	B	C	R	G	B	C
5	L	L	L	M	0.02	0.00	0.00	0.23
10	L	L	L	L	0.00	0.01	0.00	0.14
15	L	L	L	L	0.00	0.01	0.00	0.19
20	L	L	L	L	0.00	0.00	0.00	0.04
25	L	L	L	L	0.00	0.02	0.00	0.02
30	L	L	L	L	0.00	0.00	0.00	0.01
35	L	L	L	L	0.00	0.00	0.00	0.09
40	L	L	L	M	0.00	0.00	0.00	0.32
45	L	L	L	H	0.00	0.00	0.00	0.70
50	L	L	L	H	0.02	0.00	0.00	0.76
55	L	L	L	M	0.00	0.00	0.00	0.44
60	L	L	L	L	0.00	0.00	0.00	0.01
65	L	L	L	L	0.00	0.00	0.00	0.00

tween the 30^{th} and the 40^{th} second. Again, note how the system is able to provide a more precise measurement of the performance variability, which is, in any case, in agreement with the assessment given by the coach .

3.4.7 Conclusions and future work

In this section, we presented MARS, a multi-agent system for assessing rowers' coordination via motion-based stigmergy. In the system, a sensing unit allows local sensing of the strokes via motes, a tracking unit collects and integrates the sensed data, a processing unit computes crew and athlete asynchrony, and a displaying unit provides visual and aural asynchrony feedback to the coach. The processing unit is based on the emergent approach, in which software agents employ a stigmergic computing scheme to measure the extent of similarity between behavior of the rowers. This section shows both architectural and functional views. The MARS system was tested on real-world rowing scenarios, involving four athletes with different experiences on a number of runs.

The trainer we worked with is highly skilled and experienced as he is currently training Olympic level athletes, in Italy. The results obtained in terms of asynchrony demonstrate that the proposed scheme can be successfully applied in the field.

As a future work, we aim at designing a self-tuning module for the parameters that need a manual setting. We will also experiment with new sonification methods based on *earcons*, musical or vocal motifs/sounds that humans use to improve the aural display of the system.

Table 3.6. Session *B*, Coach and System assessment

Time	Coach				MARS System			
(sec.)	R	G	B	C	R	G	B	C
10	L	L	L	L	0.00	0.02	0.00	0.05
20	L	L	L	L	0.00	0.04	0.00	0.13
30	L	M	L	M	0.02	0.22	0.00	0.40
40	L	L	L	L	0.00	0.03	0.00	0.14
50	L	L	L	H	0.01	0.09	0.00	0.62
60	L	L	L	H	0.00	0.07	0.01	0.62
70	L	L	L	M	0.00	0.06	0.00	0.46
80	L	L	L	M	0.02	0.04	0.00	0.48

Table 3.7. Session *C*, Coach and System assessment

Time	Coach				MARS System			
(sec.)	R	G	B	C	R	G	B	C
5	L	L	L	M	0.09	0.02	0.00	0.28
10	L	L	L	H	0.03	0.01	0.00	0.55
15	L	L	L	M	0.00	0.03	0.00	0.33
20	L	L	L	M	0.00	0.03	0.00	0.50
25	L	L	L	H	0.00	0.09	0.03	0.89
30	L	L	L	L	0.01	0.01	0.00	0.14
35	L	L	L	L	0.02	0.00	0.00	0.01
40	L	L	L	L	0.01	0.00	0.00	0.11
45	L	L	L	H	0.00	0.05	0.00	0.51

Table 3.8. Session *D*, Coach and System assessment

Time	Coach				MARS System			
(sec.)	R	G	B	C	R	G	B	C
5	L	L	L	H	0.00	0.05	0.00	0.53
10	L	L	L	L	0.03	0.03	0.00	0.10
15	L	L	L	L	0.02	0.03	0.00	0.14
20	L	L	L	M	0.00	0.00	0.00	0.37
25	L	L	L	L	0.00	0.00	0.00	0.15
30	L	L	L	L	0.00	0.00	0.00	0.13
35	L	L	L	M	0.00	0.01	0.00	0.20
40	L	L	L	L	0.00	0.01	0.00	0.10
45	L	L	L	L	0.00	0.00	0.00	0.01
50	L	L	L	L	0.00	0.00	0.00	0.00

Table 3.9. Session *E*, Coach and System assessment

Time	Coach				MARS System			
(sec.)	R	G	B	C	R	G	B	C
10	L	L	L	L	0.00	0.00	0.00	0.00
20	L	L	L	M	0.00	0.01	0.00	0.23
30	L	L	L	L	0.05	0.07	0.00	0.00
40	M	L	L	H	0.32	0.14	0.02	0.71
50	L	L	L	M	0.10	0.03	0.00	0.26
60	L	L	L	L	0.00	0.06	0.00	0.02
70	L	L	L	L	0.00	0.01	0.00	0.00
80	L	L	L	L	0.00	0.11	0.00	0.12

3.5 Chapter conclusion

I conclude this Chapter providing following considerations:

- rowing is a complex sport, where water - oar - boat - human interactions play a major role, and any effort in the direction of better understanding this interaction will lead to interesting findings;
- ICT technologies, in particular pervasive technologies, can not only enable new insights into the sport, but also enhance the training procedures;
- the overall interdisciplinary experience, involving the collaboration between computer engineering researchers with rowing trainers, athletes, sport and psychology researchers has been highly valuable;
- the interdisciplinary approach requests special attention and an increased level of effort to lead to accepted knowledge and literature, as there often is the lack for interdisciplinary experts.

Moreover, I think that I should *here* give a special acknowledgement to Mr. Leonardo Antonini, rowing trainer, whose ideas inspired the works related to synchrony detection, and whose personal engagement lead me to further expand my interest in measurement technologies applied to rowing. In particular Leonardo sent me to the "2011 FISA rowing trainers" conference, where I met Dr. Nina Schaffert and Prof. Klaus Mattes, that eventually introduced me to the field of sport sonification, rowing telemetry and performance analysis.

4

Swimming - monitoring and providing a feedback

> Ratten, Menschen ... Spezialisten auf
> nicht-spezialistsein.
> Rats, men, ... Specialists in non-specialization.
>
> Konrad Lorenz

Swimming is a combination of buoyancy and self-induced propulsion causing translation through the water [187]. How the self propulsion is happening is still subject to debates in the research fields related to swimming (fluiddynamics, physics, phisiology, sport science, ...). Much research in computer science, dealing with swimming and other sports, is focusing attention on the applicability and application of kinematic sensors, accelerometers, gyroscopes and magnetometers, to monitor swimming activity. In this context I tried a new approach, geared towards the investigation of the most relevant factors in swimming, based on tight collaboration with swimming experts. In particular with the informally formed group made of Bodo Ungerechts, Thomas Hermann and me, we developed a novel sensing, processing and sonification system. In this chapter, and in particular in the first section I will present work, ideas and results of preliminary tests of the new device (called Swimoni), based on sensing water pressure rather than only kinematic measures. Sonifying the measured pressure values and presenting them to the swimmers will have a twofold effect: enable a novel biofeedback for water space activities (like swimming) and create a novel communication channel between athlete and trainer. Finally the whole work should help understanding not only how to communicate effectively water flow effects, but will also help getting insights about two key questions:

- "How is efficient propulsion achieved by high level athletes?"
- "How can the so called feel-for-water be communicated?"

4.1 Real-time Sonification in Swimming -from pressure changes of displaced water to sound-

This section is about the communication of moving water mass displaced by a swimmers hand. Swimming is not just a matter of correct kinematics of limbs actions but rather it is a matter of a two-body-interaction due to the fact that a body moves inside water. A major concerns is how this can be communicated what swimmer name “feel for water”? In literature there is a lack concerning this concept. In this text I wish to report about the possibility to use sonification as the enabler of a new communication channel providing the same information to swimmers and coaches simultaneously. To this end an assessing interactive system working in real-time was developed; from measurement of pressure change due to hand action, mapping the signals into an informative and acceptable sound for the use at the pool deck. As a remark, most of the contents form this section are taken from [185], a work of Ungerechts, Cesarini, and Hermann.

4.1.1 Introduction

The communication about the swimmers’ internal perception of flow and the movement control is hampered because of missing mutual information about effect of interaction of actions of limbs and invisible motion of displaced (clear) water. Interaction as part of the connectivity of a two-bodies energy sphere. According to [161] the sensory picture of a voluntary action is a template to organize motor commands and guide motor control. It is widely known that elite swimmers have an excellent perception of water motion using somatosensory, proprioceptive or vestibular and visual cues. Swimming as a self-induced activity in aquatic space means displacing water mass at low energy costs while yielding high swimming speeds in reaction and this is what elite swimmers strive to reach using a right feel for water. [179] emphasized that without pressure no propulsion exists and a pressure differential method is potentially a useful means in stroke analysis of cyclic 3D hand action. Pressure-time recordings are “essential complementary information” [123] helping to detect wrong hand positions when unusual pressure graphs occur [191] . [107] pointed out that the interaction goes with pressure changes and momentum-induced effects of displaced water mass while drag - even if it is repeated often - does not explain the interaction effects sufficiently. Hence, kinematics of limbs’ actions is not necessarily a direct indicator of flow effects. [187] highlighted that interaction is a means to transfer metabolic energy via limb’s action to a unit volume of water which changes the energy-density, known as “pressure” which in liquids or currents differs from the term pressure solid body mechanics (although in both cases the physical unit is $[\mathrm{Pa}]$). [93] pointed out the importance of change of pressure, as an “intermediate level” (Figure 4.1) in connection with momentum-induced locomotion in aquatic space, a level which lacks attention in most swimming literature.

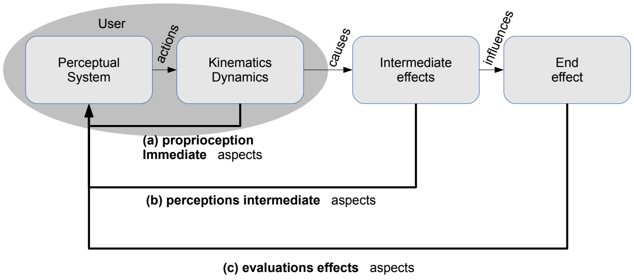


Figure 4.1. Different event levels on the route to self-induced locomotion in aquatic space (adapted from [93])

Presenting pressure changes as graphs lacks interactive aspects. Therefore the idea came up to use interactive sonification as an audible real-time feedback for the swimmer and the coach, simultaneously. Sonification is a means to map any data-flow like static pressure into functional sound emphasizing cognitive attentiveness for the essential aspects in noisy surrounding (which is more than just rhythm or change in pitch). Using audible signals as an information carrier like fishes do (profiting from the fact that pressure wave and sound wave are similar) also exists in human swimming. [112] presented a breaststroking avatar while the kinematic data of wrists and ankles were made audible using "Fairlight Aahs". Following [71] interactive sonification improve motor performance and perception of movements, after the individuals became acquainted to the functional sound and motor and auditory systems were co-activated (the relationship of cognitive levels is still a matter of multi-disciplinary research). It can be expected that swimmers, even without detailed introduction into sound perception, will optimize their perception of displaced water and thus increase performance. Moreover sonification may highlight novel aspects concerning local change of pressure and allows for a fruitful communication of aquatic events between different experts. The sonification of the intermediate level demands the selection of tools like pressure probes, pressure sensors, sonification program, loudspeakers and equipment joint in a new setting enabling operation at the deck of a pool. Before this new approach of augmented perception can be used widely e.g. as a support for talks between swimmer and coach or in cognitive studies, the device needs to be tested. It is the purpose of this section to inform about the new setting and how to generate auditory movement information, to give report on the mapping selected and the quality of the real-time feedback issue.

4.1.2 Materials and Methods

The particularity of liquid substance demands an appropriate tool to represent the intermediate level effects (Figure 4.1) namely the changes of static pressure or change of energy-density in a water volume (Pz) in flowing water due to non-steady interaction of body and water mass. The focus on changes in static pressure (not the same like the water column induced hydrostatic pressure) for sonification is justified because it represents the origin of the work done on the water [193] . Historically the omnidirectional static pressure component (Pz) in a current is measured by means of a Piezo-probe, which is a tube bluntly ending normal to the surface of an object, always perpendicular to the stream line, whilst Pitot-probe are used to measure kinetic energy (Epot is depending on the depth) (Figure 4.2). Based on this knowledge the pressure on the body surface of swimming bluefish was measured using probes, whose flared end lay snugly within the hole in the skin. It was shown that in live swimming fish pressure on the base of the tail is still negative and tail motion seem to draw water away from the peduncle of the tail [67].

