# INTUITIVE AND INTERACTIVE MOVEMENT SONIFICATION ON A RISC / DSP PLATFORM

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## ABSTRACT

A major requirement for effective and interactive sonification in rehabilitation is the availability of a mobile platform. Portable state of the art motion capturing is achieved with inertial sensors. This paper presents a real-time, low latency sonification demonstrator based on an low power consumption ARM Cortex A8 processor, which is designed for mobile usage. The sonification demonstrator is based on the Texas Instruments C6A816x / AM389x development board. It enables research in continuous real time sonification of human motion to improve the process of motion learning in stroke rehabilitation. Profiling results are used to benchmark the Integra software application against a PC based version in terms of signal processing latency. Furthermore, a new sonification mapping, basing on the beat effect, is introduced. This mapping is especially usable for people suffering from partial deafness. A subjective test series shows the understandability of this mapping for healthy subjects, in comparison to a previously proposed sonification mapping.

## 1. INTRODUCTION

Several studies in the field of sports science claim that motion learning benefits from movement sonification [1]. Sonification is the displaying of non-speech information through audio signals [2]. In the rehabilitation context, benefits from interactive movement sonification have been shown [4]. Also efficacy in stroke rehabilitation is proved [4].

The proposed demonstrator is designed for usage in stroke rehabilitation. This kind of rehabilitation focuses on regaining a maximum level of independence within daily activity. Therefore, many rehabilitation exercises focus on upper extremities movements, as these are required in basic tasks, like eating, drinking and tooth brushing. Inertial sensor system set up is chosen according to [5], with one sensor at upper arm and one sensor attached to forearm. Sonification acoustically displays the wrist position, captured by inertial sensors. This provides information about movement performance.

Using movement sonification in sports or rehabilitation requires fully mobile and portable sonification systems. Depending on the chosen mapping parameters, sample based sound synthesis gets quite computational intensive. Therefore, power demanding processors are required. PC based hardware platforms [6], [7] require a high power budget and are limited to stationary usage.

For this reason an approach for real time sonification of complex movements captured by inertial sensors on a low power consumption processor platform is presented in this paper. The sonification demonstrator consists of a Texas Instruments (TI) C6-Integra processor integrated in the C6a816x/AM389x evaluation module comprising an ARM Cortex A8 processor and a Digital Signal Processor (DSP) [8]. Movements are captured with an Xsens inertial sensor system [9] consisting of MTx sensors and an Xbus Master device. The number of MTx sensors can be scaled flexible to up to ten sensors according to motion capturing demands. Speakers or headphones can be used to listen to the generated stereo audio signal. Hardware demonstrator components and structure are shown in Figure 1. Sensor data acquisition, sonification parameter calculation and audio synthesis are handled on the Cortex A8 CPU. A setup is chosen, where sonification displays the wrist position in relation to the patient's body based on different parameter mappings.

Sample based sonification is achieved using the Sound Synthesis Toolkit (STK) [10]. The STK consists of audio signal processing and synthesis classes in C++. Thus, it allows seamless integration in the C++ based sensor system application programming interface (API) and orientation data processing framework. Different basic STK sound generators are used for sonification. The mappings are benchmarked in terms of computational latency and intuitive understandability of the sonification.

The paper is organized as follows: Section 2 presents related work. Section 3 introduces the evaluation board and the ARM processor. The proposed software architecture is explained in Section 4. Section 5 introduces the new beat effect based mapping. In Section 6, the intuitive usability of sonification mappings is evaluated. Profiling results and a benchmark against a PC based platform are given in section 7. Conclusions are given in Section 9.

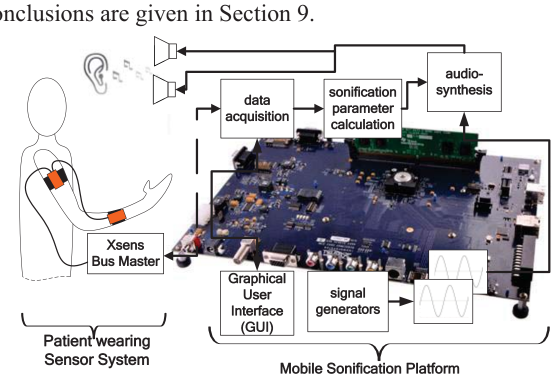


Figure 1: Hardware demonstrator structure

## 2. RELATED WORK

Movement sonification is explored in multiple research projects. Particularly, sonification on mobile devices is a research focus for several years. However, the proposed hardware platforms suffer from drastic limitations in capturing of complex movements and sonification design. Although, there are a variety of applications, like stroke rehabilitation, where mobile sonification of complex movements, provided by this proposed hardware platform is mandatory.