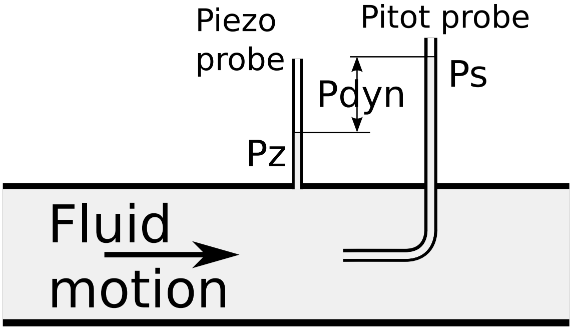


Figure 4.2. Schema of a Piezo-probe and a Pitot-probe. The Piezo-probe is to measure the change of energy-density per unit volume (Pz)

Piezo-probes are established tools to measure the change of energy-density in a water volume (Pz) (e.g. around a hand) due to interaction [184] . Whether some energy is added to water volume via body motion and accelerates (thrusting) water or the flow per unit volume slows down (braking) can be substantiated by the difference between two probes values (Pz). The setting to determine the effect of the hand action on the water mass and the transfer into sound is presented in Figure 4.3.

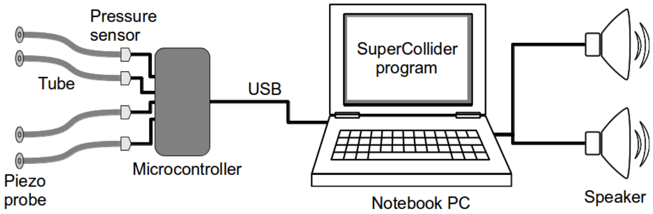
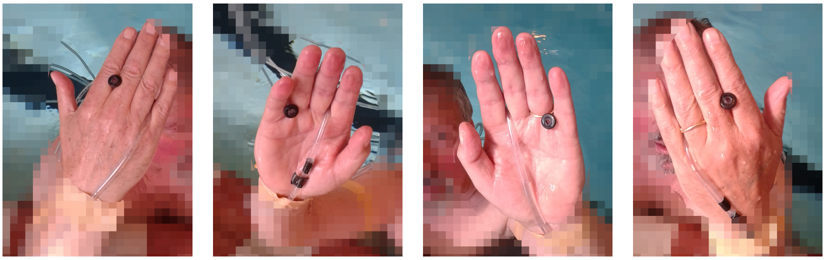


Figure 4.3. Draft version of the setting of used tools (measure pressure (Pz) until sound emitting)

Two Piezo-probes per hand, one facing to the palmar side hand the other to the back side are connected via flexible tubes (Diameter 4mm) (Figure 4.4) running along the arm via shoulder to the pressure sensors (Specs: Freescale MXP5010DP analog pressure sensor, 0-10 kPa pressure range) to a waterproof box fixed to a rod outside water held above the moving swimmer. The data from the pressure sensors (sampled at 100Hz) were processed via a microcontroller based board (Specs: Arduino Nano - Atmel ATmega328, 8-bit RISC, operating at 8MHz, programmed in C) and transmitted via USB cable to a Notebook carried on a hawker's tray. The sound was processed by a SuperCollider program and emitted via Stereo Loudspeakers.



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

Figure 4.4. Location of Piezo-probes on the swimmers hand.

Table 4.1 summarizes key acquisition and processing times of the Swimoni system.

Instrumentation of swimmers

The openings of Piezo-Probes, 2 per hand, were placed parallel to the surface, respectively (Figure 4.4); the connecting tube fastened to lower, upper arm and between

Table 4.1. Time calculation for acquisition and processing.

Name	Data	Time $[\mathrm{ms}]$
Sensors sampling frequency	$100\ \mathrm{Hz}$	$10,0$
Read analog sensor	$0,1\ \mathrm{ms} * 4\ \mathrm{sensors}$	$0,4$
USB transmission	$4800\ \mathrm{Byte/s}; 20\ \mathrm{Bytedata}$	$4,2$
TOTAL	——	**14,6**

the scapulae ending in the waterproof box with microcontroller and sensors, attached to a fishing rod; the rod was held by an assistant at pool deck who also carried the hawker's tray with PC and loudspeakers (Figure 4.5).

Figure 4.5. The test setup, with the waterproof-box fixed on fishing rod, notebook on hawker's-tray and tape-fixing of tubes on back of test person.

Selection of sound mapping

To process data, acquired through the sensors, on the PC we used SuperCollider. With SuperCollider we developed a sonification scheme and explored the mappings of changing pressure data (Pz) to sound. Mappings can be based on modulation of e.g. pitch, amplitude, loudness, loudspeaker orientation. Attention was also put into pleasantness of sound, because of continuous flow of sound is repeated over a longer period in time (depending of the period to cover a certain distance from 25 m to 400 m) the mapping should be accepted by the recipient to fulfill the task of a supplement feedback. [40] investigated a 12 tones scale for usage on a mobile system in rowing sonification. It was noticed that using either approach, discrete or continuous actually enhances different aspects of the original signal. [87] emphasized that “Parameter mapping sonification (PMSon) involves the association of information with auditory parameters for the purpose of data display”. PMSon provides a way to build a repeatable transformation from the domain of the monitored signal to that of human hearing. Before applying PMSon to data the actual difference of palmar to back pressure value is calculated. Then the left hand difference and the right hand difference pressures (Pz) are fed into the particular PMSon, respectively. The selected mapping is a

3-tone scale mapping (stepwise)

using the SuperCollider code: (55+leftPressure.linlin(0,5000,0,24)).round(3).midicps) according to the Handbook of Sonification (Hermann et al, 2011). The code represents a linear conversion from pressure values to midi numbers, rounding the result to 3 (obtaining a 3-tone scale), and finally the midi number is converted to the correct frequency value to be played back by the synthesizer. The stepwise mapping is selected to yield some aesthetics emphasizing better perception of pronounced changes in the data-flow; in addition sound of left and right hand was presented on left and right loudspeaker, respectively.

As an exploratory work also two other mappings were tested:

Pitch mapping (continuous pitch mapping)

Pure linear mapping, using the same parameters for both hands mapping 0 pressure to midi tone 65 (349.22Hz) and pressure of 5Kpa to midi tone 100 (2.63KHz) with a linear conversion to the midi scale. The pitch mapping indicates an increase of the pressure difference between palmar and back of left hand which will cause an increase of the tone pitch (sound frequency), and vice versa; in addition sound of left and right hand was presented on left and right loudspeaker, respectively (Figure 4.6 depicts the continuous pitch mapping scheme as a function).

Amplitude mapping (continuous amplitude mapping)

Modulation of amplitude, differentiation of perception of hands using different (fixed) pitch for left midi tone 65 (349,22 Hz) and for right hand midi tone 72 (523,25 Hz). The difference pressure value of each hand is used to modulate the amplitude of two fixed pitch sinusoidal oscillator working at the reported frequencies. The amplitude mapping indicates an increase of the pressure difference between palmar and back of left hand which will cause an increase of the tone amplitude (sound loudness), and vice versa; in addition sound of left and right hand was presented on left and right loudspeaker using different pitches, respectively.

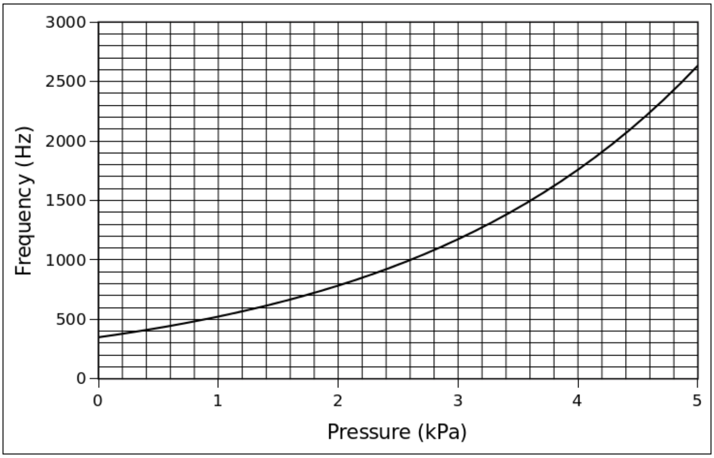


Figure 4.6. Pressure – Pitch continuous mapping, applied to the pressure difference of each hand separately.

Discrete vs continuous mapping

In the discrete mapping, pitch (or other sound qualities) can assume only discrete values, according to a predefined scale, in a manner similar to selection of notes on a piano keyboard. In the continuous mappings pitch (amplitude) can assume any value in a manner similar to fretless strings instruments like violins or human voice [151]. A discrete pitch mapping sounds more aesthetic than a continuous one. The functionality of these two opposite schemes needs however to be deeper analyzed and tested. Discrete mappings allow having an enhanced perception of changes of signals, representing the change in a complete new tone, whereas continuous mappings allow perceiving changes in the signal immediately in the output sound at expense of level of perception; this is especially important considering that the sounds should be listened to while performing movements in water. [40] investigated the usage of a 12 tones scale for usage on a mobile system in rowing sonification. It was noticed that using either approach, discrete or continuous actually enhances different aspects of the original signal that has been sonified.

Qualification of real-time aspect in terms of latency

The processes of this new setting of tools required some time and the latency of the setting needs to be evaluated. Here latency means the time delay between the voluntary start of outsweep hand action causing change of (Pz) until the sound is emitted via loudspeakers. To check the latency a fully instrumented breaststroke swimmer was videotaped (30 fps) swimming with extremely long gliding phases in a 25 m pool.

The time instant when the hands started sweeping outwards was determined from the video and the time instant of emitted sound was determined after the video's soundtrack was transferred to an Audacity program (Figure 4.7).

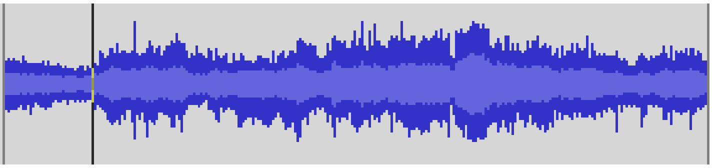
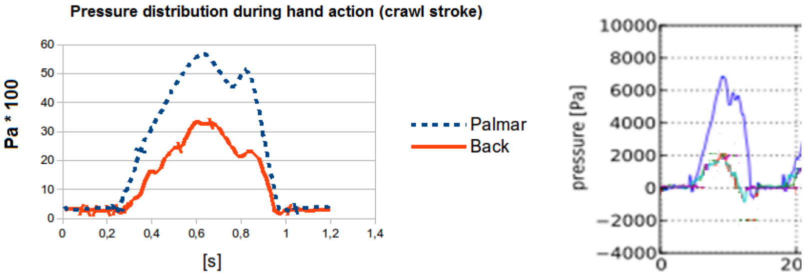


Figure 4.7. Density cloud including the total noise of a swimming pool plus the sound from the loudspeakers; a vertical line indicates the start of the sound induced by pressure changes (Pz) due to the start of the hand action after gliding

The difference of both time instants represent the latency. There is no proof value existing in the literature but probably this time should be related to the time of cognitive control loops.

4.1.3 Results

First, the pressure data (Pz) were checked. It was shown, the pressure data (Pz) per crawl stoke cycle perfectly match in magnitude and dynamic behavior to what is found in literature (Toussaint et al. 2002) using different type of pressure sensors (Figure 4.8(a) vs Figure 4.8(b)).



(a) results from our system (b) Results from [182]

Figure 4.8. Pressure distribution (Pz) acquired via the Piezo-probes during hand action below water (crawl stroke) of a slow swimming person.

Next, the latency or the quality of the real-time aspect was checked quantitatively using a test when the swimmer swam breaststroke with a remarkable long glide; per $25\ \mathrm{m}$ lane 8 breaststroke cycles were executed.

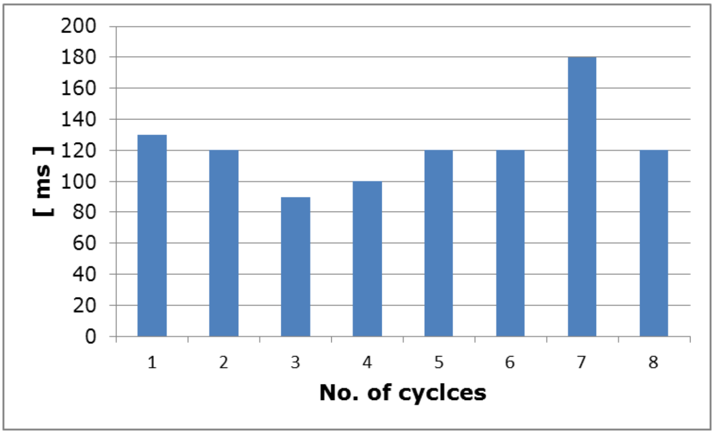


Figure 4.9. Time between start of hands into a cycle and the change of the sound from the loudspeakers.

The time duration between the voluntary start of outsweep hand action and the sound emitting via loudspeakers was in the range between $100 - 123\mathrm{ms}$ (Figure 4.9) while the mean is $123 \pm 27\mathrm{ms}$. A difference of one video frame equals 33 ms. The calculation of latency due to the "internal" time of the "electronic" transit of the setting gives 14,6 ms.