A framework designed for continuous real time movement sonification is presented in [6]. User movements are captured using an optical infrared marker based capturing system. Therefore, absolute position information is additionally provided to relative orientation information. Fully customizable sonification is achieved using Supercollider [11]. This system is not prepared for a mobile usage, because it is based on an optical motion capturing system and a desktop computer based processing.

In [12] a system for sonification of biofeedback signals is presented. Biofeedback sonification should here for example provide information to users' stress level or drowsiness. The system is capable of multiple signal sonifications. Mobile usability is achieved by operating on a Nokia N900 Smartphone with wireless connected sensors. In contrast to the work presented here, the sonification bases on basic alert signals. Additionally, there is not any complex data processing reported.

The work described in [13] generates a sonification based on captured input gestures on a PocketPC. Gestures are captured using an attached external gyroscope. The captured data is processed to identify distinct gestures and give an auditory feedback. Sonification is achieved by linking recognized gestures to very basic audio sources. Compared to the desired application proposed in this paper, this approach is not able to accurately detect and track whole arm movements and giving a complex auditory feedback.

A mobile system for improving running mechanics is developed in [14]. The system comprises a mobile phone and triaxial accelerometers and gyroscopes connected via Bluetooth. During usage, the sensor is attached to the sacrum and accelerometer data is captured. In processing steps, the runner's average center of mass is computed. Providing this information to the runner gives an objective feedback to his running technique. Due to limited computing capabilities of the chosen hardware platform, sonification is based on playback of prerecorded sound files.

Mobile sonification of sculler movements in [15] is realized using a Symbian OS [16] mobile phone. To provide information about boat velocity, a built in GPS receiver and an external acceleration sensor are used. Feedback is given via MIDI sounds. The authors report that the current approach is suffering from noticeable drift caused by accelerometer bias. In contrast to the work presented here, there is no capturing of complex, multi segment movements.

Expressive music performances are used for sonification in [17]. This work also is based on a mobile phone as hardware platform. User movements are captured via the built in accelerometer. A computation step classifies several gestures based on accelerometer data. For usage in rehabilitation context, this approach is limited, as the usage of one accelerometer only provides sparse information, when performing complex movements.

Focusing on non mobile application of sonification in rehabilitation there are numerous research activities [18], [19].

In contrast to the low latency approach proposed in this paper, in none of the platforms listed in related work, latency is considered. Overall hardware and software latency design goal is 30 ms, as higher values result in recognizable differences in visual and audio cognition [19].

## 3. MOBILE HARDWARE PLATFORM

The C6-Integra processor consists of an ARM Cortex A8 processor and a C674x fixed and floating point DSP, both operating at 1 GHz. As both processors and additional modules are integrated on a single die, this is called a 'System-on-Chip' (SoC). The Cortex A8 core is a Reduced Instruction Set Computer (RISC) especially designed for usage in mobile devices [21]. Reduced instruction set allows designing area and power consumption efficient processors, as there is less effort for instruction decoding required.

The Cortex A8 can achieve additional speedup by using the Single Instruction Multiple Data (SIMD) unit NEON [21]. This unit allows the computation of 16 64- and 128Bit-SIMD-instructions in parallel. It is designed for usage in audio and video processing applications to overcome the needs for custom hardware accelerators and therefore keep flexibility for future standards or different workloads. The unit is especially designed for floating point multiplications, shift and multiply accumulate operations.

Figure 2 shows a block diagram of the Integra SoC with additionally available accelerators and memory. Both processor cores communicate using a packet based communication protocol.

The TI C6A816x evaluation module (EVM) allows the connection of external devices using several interfaces, like USB and serial ports, video and audio interfaces and an SD-card slot. Due to the lack of an appropriate driver, the XBus Kit is connected via a Blueserial [19] Bluetooth to serial converter. User-friendly operation is achieved via an external 8" touch screen, connected by a HDMI cable. Linux is chosen as operating system to support audio and video drivers and the Qt [23] based application. The onboard stereo audio converter TVL320AIC3106 [20] allows direct connection to speakers or headphones. Additional available interfaces are Ethernet, SCART, S-Video, VG, IR and JTAG for debugging.

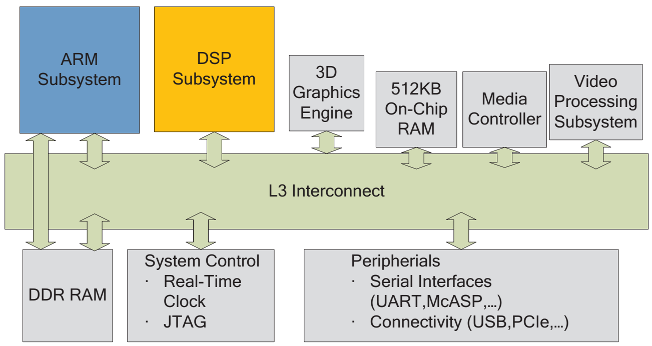


Figure 2: C6A816x System-on-Chip block diagram

# 4. SOFTWARE ARCHITECTURE

The proposed software provides auditory feedback of the wrist position in three-dimensional space. Detecting movements with up to ten inertial sensors and other processing steps enables the sonification of a variety of motion parameters, like segment accelerations, velocities, angles and relative positions. In addition, there is a graphical user interface (GUI), which visualizes movement features and allows control of the sonification process and parameters. For example, different mappings from parameter to sound can be chosen here.

The interactive human movement sonification software is based on the object oriented programming language C++. The GUI is based on the C++ class library Qt [23], which extends C++ to skills for GUI design and inter-object communication.

The application is characterized by a multi-threaded architecture. Thus, basic tasks are logically separated and run in multiple threads, basing on the producer-consumer concept.

In terms of the sonification application, the producer thread communicates with the Xsens hardware. The data of the inertial sensors is requested and then stored in a shared memory. The consumer thread retrieves the data, removes it from the queue and starts processing. The advantage of this design pattern is that the processing of data does not block the whole system, and also allows limited parallelism. The producer can obtain the data, while the consumer is running working tasks. Furthermore, an adaptation of different clock speeds is possible. For example, the intertial sensor data rate is 100 Hz, while audio samples are generated at 44.1 kHz. This allows a higher throughput, which is required for a low latency, real-time implementation of the demonstration software [5].

Figure 3 shows the class structure within the software architecture in a Block diagram.

The XsensData class represents the producer thread and communicates with the sensors on the XsensCMT library. The library handles low-level communication with the sensors. Received sensor data packets are written to a queue and the HandleData class (consumer thread) performs the processing. The wrist position vector is generated from a weighted normalized vector addition of the individual arm segments.

Coordinates system and sensor positions are chosen according to [5]. Cartesian coordinates and radius are normalized to the test subjects arm length.

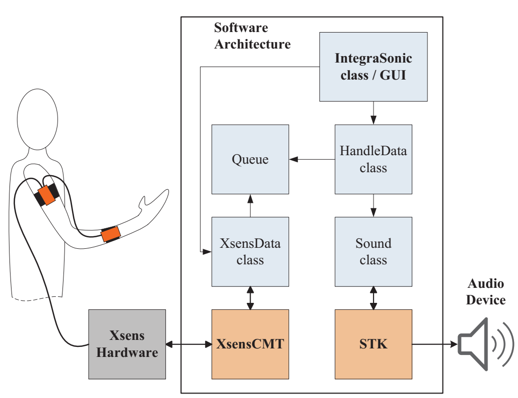


Figure 3: Software architecture

The data is then passed to the class Sound for sonification. The class Sound handles the control and the generation of the audio stream using the Sound Synthesis Toolkit (STK). The initialization of the GUI and the initializing of slots and signals are performed by the class IntegraSonic. Furthermore, this class controls the threads, as it is the main class.

## 4.1. Software optimization steps

Due to the lower operation frequency of the Integra processors Cortex A8 processor core, in contrast to the development PC, software optimization was performed to keep the overall latency constant. Therefore, functions with large processing times and most frequent calls, identified by software profiling, were optimized.