We need however to consider that in this case we consider the "total" delay of the system, from action to sound, composed of moving water, hands, flow effects, probes, tubes, transducers, acquisition, processing, reproduction of sound.

4.1.4 Discussion

Different pressure zones on the palm and the back might resemble Bernoulli's approach used in steady flow to explain circulating flow components; in non-steady flow with drastically changes of acceleration Bernoulli's approach does not apply [129, 186] . Using the presented Piezo-probe based setting for sonification of change of energy density per volume (Pz) due to disturbed water mass in aquatic actions can be advised. An identification of the effect of the sound mappings on the swimmers actual motoric activities was not of priority of this first testing. All 5 test subjects [1] told a) the tubes did not disturb stroking and b) the real-time quality was perceived as if "each action in water gives immediate reaction". The real-time check yields positive results, because a delay of 123 ms is not far from reaction threshold of sportive actions in water. The functional sound designs selected here is not yet fixed. There will be the

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[1] The 5 test subjects were characterized by different levels of swimming experience and expertise, from novel swimmers to experienced swimmer and trainer

choice of two functionality opposite schemes which needs to be deeper analyzed and tested: discrete mappings allow having an enhanced perception of changes of signals, representing the change in a complete new tone, whereas continuous mappings allow perceiving changes in the signal immediately in the output sound at expense of level of perception; the latter is especially important considering that the sounds should be listened to while performing movements in water. The selection of the 3-tone scale mapping (sounds more aesthetic than a continuous one) was not accidentally because of experience with former mappings of pressure curves [93] . One might assume that the relatively small number of trials is a limitation of our study and it is too early to judge which mapping would please the swimmer when using the real-time sonification of displaced water in training situation as well as to report which mapping is functionally the most appropriate for the non-steady flow situation.

Future perspectives

This section concentrates on individual swimmers to increase his/her ability to perceive water motion in combination with self-perception of the body action. The interactive sonification of pressure data might have the potential as augmented feedback to the swimmer directly and as a support to communicate about flow and sensation of flow. Since the link between kinematics of the hand and the resulting body motion is not yet fully understood sonification -probably in conjunction with an effect variable like intracyclic velocity-variation- a better communication between swimmers/experts about flow and the sensation of flow is needed (Figure 4.10 describes the *legacy* way of training, while Figure 4.11 describes the new audio-enhanced communication channel enabled between trainer and athlete) .

The real-time sonification of pressure changes due to displaced water mass is expected a major step towards the aims a) to enhance interrelated perceptions of effects of actions via sound (instead of prescribing a movement) and b) to discover unknown relevant patterns of the (non-steady flow) data. Real-time sonification of moving water masses is undoubtedly a promising tool for training sessions with elite swimmers at least concerning two aspects: one is related to the cognition-levels of the swimmer who can now use another channel together with the existing own neural network concerning the intimate “feel for water”-competence and the other aspect is a completely new way of communication between coach and (elite) swimmers about a more effective action of hands (Fig 8). If communication about sensing the flow, a somewhat neglected topic until now, surely will lead to improvements is likely but needs to be examined. Compared to “informative paddles” introduced by [49] for real-time auditive feedback of manual hydrodynamic pressure to the swimmer the new

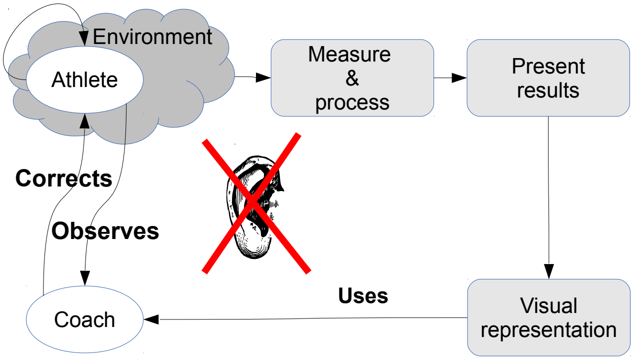

Figure 4.10. Schema of the old (legacy) approach of training, without the additional channel

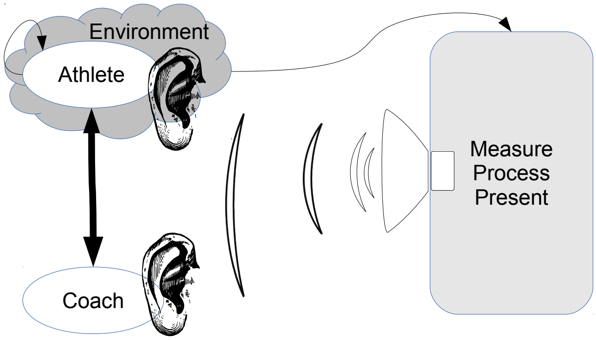

Figure 4.11. Schema of a new approach of training communication using a new setting

setting provides some developments. Here the hand needs not to be equipped with paddles, no “chosen strength limit” needs to be overtaken and the conflict of mixing terms like “hydrodynamic pressure”, “static pressure” and “hydrodynamic forces” is solved because the new setting is opt to be sensitive to static pressure (which is not possible with the paddles). In summary, swimmers benefit from this interactive bio-feedback as a “self-control means” learning, coaches will be informed more detailed and experts from flow physics could use the original pressure-time-data for analysis of non-steady flow behavior.

4.2 SwiMozzi - Swimming sonification on an embedded device

In Section 4.1 we described how moving water masses represent the effects of hand actions and are the relevant factors in propulsion of swimmers. We also showed how to transform such a measure into e valuable information to swimmers and trainers, through the usage of a PC based synthesis environment, SuperCollider. In this Section 4.2 we explore possibilities to build an embedded system, incorporating the functionality of SwiMoni [2] and expanding it with the possibility to synthesize sounds in the embedded system. As shown in Section 4.1 the possibilities opened by sonification for swimming are:

- the swimmer can perceive in real-time the effect of performed movements, allowing him to *listen* to errors, and correct movements without the intervention of the trainer;
- the trainer can *listen* to the performance of the swimmer, and through this find possible areas of improvement for the athlete;
- for the trainer it is possible to transmit information about movements exploiting the common information carried by sound;
- in the case of visually impaired or blind athletes / trainers the common audio channel will possibly enable a more natural communication about actions in water.

This Section is concentrated on ways to build a low-cost, low-tech embedded sonification system for swimming. The complete embedded wearable system for biofeedback of relevant intermediate effects of swimming actions presented here is called SwiMozzi [160]. The system is based on Arduino [1] and the Mozzi [3] audio synthesis library for Arduino.

4.2.1 Swimming styles

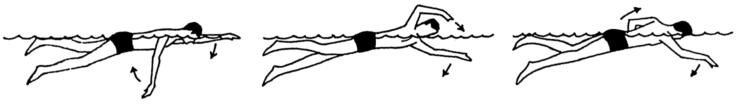

Figure 4.12. Crawl swimming style

The principal swimming styles are:

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[2] Swim-monitoring device developed during the visiting period of the author of this Thesis at CI-TEC institute in Bielefeld, Germany, in 2013

[3] `http://sensorium.github.io/Mozzi/`

- *crawl*: it is the style that combines the maximum propulsion at the minimum energy cost. Propulsion phases of arms and lower limbs are alternated;
- *backstroke*: in this style the swimmer is swimming on the back. Similarly to crawl, it is an alternating style for arms and lower limbs;
- *breast stroke*: slower and more technical than other styles, it is characterized by a lateral symmetry;
- *dolphin crawl*: it is the style that generally needs the highest amount of energy and high degree of coordination. It is a symmetric style, using frontal respiration.

4.2.2 Development phases

In this Subsection we describe the development process of SwiMozzi. We first developed a prototype board (based on Arduino Uno) to implement preliminary sonification schemes. After some preliminary experiments with Mozzi on Arduino, we studied several different sonification schemes, implemented with Mozzi, working with real data (acquired during June 2013 in Bielefeld University [41]). The final design provides a series of schemes (sketches in Arduino language) to be used in crawling swimming style.

Prototype

The first prototype is based on the Mozzi library running on an Arduino Uno[4] board, assembled as suggested by the Mozzi tutorial[5]:

- 2 photoresistors VT90N2;
- 2 potentiometers with impedance of $[0-10]\ \mathrm{kOhm}$;
- 1 TRS audio jack;

Moreover we implemented two circuits:

- an RC (Resistive Capacitive) low pass filter, with a cut-off frequency of $[6\ \mathrm{kHz}$, obtained with a $270\ \mathrm{kOhm}$ resistance and a $4.7\ \mathrm{nF}$ capacitance;
- a special circuit, to implement the Mozzi "HIFI" mode, obtained connecting two PWM (Pulse Width Modulation) digital pins, with a $3.9\ \mathrm{kOhm}$ resistance, a $499\ \mathrm{kOhm}$ resistance and a $4.7\ \mathrm{nF}$ capacitance.

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[4] `http://arduino.cc/en/Main/arduinoBoardUno`

[5] `http://sensorium.github.io/Mozzi`

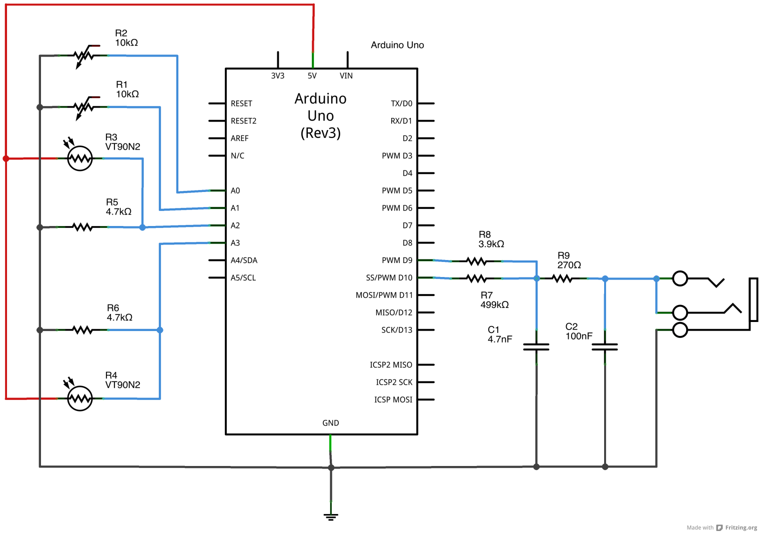

Figure 4.13. Logic connections of first prototype

Sonification for crawling swimming

Based on the experience gathered during the preliminary experiments with the first prototype, the experiments with SwiMoni [41] and on literature study [93], we searched for sonification schemes able to provide meaningful feedback for crawling swimming.

To guide the design of the sonification schemes we used data acquired during the test sessions performed during June 2013 [37, 41] with the SwiMoni system.

Data format

The data produced by SwiMoni is stored in CSV [6] files. Each row of the file contains five fields:

- Timestamp
- Left hand, palmar pressure (LxP) [expressed in Pascal - Pa];
- Left hand, dorsal pressure (LxD) [expressed in Pascal - Pa];
- Right hand, palmar pressure (RxP) [expressed in Pascal - Pa];
- Right hand, dorsal pressure (RxD) [expressed in Pascal - Pa];

Code 4.1. Excerpt of the SwiMoni file

```
 Time[s], LxP[Pa], LxD[Pa], RxP[Pa], RxD[Pa]
3.605814,    5354,     149,    1211,    1462
```

---

[6] Comma Separated Values

```
3.621887,     5448,      148,     1220,     1451
3.637852,     5489,      177,     1234,     1442
```

For all further elaborations of signals we processed that data to obtain the pressure difference between palmar and dorsal for left and right respectively, thus obtaining following data:

Code 4.2. Excerpt of the processed data

```
 Time[s], LxP-D[Pa], RxP-D[Pa]
3.605814,      5205,        251
3.621887,      5300,        231
3.637852,      5312,        208
```

In Figure 4.2.2 we represent pressure differences for left and right hand.

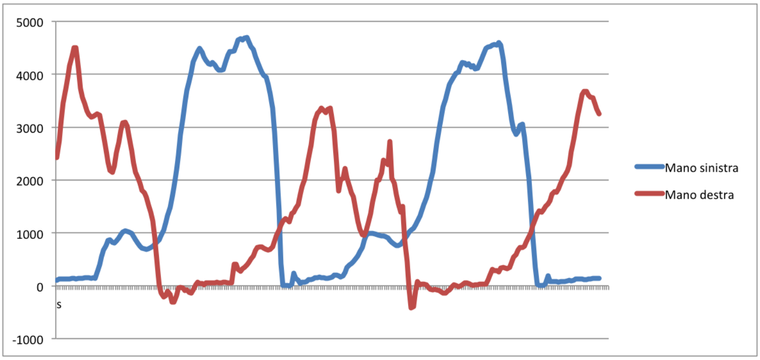

Figure 4.14. Pressure difference for left and right hand

4.2.3 Explored sonification schemes

We explored following sonification schemes:

Continuous sonification
Threshold based sonification
Event based sonification

4.2.4 Implementation of SwiMozzi

After we explored the potential use of Mozzi on Ardunio, we searched for the most suitable sonification schemes for crawling swimming. For this we present two approaches: (i) sonification of regularity of arm movement cycles through comparison of maximum pressure (ii) sonification of energy transfer per arm cycle.