Since the queue was identified to have major impact on the processor load, two approaches were implemented to reduce this burden. First, the class QQueue of the Qt framework has been replaced; second the extension QWaitCondition has been integrated, to stop trying to poll data items when the Queue is empty. The originally used class QQueue was replaced by a simplified queue class, which contains only the most basic functions. These are:

- Adding an element to the queue
- Removing an element from the queue
- Check that objects are present in the queue.
- Number of elements in the queue

The items in the queue are inserted as objects of class QueueElement, which include not only the item itself, but also have a pointer to the next element.

QWaitCondition (an extension of the Qt framework) was integrated into the application to allow a better synchronization of threads, to reduce computational load.

This extension allows threads to signal another thread that a certain condition is met. Thus, an instruction can hold a thread until another thread calls a wake.

Within the application this functionality is carried out by the XsensData class; when data is stored in the queue, it wakes the HandleData thread by calling the function wakeAll(). The HandleData thread can now remove the data from the queue and performs computation. When the thread task is finished, a sleep state is obtained by calling the function wait(). This sleep state again is terminated when waking is performed, or 10ms have passed. (10 ms = sensor system sampling interval)

# 5. PARAMTER MAPPING

Presenting movement information for stroke patients via sonification has to ensure being understandable and intuitive for these persons. Therefore, mappings using stereo effects might be impractical, as [25] shows a large impairment in audio perception of stroke patients. The study reported that significant problems in stroke patients passing the dichotic competing sentence testing (DCST) occurred. Therefore, the stereo effect based mapping presented in [5] does not fit to the requirements. The new proposed beat effect mapping considers these effects, therefore it is limited to frequency and volume based sonification mappings.

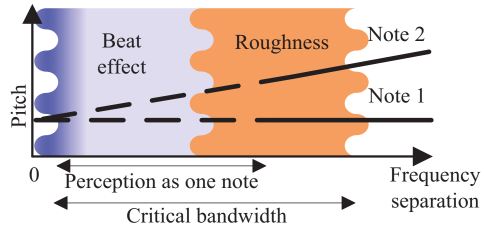


Figure 4: Acoustical beat effect in relation to frequency separation [26]

Different sound frequencies are assigned to relatively broad excitation zones in the ear, so that in case of low frequency differences, the corresponding excitation zones overlap. Thereby, the psychoacoustic beat effect is generated. Figure 4 shows the human perception influenced by frequency separation. Pitch indicates the sine generators base frequencies.

Acoustical beat is realized using two sound synthesis toolkit [10] sine generators, operating at slightly different frequencies according to [26]. As this kind of sonification does not rely on stereo effects for displaying information, it is also applicable in rehabilitation of stroke patients with partial deafness. The general concept is shown in Figure 5.

For frequency differences up to 10 Hz, the tones are perceived as volume fluctuations, corresponding to the mean of the frequencies. Further increases result in a perception of quick succession of beats, which blend at above 15-20 Hz difference to one tone at a constant volume with a rough sound character. This roughness increases up to a frequency deviation of 10% and then falls, until two harsh sounds are perceived. Exceeding the critical bandwidth this roughness disappears. The critical bandwidth is in the range of a major and a minor third.

For both coordinate systems, the origin is located at shoulder joint and wrist position is computed assuming a rigid body [5]. A test series is set up to show if coordinate system choice influences intuitive understandability of the sonification mapping. Finally, conclusions are given by comparing the proposed beat effect sonification against a sonification based on a single sine generator and an artificial instrument in terms of computation effort, intuitive understandability and ambience.

| **Instrument** | Volume | Base frequency |
|---|---|---|
| Cartesian (x, y, z) | amplitude (A) = 0.8-0.5 * y<br>left channel volume = A * (⅔ * x + ⅓)<br>right channel volume = A * (- ⅔ * x + ⅓) | ranging from a (z < -0.92) to as’’ (z > 0.92) in steps of 0.09 on a chromatic scale (a=220 Hz; as’’=830.6 Hz) |
| Spherical (r, φ, θ) | amplitude (A) = 2-1.8 * r<br>left channel volume = A * (φ – ⅓ π)<br>right channel volume = A * (φ – ⅔ π) | ranging from a (θ > 2.42 rad) to as’’ (θ < 0.79 rad) in steps of 4° on a chromatic scale (a=220 Hz; as’’=830.6 Hz) |