SwiMozzi device design

Based on the explored functionalities of the first prototype we designed SwiMozzi: we removed the photoresistors, and included two MXP5010DP FreeScale differential pressure sensors. We used the HIFI mode version of the prototype, enabling a higher quality of produced sound, obtaining the design shown in Figure 4.15.

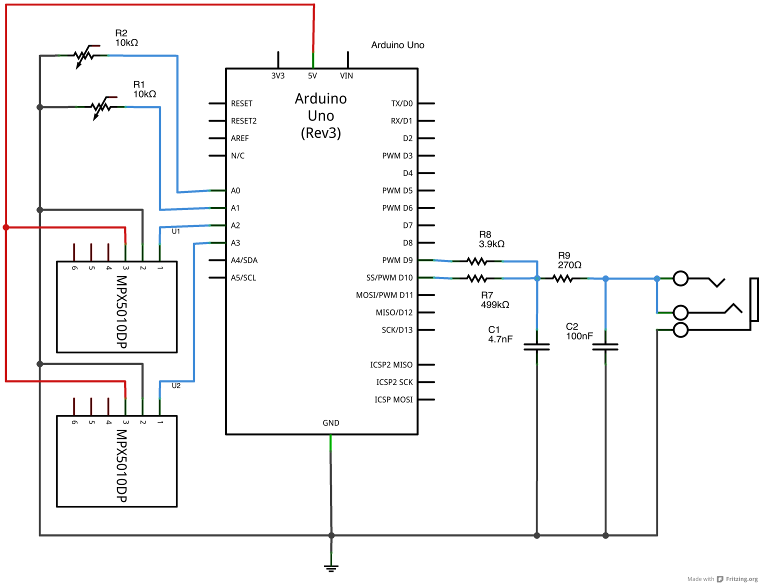

Figure 4.15. Logical connections of SwiMozzi device

4.2.5 Conclusions of SwiMozzi design - future perspectives

Sonification of motor activities represents a promising application field of pervasive systems combined with *Auditory Display*. As we observed from out experiments Mozzi and Arduino are suitable to provide a real-time feedback for swimming activity, although the actual implementation of Mozzi on Arduino supports onlu monophonic audio output.

Future steps

Stereophonic audio synthesis

as long as the Mozzi Library will not support stereophonic audio output, the only viable solution to provide a stereophonic output seems to be the combination of 3 Arduino devices: one as controller, two as synthesizers.

Application to symmetric swimming styles

We will in future explore viable sonification schemes designed to enhance training of symmetric swimming styles (dolphin, breaststroke). The envisioned results of such a development are a system to enhance the symmetry of energy transfer from limbs (hands) to water.

Development of a dedicate Arduino shield

The development of a dedicated Arduino shield to incorporate all components of SwiMozzi (depicted in Figure 4.15) would allow for further development of the system, without the need for a prototype board, and possibly enable the development of a waterproof device, usable to provide sound feedback in water, coupled with waterproof earplugs.

4.3 Conclusion and future perspectives

I strongly believe that sonification of moving water masses, as presented in this Chapter can both provide a bio-feedback to swimmers while swimming, and represent the enabler of a new and unknown way of communicating about water flow effects on swimmers. This channel will be usable by trainers and swimmers, trainers and trainers, swimmers and swimmers, and maybe enter also the field of non-stationary fluid dynamics research.

We are currently involved in extensively testing the potential of our system with help of test persons, and aiming at testing the system with elite level athletes and the collaboration of international level trainers. First results show that an on-line real-time sound can change the way people execute movements, and most of all, change the intermediate flow effects, measured as pressures.

5

Running - flight / contact phase estimation

> The miracle isn't that I finished.
> The miracle is that I had the courage to start.
>
> John Bingham

In last years technology is being increasingly exploited to monitor sports performance and it is true in athletics too. The present study aims to give support to coaches and athletes in evaluating the running technique, by means of an unobtrusive and cheap instrumentation. A single triaxial accelerometer, fixed to the subject's lower back, can be used to identify the two main instants (the *relevant variables*) characterizing the running gait, foot-strike and foot-off. The same approach works also for vertical jumps, so it is useful to assess durations of contact and flight both in the common running or sprinting activities and in the typical force evaluation tests executed in track and field training.

In this chapter we will introduce a method to monitor foot contact and flight duration assessment with a single triaxial trunk mounted accelerometer during running, in Section 5.1 and a method to *virtually align* the axes of a trunk mounted accelerometer, in Section 5.2.

5.1 Foot contact and flight duration assessment with a single triaxial trunk mounted accelerometer

The application consists in a device (e.g. a smartphone) embedding the inertial sensor and collecting the data and in a signal processing module. This software analyzing the acceleration can be implemented both on an external PC for an offline analysis and directly on the mobile device itself for an online analysis. Tests were conducted on a conductive mat (*Pedana di Bosco* for *Ergojump Protocol*) for jumping and on a force measuring system (*Zebris FDM-T System*) for treadmill running. In both tests, results show high agreement for jump and step duration, and moderate agreement for contact and flight times (higher in jumping than running). For sprinting it was only possible to manually count the number of steps because of the lack of a reference measuring system: for this measured variable we obtained a excellent correspondence with the ground truth [32].

5.1.1 Introduction

Since about a decade there was a increasing interest in computing technologies to enhance athlete performance [47] in a lot of different sports (rowing, swimming, running, winter sports) [102, 101].

Fleming et al. [76] conducted a study on some runners, sprinters and their coaches to evaluate the perception of technology and identify the most important characteristics to be monitored. Most of the participants agreed that technology could help improve technique, preferring small, light, unobtrusive devices capable of providing information quickly and easily interpretable with a real-time data collection and feedback. Furthermore stride frequency and foot contact duration were relevant characteristics both for sprinters and distance runners, as already shown in previous researches [142, 175]. The existing instrumentation (force plates, force sensitive resistors [44, 45], motion capture, high-speed camera, infrared light system [88]) usually used to measure these kinematic variables suffers of many drawbacks: portability, cost, time and expert to analyse data, and restriction to a laboratory environment.

So many researches focused their attention on wireless inertial sensors (accelerometers, gyroscopes) to develop methods to extract gait related information at various intensity (walking [126, 202, 201, 28, 118], running [116, 117, 143, 196, 132] and sprinting [43, 46, 60, 115, 183]).

Although walking and running biomechanics are different [144, 70], mainly for the absence of double support phase in latter, studies on walking are interesting to analyse their approaches in sensor positioning and signal processing. Moreover we can consider the error obtained in their comparative tests: Mansfield and Lyons [126] observed a typical delay of about 0.15 s (with an intra-subject standard deviation from 0.024 s to 0.086 s) in heel contact between accelerometer and force sensitive resistor (FSR); Zijlstra and Hof [202, 201] obtained a mean error of roughly 0.01 s in heel contact instant comparing an accelerometer-based peak-detection algorithm and a ground reaction forces (GRF) method; Lee at al. [118] extract duration of different phases of walking gait from acceleration signal, with errors on mean durations (compared with footswiches) ranging from -0.03 s to 0.03 s.

The measured variables (i.e. the output of the developed applications) by the related works previously cited are various. In order of assessment complexity, first of all we can cite step count, duration and frequency, obtained via zero-crossing [115] or peak-detection [183] algorithm or via the Fast Fourier Transform (FFT) [143]. Then we have stance (contact) time and swing (flight) time measured in [43, 46, 116, 117, 196, 132], from which it is possible to calculate also the simpler characteristics just mentioned. Finally there are more complex variables. Examples are the qualitative analysis of sprinting technique [60] with the needing of expert's analysis. Then we have the estimation of velocity that requires the knowledge of the real covered distance [183] and sensor fusion [115]. Furthermore the step length [202, 201, 28] can be calculated using the pendulum model by means of the double integration of the vertical acceleration, resulting in low accuracy caused by the drift.

All these existing studies use accelerometers and/or gyroscopes placed on different body locations: upper part of the trunk [143], lower back [126, 202, 201, 28, 46, 116, 117, 196, 60, 115], hip, shank [43, 132, 183] and ankle [118].

The aim of the study described in this section was to realize an application that could provide immediately interpretable and interesting information to evaluate running and sprinting technique and performance: the choice fell on contact and flight times. The sensor required to collect raw data is a single tri-axial accelerometer, that should be fixed on the lumbar spine by means of a belt, near to the body center of mass (CoM). This because we wanted to maintain the hardware requirements as little as possible, exploiting a readily available and unobtrusive (i.e. comfortable to wear) technology. So, basing on the approach presented in [196], an algorithm for automatic detection of foot-strike (or touchdown) and foot-off (or takeoff) instants was developed. It uses only the vertical acceleration, because its estimation is more accurate than that of anterior-posterior and medio-lateral components. The virtual online alignment of the vertical axis with gravity allows an immediate use of the application, without a preliminary calibration phase.

To validate the algorithm some tests were conducted. In the first, data extracted from acceleration during vertical jumps executed according to Bosco Ergojump Protocol were compared to ones provided by the *Pedana di Bosco*, a conductive (resistive or capacitive) platform connected to a digital timer triggered and stopped by the athlete jumping on it [26]. The resulting good level of agreement between the jumping parameters as calculated by the two instrumentations showed that the accelerometer based approach works well for jumping.

A second comparison was performed during treadmill running using the Zebris FDM-T System as reference, a measuring system for determining ground reaction forces. Simply considering zero forces as swing phase and non zero values as stance phase, the mean true errors obtained were comparable with those presented in [132], i.e. small differences in stride time and moderate differences in contact and flight times. Using thresholds on GRFs different from zero [98] to detect touchdown and takeoff resulted in an improved agreement.

For overground running, in particular for sprinting, in absence of a reference measuring instrumentation, the number of steps performed on 60 m was manually counted and compared to that detected from the acceleration. Very small differences were obtained, likely caused by an imprecise manual stopping of the stopwatch, too.

5.1.2 Methodology

The athlete's gait parameters were extracted during running, sprinting and jumping processing the data acquired by an accelerometer.

Equipment

Acceleration data were acquired via a triaxial accelerometer embedded in a smartphone. The signal were sampled at the maximum rate allowed by the device (about 80 Hz on average). The device, weighting approximately 140 g, was fastened around the subject's waist by a belt, in correspondence to the body CoM (i.e. between the lumbar and the sacral region). Didn't matter how the axes of the sensor are aligned, because it is possible to virtually realign them in order to extract the relevant information. Signal samples with their timestamps were stored on the SD card for an offline processing on a PC, but they were also analysed online directly on the smartphone, with the possibility to give the runner a "near to real time" audio feedback.

Definition of measured variables

Analysing the acceleration signal, the instants when the foot touches the ground (touchdown TD) and in which it releases the soil (takeoff TO) can be identified. In this manner it is possible to derive a lot of gait or jumping parameters (g is the value of gravity acceleration, i.e. $9.0865\ m/s^2$):

contact time (t_c)
: time from TD to TO of the same foot

flight time (t_f)
: time from TO of a foot to TD of the contra lateral foot

step duration (d)
: time from TD of a foot to TD of the contra lateral foot
: $d = t_c + t_f$

stride count
: number of steps

stride frequency
: number of steps taken in a given period, divided by the amount of time required to execute them

height (h)
: height raised by the CoM during vertical jumps [12]
: $h = \frac{g \cdot t_f^2}{8}$

mechanical power (p)
: mechanical power per body mass generated by leg extensor muscles during vertical jumps (expressed in Watt/kg) [26]
: $p = \frac{g^2 \cdot t_f \cdot d}{4 \cdot t_c}$

5.1.3 Data processing

Reorientation of the accelerometer

To extract parameters of each step it is necessary to analyze the acceleration along axes "fixed" to the athlete's motion (Figure 5.1): *longitudinal* axis (vertical direction), *sagittal* axis (antero-posterior direction), *transversal* axis (medio-lateral direction). It is necessary to derive accelerations along athlete's axes from the acceleration read from the sensor, that is arbitrarly placed. The derivation can e a rotation of the reference system of the accelerometer, in order to (virtually) align the Z axis with the direction of gravity acceleration, the X axis in the forward direction, and the Y axis perpendicular to the first two.

Gravitational component

To align the Z axis vertically it is necessary to first understand what is the contribution of the acceleration of gravity, read from the axes of the sensor, and then rotate them so that only Z experience gravitational acceleration. To do so we have to separate the static from the dynamic component mediating or low-pass filtering the acceleration

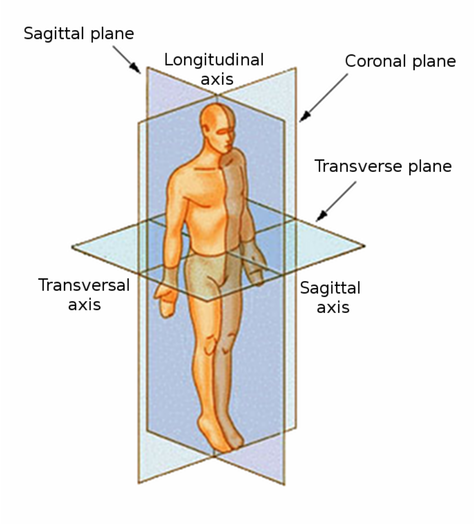

Figure 5.1. Principal axes of human body: reference system of the athlete

signal over a certain time interval [135]: calculating the average value of the acceleration in a window suitably chosen, the dynamic component tends to vanish, leaving out the static component.

To estimate the grativational component of the acceleration we can use different methods, presented below, with a brief analysis of pros and cons:

1. low pass filtering of the whole signal with a rectangular filter with a $0.9\ \mathrm{Hz}$ band (Figure 5.2)

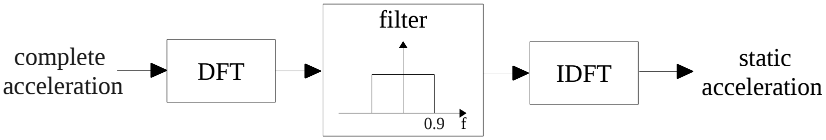

Figure 5.2. Frequency filtering of the acceleration to calculate the static component

   - it is the method that provides best results
   - it assumes to know the whole signal, thus it is unusable in real-time (it would need to know future)

2. *exponential moving average filter*

$$a_s(t) = \beta \cdot a_s(t-1) + (1-\beta) \cdot a(t)$$

  - extremely low complexity
  - it does not provide good results, as all past history is considered for current $a_s(t)$

3. analysis of the signal through sliding windows
   a) *median* [139] – it does not provide good results
   b) *average* [134, 170, 137, 135] – quite good results. In particular, using a weighted average with decreasesing weights from the sample of the current acceleration, we get a good approximation of a low pass filter
   c) *FIR Windowed-Sinc filter* [174, 198, 197] with a cutoff frequency of $0.9\ \mathrm{Hz}$ and a band roll-off normalized to 0.04 the results are satisfactory

Other two factors that affect the quality of the resulting gravitational signal are the window size and the window position with respect to current acceleration sample:

- *size* – optimal size is equal to double period of the signal. The size should not be to big, in order to quikly adapt to changing positions [170]; considering real-time analysis it is needed to determine the window size before deployment;
- *position* – the best position of the sample is at the center of windows. This is however difficult to use in real-time as it imposes a delay equal to half the window. Thus in practical real-time applications current sample is positioned at the end of the window.

Summarizing the best solution for real-time processing of accelerometer signals is represented by a FIR Hamming Windowed Sinc filter, with a cut-off frequency of $0.9\ \mathrm{Hz}$, and a roll-off band of 0.04.

Reorientation

Once we determined static component of acceleration, we can perform a rotation of the reference system such that the static component is present solely by the Z axis (Z axis aligned with gravity, and X and Y lying on horizontal plane, with an unknown rotation around Z, as gravity is invariant to rotation around vertival axis).

Section 5.2 deals with the rotation of the axes on the horizontal plane, considering that the acceleration signal over mediolateral axis in running or walking man exhibits some sort of simmetry for each step. This simmetry is caused by the almost-equivalent forces applied by the feet step after step, along medio-lateral direction.

5.1.4 Recognition of flight and contact phase

Once the Z-axis has been realigned with the direction of gravity, we can analyze the vertical component of the total acceleration to detect the time instants that allow us to calculate the various parameters of interest of the steps:

- instant of start of flight phase,
- instant of start of contact phase.

Flight phase

In [197], the comparison between pressure sensors and acceleration values shows that vertical dynamic acceleration becomes zero when foot leaves ground. In case we want to consider global (dynamic and static acceleration), we can determine the beginning of flight phase when vertical acceleration becomes less than g ($9.8065\,m/s^2$), (Figure 5.3).

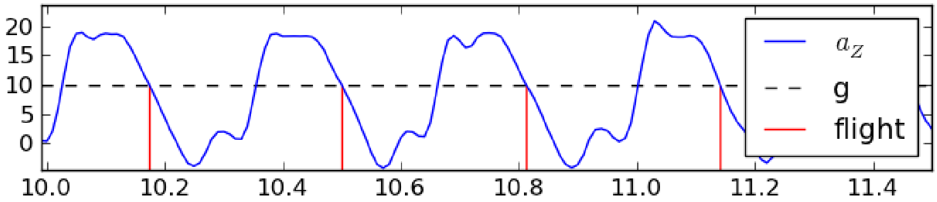

Figure 5.3. Start of flight phase: instant of vertical acceleration crossing g

Contact phase

Following [197, 14, 13, 147, 100, 55] and experiments in [32] we recognize the beginning of contact phase when, during flight phase vertical acceleration exhibits a "high" positive peak. This is corresponding to the last instant in which the derivative of acceleration, known as *jerk*, is below a given threshold and the value of acceleration becomes bigger than g (Figure 5.4).

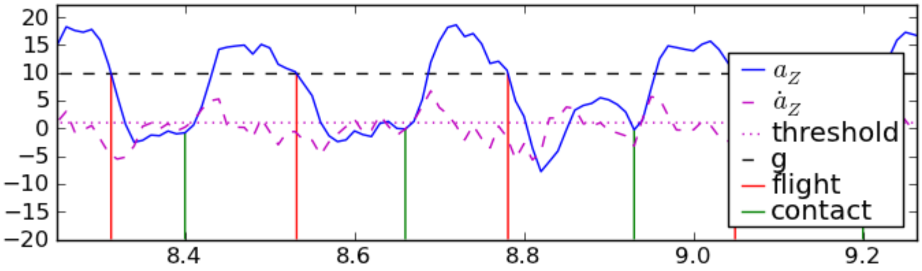

Figure 5.4. Start of contact phase

Presented concepts have been implemented on an Android device [32]. Tests of application are presented in following Subsection 5.1.5.

5.1.5 Tests and results

To validate the algorithms and the developed application we performed field tests:

- the first test was done using jump exercise on *pedana di Bosco* (fixed contact plane), to obtain numeric values to compare with measures of our system,
- other tests performed over short running trails (60 to $200\ \mathrm{m}$, measuring time and steps with a stepwatch.

Results

Pedana di Bosco

For the test on the *pedana di Bosco* results were quite satisfactory, with typical errors in the order of 10 to $20\ \mathrm{ms}$. Considering that acceleration data were sampled at a maximum of $100\ \mathrm{Hz}$, the error reported during tests is comparable to the period of sampling $10\ \mathrm{ms}$.

Running trails

Over the distance of $60\ \mathrm{m}$ steps were counted by the trainer and times taken with a stopwatch. Results were as follows:

- number of steps detected by the application corresponds with the manually counted
- time of flight and contact could not be measured on field, however they comply with values reported in existing literature [25].

Preliminary tests performed on a Zebris FDM-T sensorized running treadmill show that also during running the proposed algorithms are able to accurately (with errors within the order of $20\ \mathrm{ms}$) monitor flight and contact phases. Thus we can conclude that our proposed system can be used for vertical jumps and for running monitoring.

5.1.6 eMGeeAWeb

To enable users to access information gathered through the *eMGeeA* Android application, described in Section 5.1, we developed a specific web application, called *eMGeeAWeb* [34].

To provide geolocalized information about steps we implemented the original eMGeeA Android application with GPS data acquisition. Moreover the web application was enriched by a trainers / athlete mode, to enable trainers to review training sessions of athletes.

eMGeeAWeb implements following functionalities:

- store collected data, uploaded through the mobile application or through standard web upload functionality
- allow different users to download the data
- represent collected data, enriched with GPS location information, on a map
- represent collected data (jump height, flight/stance time, power per step) on interactive graphs based on AJAX [1] paradigm

Web interface

Figure 5.5 shows how the web application represents flight time and contact time of feet, using jQuery graphic capabilities.

Figure 5.6 shows how the web application represents jump height and power per step, using jQuery graphic capabilities.

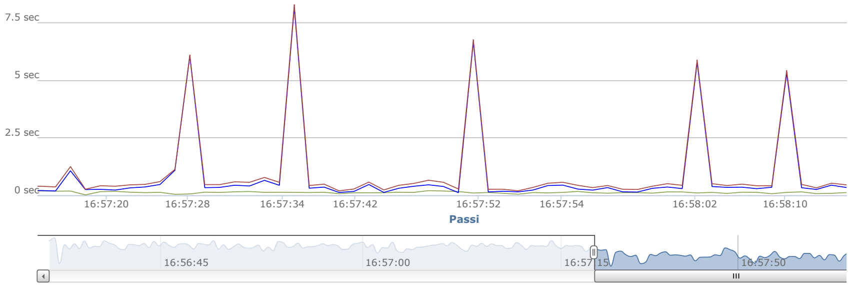

Figure 5.5. Web representation of step flight and stance time using jQuery

Moreover, two other functionalities have been implemented in the web application:

- **data annotation** to enable users to annotate data, store and share annotations. Annotations can be produced by trainers, to communicate information to athletes;
- **data processing** to enable users to process data, through aggregation functions (MIN, MAX, AVERAGE).

eMGeeAWeb is currently under test, with help of final users, in order to find problems, or new possible enhancements or functionalities.

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[1] Asynchronous JavaScript and XML

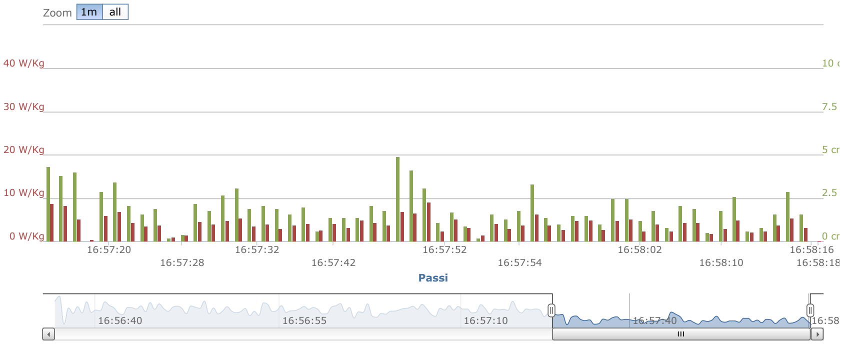


Figure 5.6. Web representation of step height and power using jQuery

5.2 Using gait symmetry to virtually align a triaxial accelerometer during running and walking

During running and walking human center of mass experiences a symmetric acceleration along the mediolateral direction. We show how to exploit this knowledge to correct misalignments of the axes of a trunk-mounted accelerometer with respect to the body axes. After vertical alignment, based on the gravitational component of the signal, our technique computes the virtual rotation angle of the axes lying in the horizontal plane. The chosen angle minimizes the autocorrelation of the signal along the mediolateral direction.

5.2.1 Introduction

The knowledge of the center of mass acceleration components is crucial to study human gait [199]. The body reference system consists of the sagittal axis X (antero-posterior direction), the coronal axis Y (mediolateral direction) and the vertical axis Z (aligned with the gravitational vector g). To sample acceleration components, a triaxial accelerometer is usually placed on the lower back of the subject, i.e. near to the center of mass of body. Errors due to the initial and usage misplacement of the device with respect to the body reference system must be corrected. This can be achieved by a virtual rotation of the device's axis (x-, y- and z-axis), in a similar way to the one presented in [139].

The congruency between the accelerometer's axes and the body reference system can be obtained in two steps: vertical alignment of the z-axis and rotation of the x- and y-axis in the horizontal plane. Numerous methods have been proposed to align the z-axis with the direction of g, based on the gravitational component of the signal. This statical acceleration can be estimated using a running mean [171] or a low-pass filter [199] and then used to apply a rotation to the three acceleration axes. The most effective method is the combination of a Hamming windowed sinc (HWS) low-pass filter with the calculation of the angles between the horizontal plane and the x- and y-axis [136].

Once the z-axis is correctly aligned with g, the x- and y-axis lie in the horizontal plane. A virtual rotation around Z must then be performed in order to align the x- and y-axis with the antero-posterior and mediolateral directions, respectively. To this purpose, the gravitational acceleration is not useful, so we must rely on some specific features of the signal. This Letter presents a novel technique that exploits gait symmetry during running and walking activities. Using the autocorrelation function of the acceleration along the coronal axis, we search for the rotation angle that maximizes the gait symmetry, which is measured by the autocorrelation coefficient at the first dominant period of the signal [137].

5.2.2 Methodology

Accelerometer values were collected during running or walking using the triaxial accelerometer embedded in a smartphone. The device was fastened around the subject's waist by a belt, near to the body center of mass. Data were sampled at the maximum frequency allowed by the sensor and, because of its quite variable sampling rate (80 Hz on average), it was necessary to re-sample the signal at a constant frequency (100 Hz) by linear interpolation.