Table 1: Instrument sonification parameters

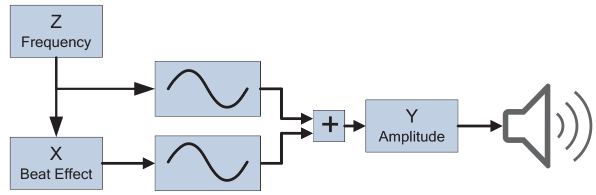


Figure 5: Beat effect realization

| **Beat effect** | Volume | Base frequency | Frequency difference |
|---|---|---|---|
| Cartesian (x, y, z) | volume = 0.3+0.7*abs(y) | frequency= z*3300+550 | diff= (x+1)*10 |
| Spherical (r, φ, θ) | volume = 0.3+0.7*abs(θ/π) | frequency= r*330/π+550 | diff= φ *10/π+10 |

Table 2: Beat effect sonification parameters

## 6. EVALUATION OF THE INTUITVE UNDERSTANDING OF SONIFICATION

A subjective test series with 40 participants was set up to compare sonification mappings according to [5] (Instrument based wrist position sonification based on spherical coordinate system, later referred as A) and the proposed beat effect mapping. Furthermore wrist position information was provided using a Cartesian and a spherical coordinate system. Participants were encouraged to report if they were able to identify movement influence on the generated audio signal and rate the acceptability (pleasant and encouraging sound). Therefore, participants were blindfolded to constrain movement perception to auditory and proprioceptive information.

### 6.1. Subjects

The subjects participating in the study were 36 male subjects and 4 female subjects between 16 and 31 years. Only non experts were questioned. To suppress learning effects, the presented mapping order was randomized. Persons with previous experience in movement sonification were identified. The questionnaire was designed according to ITU-R recommendations for subjective sound quality assessment [27]. In order to achieve a good sound quality, Sennheiser PXC310 headphones were used in a configuration according to Figure 6.

### 6.2. Test Setup

Sonification setups according to Table 3 were presented in a randomized order to the subjects. During 45 seconds, the participants were asked to perform free movements and try to discover to influence of movements within the sonification mapping without any previous knowledge.

| Identifier | Sonification Mapping | Coordinate System |
|---|---|---|
| A | Instrument | Spherical |
| B | Beat effect | Spherical |
| C | Instrument | Cartesian |
| D | Beat effect | Cartesian |

Table 3: Evaluated sonification mapping setups

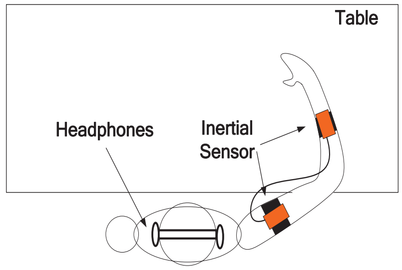


Figure 6: Setup used for evaluation

The questionnaires datasets were submitted to two-way analyses of variances (ANOVA) with the between-factor Group and the within-factor treatment. Post hoc comparisons were made with Fisher's LSD-tests. Independent one-sample t-test was used to identify significant differences of the mean values in the understandability evaluation in comparison to the "No Correlation" statement.

### 6.3. Questionnaires Design

Test subjects were asked to rate the acceptance and understandability of the four different parameters to sound mappings. Acceptability had to be rated on a four point scale ranging from comfortable to annoying. The understandability of the presented movement information was rated on a five point scale ranging from clearly perceptible to no correlation.

After performing each of the four test trials, the test subjects answered the questions according to acceptance and understandability. Finally, the test subjects were asked to chose their favorite mapping according to understandability.

Table 4 and Table 5 give the interpretation of results shown in further figures and the questionnaires ratings.

| **Rate** | **Coding** |
|---|---|
| Comfortable | 1 |
| | 2 |
| | 3 |
| Annoying | 4 |

Table 4: Acceptability (comfort) evaluation mapping

| **Rate** | **Coding** |
|---|---|
| Clearly Perceptible | 1 |
| Perceptible | 2 |
| Moderate Perceptible | 3 |
| Hardly Perceptible | 4 |
| No Correlation | 5 |

Table 5: Understandability evaluation mapping

### 6.4. Subjective Test Series Analysis

Results of the survey after questioning 40 subjects are given in Table 6. Evaluation shows that Sonification C (Instrument; Cartesian coordinates) was rated as the most pleasant mapping. Regarding understandability, test subjects rated Sonification A (Instrument; Spherical coordinates) best.