Every sample is processed in the way shown in Fig. 5.7: first, the z-axis is aligned with g using a HWS low-pass filter (cutoff frequency: 0.9 Hz) and computing the tilt angles (θ_X, θ_Y) of x- and y-axis with respect to the horizontal plane; then, these are rotated around the vertical axis by an angle ψ using the algorithm described in the following Section.

We implemented this processing both on a smartphone, using Android SDK for an on-line analysis, and on a PC using Python scripts to perform off-line analysis.

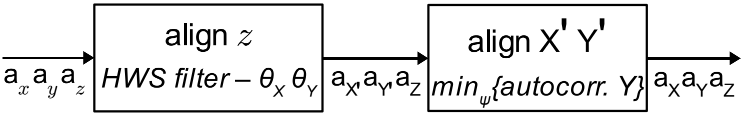


Figure 5.7. Acceleration processing

5.2.3 Algorithm

Once the z-axis is correctly aligned with g, the procedure to align the x-axis with the antero-posterior direction and the y-axis with the mediolateral one is based on the knowledge of two main features of the acceleration signal sampled during running or walking:

- The step duration is given by the first dominant period of the vertical acceleration signal. This can be computed applying the autocorrelation function to the acceleration along Z.
- In a symmetric gait, the mediolateral acceleration is almost specular at each step, as it is generated by the two limbs applying forces in opposite directions. This means that the autocorrelation coefficient of the mediolateral acceleration (i.e.,

along Y), computed at the lag corresponding to the step duration, must approach the value of -1.

Under these assumptions, the alignment of x- and y-axis can be done as follows (Fig. 5.8):

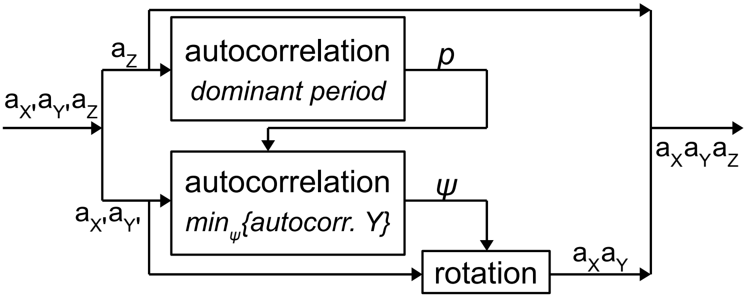


Figure 5.8. Alignment of x and y axes

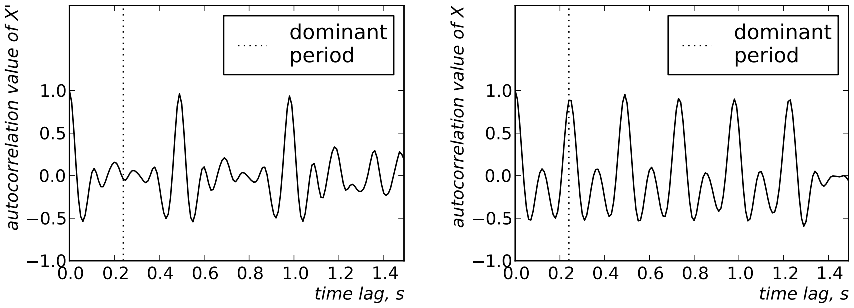
1. the dominant period p of the signal is determined using the autocorrelation of the vertical acceleration a_Z;
2. among all possible rotation angles of X' and Y' axes around Z, the angle ψ minimizing the autocorrelation coefficient of the mediolateral acceleration a_Y at the dominant period is selected;
3. the X' and Y' axes are rotated around Z by ψ, using the rotation matrix:

$$\begin{bmatrix} a_X \\ a_Y \\ a_Z \end{bmatrix} = \begin{bmatrix} \cos\psi & \sin\psi & 0 \\ -\sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} a_{X'} \\ a_{Y'} \\ a_Z \end{bmatrix}$$

5.2.4 Results

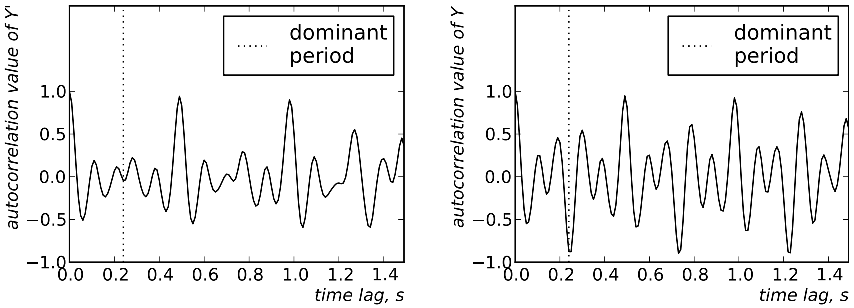
Given the practical difficulties in obtaining a direct measurement of the rotation angle ψ and of the acceleration values along the X and Y axes, we validated our technique by carrying out the following two qualitative tests:

Test 1: Data were collected with the accelerometer arbitrarily oriented, and then an inspection of the shape of the autocorrelation of acceleration components in the horizontal plane before and after the rotation was conducted. The comparison between the functions along X' (i.e., before rotation, Fig. 5.9(a)) and along X (i.e., after rotation, Fig. 5.9(b)) shows that, thanks to the applied processing, the autocorrelation assumes the typical pattern of running/walking (similar to the one



(a) Before (b) After

Figure 5.9. Test 1: Autocorrelation function along x



(a) Before (b) After

Figure 5.10. Test 1: Autocorrelation function along y

described in [137]). Similarly, in Fig. 5.10 we can observe that, after the rotation, the autocorrelation along Y is characterized by negative peaks at odd multiples of the dominant period and positive peaks at even ones (Fig. 5.10(b)), which is the expected shape of the function along the mediolateral direction (as demonstrated in [137]).

Test 2: Data were collected with the accelerometer placed with the x- and y-axis rotated of roughly $90°$ clockwise (i.e., with the x-axis in mediolateral direction and the y-axis in antero-posterior one, as shown in Fig. 5.11). In this case, we expect a counterclockwise rotation angle with values close to $90°$, and an alignment of the original signal (a_x, a_y) resulting in $a_X \approx a_y$ and $a_Y \approx -a_x$. Results of this test (shown in Fig. 5.12 and Fig. 5.13) confirm our expectation.

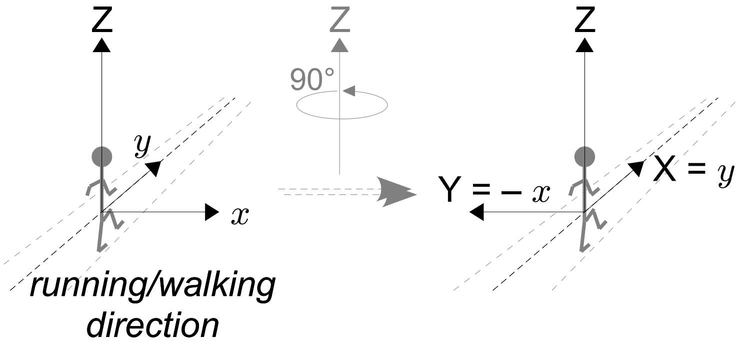


Figure 5.11. Test 2: Procedure

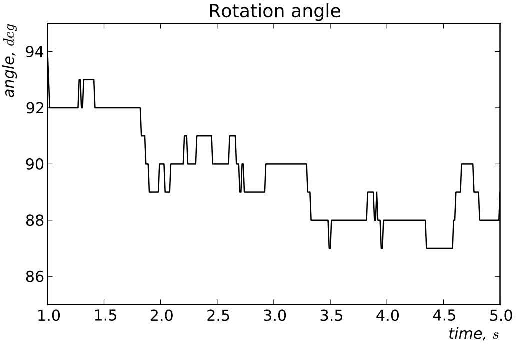


Figure 5.12. Test 2: Rotation angle values

5.2.5 Remarks

We demonstrated that gait symmetry, represented by the autocorrelation of the mediolateral acceleration measured during running or walking, can be used to virtually align a triaxial accelerometer with the body reference system. The proposed technique allows us to implement a self-contained, accurate monitoring system that does not require additional sensing units (e.g., gyroscope, magnetometer, GPS) other than the accelerometer itself. Applications that can benefit from using our technique include noninvasive monitoring of human movements [7] and mobile healthcare [3].

5.3 Conclusion

We presented a system to recognize relevant factors of running and a technique to virtually realign the axes of a trunk mounted accelerometer to become coherent with the direction and sense of motion of a running human. We conclude that using a single

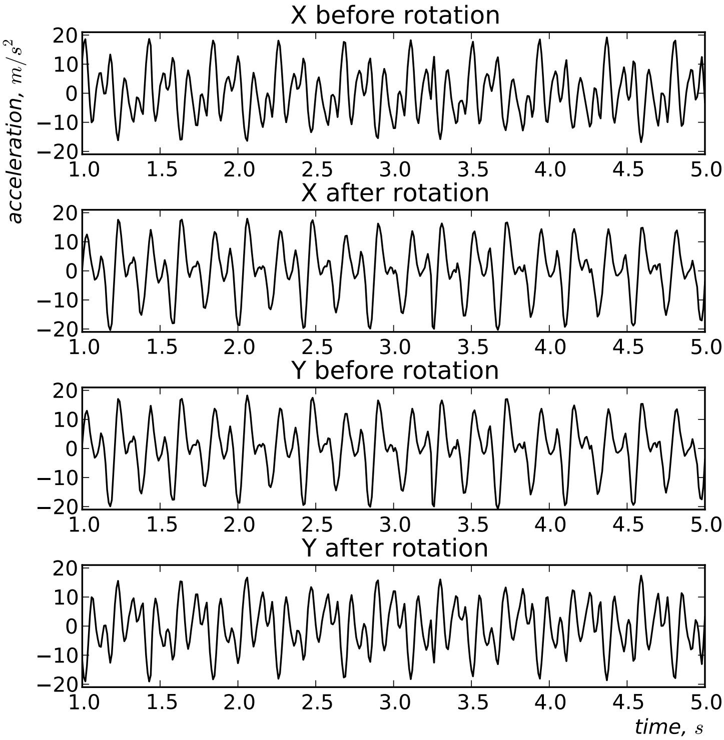


Figure 5.13. Test 2: Signal before and after rotation

trunk mounted accelerometer can provide information regarding quality of running, both in terms of symmetry and of feet flight-contact ratio.

6

Environmental sensing and problems of sensing systems

> If you want to succeed,
> double your failure rate.
>
> Thomas J. Whatson

Glacial environment monitoring is a key task in understanding natural phenomena related to global warming. For the last 30 years, Automatic Weather Stations (AWSs) have been spreading among the meteorological and geophysical community, and are on the way to become a *de facto* standard to perform long-lasting unattended data acquisitions in single localized points of interest. Sensor Networks (SNs), on the other hand, promise the possibility to perform measurements with a higher spatial density and lower cost. Designing and developing a SN for glacial environment face particular challenges for embedded electronics and sensor systems, which is why SNs are still under research and development in this field. This chapter surveys the AWSs and SNs for glacial monitoring applications and compares their characteristics.

6.1 From single point of measurement to distributed sensing in long-term glacier monitoring

Studying the evolution of glaciers became an essential task to follow global climate changes and its local effect [145]. Monitoring the state of glaciers (and in general of glacial environment) is important also for safety reasons. It enables early warning generation in case of an avalanche, or permafrost cracks and falls from mountains. Scientists today benefit from a broad range of technologies to better understand the phenomena in glacial environments. These means can be categorized based on whether they sense physical quantities remotely or locally.

Remote measurements can be carried out using satellites, planes or using ground-based devices, to take images in the visible light range (photogrammetry), or other spectral frequencies like infra-red (thermal imaging). Thermal imaging enables obtaining a temperature distribution image over the whole terrain or snow [121]. Laser or radar ranging allows to reconstruct 3D surfaces of the terrain, and compare two subsequent images to detect changes or movements. Local measurements, on the other hand, are carried out using sensing devices with output that varies based on proximal physical quantities. The sensors (temperature, water level, deformations, movements, etc.) are attached to devices able to store data (dataloggers).

Automatic Weather Stations (AWSs) are specialized measuring units, aimed at the monitoring of weather-related parameters. They are built around bigger dataloggers, that enable multiple sensors readings. In particular, AWSs deployed in glacial regions allow to investigate the micro-meteorological variables and processes related to glacier behavior caused by global climate changes. Establishing remote communication with the AWS is necessary to enable real-time data availability and timely detection of damage or malfunctions.

As the cost of hardware is decreasing, it becomes feasible to develop distributed measurements over glaciers. Deploying a network of spatially distributed sensing systems on different places of the same glacier, or in different glaciers, allows to perform real-time streamflow monitoring or modeling, enriched by dense environment data [4]. Sensor Networks (SNs), composed of multiple distributed wired or wirelessly communicating sensing devices, represent a possible enhancement to AWSs in terms of spatial resolution and costs. Open problems with SNs are related to their relatively complex setup phase and commercial availability.

A thorough study of existing literature showed the lack of a systematic overview of measuring devices used in glacial monitoring, particularly with respect to Automatic Weather Stations. These devices have been a common tool within a highly skilled community interested for measuring climate-related physical events and quantities. In this chapter, we present an overview of AWSs, as they represent a standardized environmental monitoring solution. In addition, we analyse key opportunities and issues related to SNs, that could offer a higher spatial resolution of the AWSs measurements. Section 6.2 presents AWSs in glacial monitoring, from the hardware and software point of view. Section 6.3 discusses possibilities of using SNs to enhance the available solutions based on AWSs. Section 6.4 concludes the chapter.

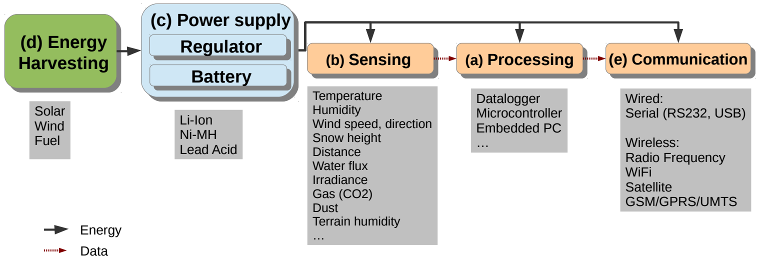


Figure 6.1. Scheme of typical components of an Automatic Weather Station

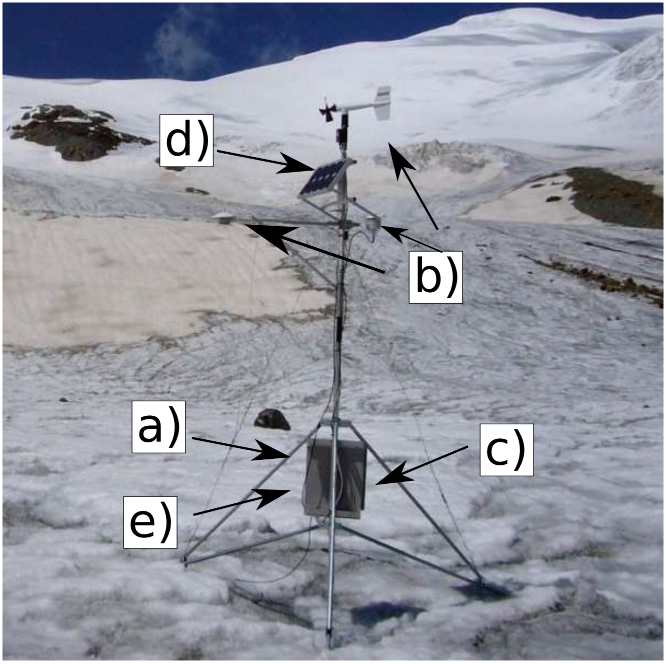
6.2 Automatic Weather Stations for glacier monitoring

A typical AWS is composed of a datalogger, sensors, a power supply, energy harvesting unit (optional), and a communication unit (optional). Fig. 1 shows a schematic view of an AWS, with the energy and data flow. Possible sensors, communication devices, harvesting and battery technologies are presented in the grey boxes in the figure. Energy harvesting unit enables replenishing the battery with energy from the environment (solar, wind, etc.), providing longer autonomy of the AWS. Communication unit enables remote access to the collected data and notifications in case of malfunctions of the AWS. Both enhancing autonomy and real-time data access are useful for geologists, since usually a glacier station can be reached only during short time slots during the year.

Programming the behavior of battery-powered acquisition systems, in terms of sampling and communication rates, impacts on storage, energy and transmission. A higher acquisition rate causes higher energy consumed by the sensors, requires more storage resources and more data transmission. Wireless data communication also causes high energy consumption and, if using GSM or satellite connections, non-negligible financial costs. This motivates researchers to adapt sampling rate and use compression algorithms to obtain energy awareness in the system, enabling better usage of energy and financial budget.

A Glacial Automatic Weather Station (GAWS) can be considered as standardised within the scientific community, that accepted and adopted the basic composition of GAWS introduced in the 1990s by IMAU [27]. A typical GAWS is composed of 5 main subsystems: datalogger, energy harvester (solar panel), communication device (satellite, RF, WiFi), sensors, battery. The sensors of a GAWS are: snow level, wind speed and direction, temperature and humidity, direct and indirect irradiance. In Fig. 6.2 a typical GAWS is presented. Since the datalogger is the main component of an AWS, we will deepen the analysis of its features and compare the most used models.

Figure 6.2. a) Datalogger: MCU, EPROM, ADC b) Sensors: temperature, wind, humidity, snow height, irradiance c) Power supply: battery (Li-Ion, lead acid), charge regulator d) Energy harvesting: photovoltaic panel e) Communication device: satellite



6.2.1 Dataloggers

Table 6.1 reports about commercially available complete systems for the development and deployment of AWSs. The comparison should give a quick overview of systems and producers, to speed up the process of choosing a particular one. From the specifications of reported loggers and producers, it is extremely difficult to understand which producer is using which software architecture or programming language. The only producer that is documenting hardware and software of dataloggers is Campbell Scientific (CS). Their CR1000 datalogger (as well as other dataloggers from the same family) executes an operating system (OS). The OS is not directly accessible, but they allow to code scripts in CRBASIC (a Basic dialect) to manage the acquisition, processing and communication policies. Other producers don't enable programming of their products. The absence of fine grained programmability in the majority of products is an advantage for the primary customers (field scientists). Although most of the dataloggers are nowadays based on programmable microcontrollers, often the producers offer only preconfigured solutions, without the possibility of programming the system independently. So, for researchers interested in experimenting with differ-

Table 6.1. Specifications of most popular dataloggers

Producer	Product	Temperature range	Sleep, Active Power	Enclosure
Gemini	TGP-4020 [83]	-40°C ... +85°C	$0.5\mathrm{mW}$ Average	Waterproof
Campbell Scientific	CR1000 [30]	-25°C ... +50°C	$6\mathrm{mW}, 15\mathrm{mW}$	Simple
Vaisala	QML201 [189]	-50°C ... +60°C	$< 60\mathrm{mW}$ Active	Simple
Delta-T Devices	DL2e [56]	-20°C ... +60°C	Not documented	Simple
Aanderaa	3660s [2]	-40°C ... +60°C	$0.5\mathrm{mW}, 150\mathrm{mW}$	Simple
MSR Electronics	MSR145 [141]	-20°C ... +60°C	Not documented	Waterproof
LSI-Lastem	e-log [124]	-20°C ... +60°C	$2.4\mathrm{mW}, 240\mathrm{mW}$	Simple
IMAU	i-AWS4Polar [188]	Not documented	Not documented	Waterproof
SensorScope	DS3 [99]	Not documented	Not documented	Waterproof

ent sensing, processing and communication policies, the possibilities offered by CS remain the only viable solution.

6.2.2 Software and data management

Programming the datalogger of an AWS often only requires setting some variables in a graphical interface on a PC connected to the datalogger, or to regulate physical handles on the housing of the logger, that set the sensors acquisition rate. Measurements taken on dataloggers are typically stored as simple log files, containing the raw sampled values. In some cases, the data is preprocessed before being logged, performing some kind of aggregation (e.g. averaging, min, max) on it, in order to reduce the amount of stored samples. Stored data are collected manually during field visits to the AWS or, if the system is equipped with some transmission device, like RF or satellite, data can be remotely sent to a computer (telemetry).

The World Glacier Monitoring Service (WGMS) is a unique place to store standardised observations on changes of mass, length, volume, area of glaciers over time [1]. It is a kind of a database, but its consistency and meaning are maintained by people. It would be a great advantage to automate at least some of the steps needed to populate the WGMS, e.g. through systems like Global Sensor Network (GSN), that ease the job of managing sensors data and process them using the notion of virtual sensor. In that way, it becomes possible to have real-time elaboration and storage of sensor data [2].

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[1] World Glacier Monitoring Service - http://www.wgms.ch/about.html

[2] Global Sensor Network - http://www.swiss-experiment.ch/index.php/GSN:Home

Table 6.2. Some AWS deployments (with datalogger producers). Acronyms: Italy (ITA), China (CHI), Netherlands (NED).

Institute	Location	Producer	Hardware	Time
Universities (ITA) [31]	Italian Alps	Campbell Scientific	GAWS+Sat	2004-present
IMAU (NED) [172]	Worldwide [188]	Campbell Scientific	GAWS	1995-present
Universities (ITA) [59]	Italian Alps	LSI-Lastem	GAWS+GSM	2007-present
University (CHI) [189]	Himalaya	Vaisala	AWS	2000-2010

6.2.3 Deployments

Table 6.2 presents a selection of AWS deployments in glacial environments. The first three are maintained until today, while the last one has been implemented using mobile AWS (transferred from place to place every few days), to perform measurements in different places on Himalaya. Automatic Weather Stations represent a stable technology and, as we can see from Table 6.2, they have been used for the last 20 years in different parts of the world and by different organizations. However, recent glaciologist conferences show that there is a growing interest in spatially distributed measurements in such harsh environments [188]. In the following section, we will discuss main challenges in designing and deploying Sensor Networks that need to be reliable, easy to use and robust, just as AWSs are today.

6.3 From Automatic Weather Stations to Sensor Networks

Automatic Weather Stations, built around dataloggers, are a well known and widely used measurement systems for monitoring glacial environments. They are robust and reliable, but as a drawback, they represent a single point of measurement and a single point of failure.

During the last decade, in the scientific community a new requirement emerged: enhancing single points of measurements with spatially distributed measurements. Small rugged dataloggers, like the TinyTag2 [83] or the MSR145 [141], have been used for years by scientists to acquire temperatures and humidities during long periods. They are much cheaper than AWSs. The data from the sensors is stored and collected manually afterwards. Distributed Thermal Sensors (DTS), on the other hand, allow to monitor temperature along fiber-optical lines, with a spatial resolution of about 1 m. Some experiments even use DTS to measure soil moisture [176].

A technology enabling distributed measurements and communicating data to the user in an automated fashion is Sensor Networks [89]. The architecture of a sensor node comprises the same components like an AWS (Fig. 6.2), only in smaller scale.

Table 6.3. Some WSN deployments on glaciers

Project	Locations	Nodes	Number of nodes	Time
SensorScope [99]	Switzerland	TinyNode	~ 15	2007
PermaSense [23]	Switzerland	TinyNode	~ 25	2006-present
GlacsWeb [128]	Norway, Iceland	GWNode	~ 20	2004-present

The sensors are connected to a microcontroller, that controls the acquisition, storage, processing and communication of the acquired data. The microcontrollers are often programmed using standard languages (C/C++), thus it is possible to develop new behavioural paradigms by computer scientists or electronic engineers.

In wired sensor networks, nodes are connected with wires to the base station, like in [138]. An interesting commercial solution is Thermistor Chains RBR [155] — cables with termistors attached, that can be used in water, cement, ice, etc. In a Wireless Sensor Network (WSN), sensor nodes communicate wirelessly, usually containing a radio in GHz or MHz frequency band, using WiFi, ZigBee or similar standardized protocols.

WSNs have become a hot topic in the last 10 years. The biggest challenge in WSNs is to provide enough energy to the node to enable autonomous operation [6]. Another challenge is to obtain reliable wireless communication in harsh environments (with water, ice, etc.), often requiring using lower communication frequencies (MHz or lower). Those are key reasons that WSN applications in glacial environment are still under development.

There are few successful deployments of WSNs in glacial environment. Table 6.3 shows most popular ones. Comparing with Table 6.2, we notice that some WSN deployments lasted almost as long as some AWS deployments. It is necessary to emphasize, though, that WSN deployments were part of multidisciplinary research projects and experienced operation outages (of the whole network or only of particular nodes), requiring often maintenance and modifications during the years. On the other hand, AWSs are based on mature and commercially available technologies and have had a more stable operation, although they were deployed directly by field scientists. PermaSense and GlacsWeb deployments are still active and under development. In [103], we compare those two projects and introduce possibilities of performance enhancements.

WSNs represent an interesting opportunity to enhance measurements of AWSs. Nowadays, programming and electronic skills are still needed to configure, deploy and maintain WSNs successfully. In order to become an established technology, they need to be improved in terms of simplicity of usage and robustness.

Table 6.4. Key characteristics of AWSs and WSNs

AWS	Centralized	Single point of failure	Established	Easy to use
WSN	Distributed	Redundancy	New	Complex

6.4 Conclusion

In this chapter we survey the technologies for sensing in glacial environments, in order to help: a) glaciologists — to choose equipment for their application and deploy it with minimal effort and engineering skills; b) engineers — to understand the field requirements and design standardized solutions that would be easy to maintain, interoperable and scalable, in terms of software and hardware. We describe the characteristics of Automatic Weather Stations, and discuss their benefits and drawbacks. In addition, we discuss the possibilities to use sensor nodes (wireless or wired) to obtain dense spatial resolution of the measurements. The wireless sensor networks present a promising advantage for spatially distributed measurements in remote areas, but, as summarized in Table 6.4, they still need to be improved in terms of robustness and simplicity of usage.

Acknowledgment

The work reported in this chapter has been partially funded by the Italian MIUR Project PRIN 2010-11: “Response of morphoclimatic system dynamics to global changes and related geomorphological hazards”, and by the European Community Seventh Framework Programme under grant No. 285939 (ACROSS). The author would like to thank Luca Carturan for glaciology-related discussions.

7

Conclusion

In this dissertation, we have primarily faced issues related to sport engineering, by exploring some applications of pervasive technologies in that field. Exploration of applicability of pervasive technologies to sports is in our opinion a way to provide a controlled and safe development and test environment to "more serious" applications, like rehabilitation aids or assistive technologies. Moreover we faced the problem of still scarce adoption of Wireless Sensor Networks in the particular field of glaciology, as a case of study to analyse key factors preventing WSNs from becoming more widely used.

7.1 Rowing

The sonification of a rowing boat's motion has proven to be effective in providing information to athletes and trainers about quality of movement of a boat. We describe how to build a smartphone based and a PC based solution for telemetry and sonification of on-water rowing training .

Synchrony of rowers confirmed to be a relevant factor in contributing significantly to overall performance of rowing boat. Two approaches, based on Wireless Accelerometer Sensor Network to sense kinematics of oars, have been proposed and described. The first, based on Pearson's correlation function, proved to be effective to assess in real-time if two parts (body or oars) are moving at same time, in synchrony. The system was tested in collaboration with high level rowing trainers and athletes, and proved to be able to communicate in real-time ($500\ \mathrm{ms}$ maximum delay) the level of synchrony between two athletes. The second proposed approach to monitor and recognize synchrony level of a rowing team is based on the emergent paradigm called stigmergy, inspired by the communication of colonies of ants or termites. With respect to the approach based on correlation this proved to be able to extract information about the whole crew, in an intuitive and qualitatively significant way: the proposed system is called MARS, a multi-agent system for assessing rowers' coordination via motion-based stigmergy. In the system, a sensing unit allows local sensing of the strokes via motes, a tracking unit collects and integrates the sensed data, a processing unit computes crew and athlete asynchrony, and a displaying unit provides visual and aural asynchrony feedback to the coach. The processing unit is based on the emergent approach, in which software agents employ a stigmergic computing scheme to measure the extent of similarity between behavior of the rowers. The MARS system was tested on real-world rowing scenarios, involving four athletes with different experiences on a number of runs. The trainer we worked with is highly skilled and experienced as he is currently training Olympic level athletes, in Italy. The results obtained in terms of asynchrony demonstrate that the proposed scheme can be successfully applied in the field.

In future we will investigate how the calculated level of synchrony, transformed into sound (sonified) and provided as a real-time sonic feedback alters the way athletes perceive actions of other team members, to understand whether it will lead them to change their own actions to actually increase overall synchronism.

7.2 Swimming

We presented swimming, and discussed why we consider that the most relevant parameter in swimming actions is the interaction between hands and displaced water masses. This interaction causes motion of water, represented by flows, and measurable by means of pressure probes. The real-time sonification of pressure changes due to displaced water mass is expected a major step towards the aims a) to enhance interrelated perceptions of effects of actions via sound (instead of prescribing a movement) and b) to discover unknown relevant patterns of the (non-steady flow) data. Real-time sonification of moving water masses is undoubtedly a promising tool for training sessions with elite swimmers at least concerning two aspects: one is related to the cognition-levels of the swimmer who can now use another channel together with the existing own neural network concerning the intimate "feel for water"-competence and the other aspect is a completely new way of communication between coach and (elite) swimmers about a more effective action of hands (Fig 8). If communication about sensing the flow, a somewhat neglected topic until now, surely will lead to improvements is likely but needs to be examined. Compared to "informative paddles" introduced by [49] for real-time auditive feedback of manual hydrodynamic pressure to the swimmer the new setting provides some developments. Here the hand needs not to be equipped with paddles, no "chosen strength limit" needs to be overtaken and the conflict of mixing terms like "hydrodynamic pressure", "static pressure" and "hydrodynamic forces" is solved because the new setting is opt to be sensitive to static pressure (which is not possible with the paddles). In summary, swimmers benefit from this interactive bio-feedback as a "self-control means" learning, coaches will be informed more detailed and experts from flow physics could use the original pressure-time-data for analysis of non-steady flow behaviour.

7.3 Running

A single triaxial accelerometer, fixed to the subject's lower back, can be used to identify the two main instants characterizing the running gait, foot-strike and foot-off. The same approach works also for vertical jumps, so it is useful to assess durations of contact and flight both in the common running or sprinting activities and in the typical force evaluation tests executed in track and field training. The application consists in a device (e.g. a smartphone) embedding the inertial sensor and collecting the data and in a signal processing module. This software analysing the acceleration can be implemented both on an external PC for an offline analysis and directly on the mobile device itself for an online analysis.

Moreover we demonstrated that gait symmetry, represented by the autocorrelation of the mediolateral acceleration measured during running or walking, can be used to virtually align a triaxial accelerometer with the body reference system. The proposed technique allows us to implement a self-contained, accurate monitoring system that does not require additional sensing units (e.g., gyroscope, magnetometer, GPS) other than the accelerometer itself. Applications that can benefit from using our technique include non-invasive monitoring of human movementsand mobile healthcare.

7.4 Sonification

In the field of sonification we proposed a mobile application based on Android devices, designed with a research group in Geneva, Switzerland, called SeeColOrMobile. This application was published on the GooglePlay Mobile Application market and is currently being tested in cooperation with Retina Italia Onlus association.

The use of sonification to convey information in an immediate way is from our point of view one of the greatest opportunities to enhance the level of pervasiveness of systems.

7.5 Wireless Sensor Networks adoption

We described the characteristics of Automatic Weather Stations, and discussed their benefits and drawbacks. In addition, we discussed the possibilities to use sensor nodes (wireless or wired) to obtain dense spatial resolution of the measurements. The wireless sensor networks present a promising advantage for spatially distributed measurements in remote areas, but they still need to be improved in terms of robustness and simplicity of usage.

7.6 Context-aware systems, design and interaction

Designing context-aware systems, pervasive systems, needs interaction, on different levels:

- interaction between researchers and technology, to explore possible uses of technology;
- interaction between researchers and users, to understand what users want;
- interaction between users and systems, to fulfil the envisioned goals;
- interaction between users and users!

We don't want to replace interaction, we don't want to replace real life, we want, as much as possible, as much as reasonable, and as much as society asks for it, to enhance it.

7.7 Conclusion of conclusion

Information technology, in form of embedded and pervasive systems, can provide the means to create new applications, enable new research fields, and solve problems of sports, rehabilitation and disabilities. To be *effective* and *efficient* it is however mandatory not only to study the intended application field of the technologies, but also to enter the field, through a deep interdisciplinary work, aimed at giving *sense to the context*.

7.7.1 Information technology and sport

Information technology in sports, as in other fields, is rarely of value on its own "as is". In fact considering the context, the special needs, understanding the terminology, the communities, getting in touch with field experts and stakeholders (scientists, trainers, athletes, ...), understanding which challenges are open, where theory and practice show that the introduction of sensing and automatic processing, or automation of manually performed tasks and finally of relevant feedback to performers can enable the development of the next "killer app" of pervasive technology.

7.7.2 From context to technology, and from technology to context

In this thesis we show a series of different uses of information pervasive technology in different application *contexts*. The contribution of the work is hence twofold: the first one and most evident is technical, characterized by hardware, software, algorithms, frameworks, sensors based solutions; the latter is composed of the ensemble of heterogeneity of application contexts, and of the consequently arising methodological knowledge, emerging from the analysis of common problems and of the similar approach used to propose innovative (information and pervasive technology) solutions.

The common feature of all the works presented in this thesis is truly the methodological approach: the convergence with non-computer-engineering/science disciplines, the discussion and exchange with experts (users and researchers) from different fields (sport, medicine, rehabilitation, ...), exchange of ideas, the development of prototypes tested on field, experiments and adoption of technology solutions by final users (at least in the form of proof-of-concept).

Context Aware Computing

In the context of this work we clearly stretch the widespread definition of *Context Aware Computing* [169] into something different, putting more emphasis on the importance of understanding the *Context* of operation of the designed (pervasive) systems, rather than on methodologies falling within the original definition of Context Awareness, that is more concentrated on what the computing system should do to adapt to the environment, than on the sense of the system. We think that the systems we design should support evolution, in fact: “[...] our concern is not simply to support particular forms of practice, but to support the evolution of practice - the ’conversation with materials’, out of which emerges new forms of action and meaning.” [64].

8

List of publications

In the Thesis I presented a part of the work carried out during the time I was a PhD student at the University of Pisa, Department of Information Engineering. For completeness I here report all publications, ordered by date:

Year 2012:

- S. Abbate, M. Avvenuti, D. Cesarini, A. Vecchio (*) – Estimation of Energy Consumption for TinyOS 2.x-Based Applications – Procedia Computer Science, Volume 10, Pages 1166-1171 [5]
- M. Avvenuti, A. Casella, D. Cesarini (*) – Using gait symmetry to virtually align a triaxial accelerometer during running and walking – IET Electronic Letters, 2012 [15]

Year 2013:

- S. Abbate, M. Avvenuti, L. Carturan, D. Cesarini (*) – Deploying a Communicating Automatic Weather Station on an Alpine Glacier - Procedia Computer Science, Volume 19, 2013, Pages 1190–1195 [4]
- D. Cesarini, N. Schaffert, C. Manganiello, K. Mattes, M. Avvenuti – A smartphone based sonification and telemetry platform for on-water rowing training - Proc. of the 19th Int. Conference on Auditory Display, Lodz, Poland, July 6-11 2013 [39])
- V. Jelicic, D. Cesarini, V. Bilas - Enhancing performance of wireless sensor networks in glacial environments using wake-up receivers - IOP Sensors & their Applications XVII - Journal of Physics: Conference Series (JPCS) [104]
- D. Cesarini, V. Jelicic, V. Bilas, M. Avvenuti - From single point of measurement to distributed sensing in long-term glacier monitoring - IOP Sensors & their Applications XVII - Journal of Physics: Conference Series (JPCS) [38])

- M. Avvenuti, L. Cassano, D. Cesarini, S. Mandalà (*) - Simulation of Automatic Weather Stations for the Energy Estimation of Sensing and Communication Software Policies – Extremecom 2013 [16]
- M. Avvenuti, D. Cesarini, Mario G.C.A Cimino (*) – MARS, a multi-agent system for assessing rowers' coordination via motion-based stigmergy – Sensors Journal – MDPI [17]
- D. Cesarini, T. Hermann, B. E. Ungerechts – Real-time sonification in swimming – from pressure changes of displaced water to sound – Multisensory Motor Behaviour: the Impact of Sound - Leibniz Universität Hannover & ETH Zurich [185]
- D. Cesarini, T. Hermann, B. E. Ungerechts – Interactive Sonification of displaced water masses – Interactive SONification Workshop – Fraunhofer Institute Erlangen (non peer-reviewed poster).

Year 2014:

- D. Cesarini, L. Cassano, A. Fagioli and M. Avvenuti – Modeling and Simulation of Energy-Aware Adaptive Policies for Automatic Weather Stations - Engineering Simulations for Cyber-Physical Systems Workshop, Date 2014 Conference [36]
- B. E. Ungerechts, D. Cesarini, T. Hermann – Real-time sonification in swimming -from pressure changes of displaced water to sound – The XIIth International Symposium on Biomechanics and Medicine in Swimming (BMS), Canberra, Australia, April 28 – May 2, 2014 [187]
- D. Cesarini, N. Schaffert, C. Manganiello, M. Avvenuti, K. Mattes – AccrowLive: a multiplatform telemetry and sonification solution for rowing – The 2014 conference of the International Sports Engineering Association (ISEA), Sheffield, UK, July 14-17 2014 [40])
- D. Cesarini, T. Hermann, B. E. Ungerechts – A real-time auditory Biofeedback system for Sports Swimming – International Conference on Auditory Display (ICAD2014), Sonification for Sports and Performance Workshop, June 22, 2014, NYU's Steinhardt School of Culture, Education and Human Development, NY, USA - to be published
- D. Cesarini, M. Avvenuti, G. Lelli – Are we synchronized? Measure synchrony in a team sport using a network of wireless accelerometers – International Workshop on Web Intelligence and Smart Sensing IWWISS 2014 – under review [35])

Note: publications marked with (*) have authors in alphabetic order.

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