In coincidence with the observations in Figure 7, ANOVA of the acceptability evaluation showed a significant effect of the different sonification mapping A-D ($F_{(3,117)}$=8.92, $p$ < 0.001 $\eta^2$=0.314). Post hoc analysis of the acceptability evaluation confirmed, that mapping A significantly differs from B ($p$ < 0.05), and B significantly differs from all others ($p$ < 0.05), and C significantly differs from B and D ($p$ < 0.05), and D significantly differs from B and C ($p$ < 0.05).

In accordance with the observations in Figure 8, ANOVA of the understandability yielded a significant effect of the sonification mapping ($F_{(3,117)}$=13.30, $p$ < 0.001, $\eta^2$=0.462). Post hoc analysis of the understandability evaluation confirmed that sonification mapping A significantly differs from B and C ($p$ < 0.05), and B is significantly different from all others ($p$ < 0.05) and C significantly differs from A and B ($p$ < 0.05), and also D significantly differs from B ($p$ < 0.05).

Students t-test confirmed, that all sonification mappings differ significantly from 5 ("No Correlation"), (A: $t_{(39)}$=-24.60,.B: $t_{(39)}$=-15,77, C: $t_{(39)}$=-23.80, D: $t_{(39)}$=-22.80, with $p$ < 0.001).

| **Identifier** | Acceptability | | Understandability | |
|---|---|---|---|---|
| | mean | sd | mean | sd |
| Sonification A | 2.00 | 0.78 | 1.63 | 0.87 |
| Sonification B | 2.63 | 1.00 | 2.63 | 0.95 |
| Sonification C | 1.88 | 0.82 | 1.83 | 0.84 |
| Sonification D | 2.25 | 0.93 | 1.95 | 0.85 |

Table 6: Survey results

Figure 7 shows results of the acceptability evaluation with the corresponding error bars of the sonification according to Table 3. The results show that most test subjects favor the instrument and stereo effect based mappings A and C. Only one test subject could not find any correlation while performing the free trial using these mappings. All others found the mappings to be at least moderate perceptible.

Analysis of the understandability evaluation of the sonification according to Table 3 in Figure 8 shows, that also here the artificial bowed instrument based sonification was rated best. The beat effect based sonification shows remarkably results when using a Cartesian coordinate system. In contrast to beat effect based sonification, in instrument based sonification there is only a small difference in understandability, dependent on the coordinate system. The beat effect showed significantly better results when using a Cartesian coordinate system for wrist position calculation.

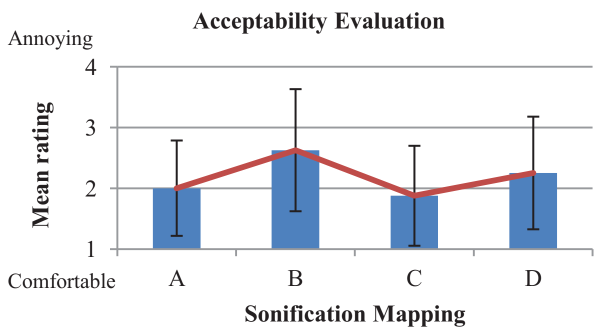


Figure 7: Acceptability evaluation

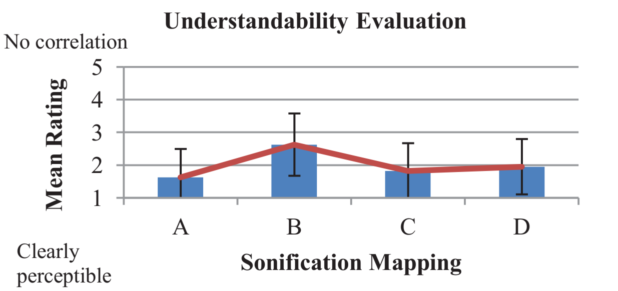


Figure 8: Rating of the individual sonification mappings

After finishing all four free trials the test subjects were asked to vote for their most favorite sonification. Figure 9 shows the rates of this survey. It becomes clear, that instrument sonification is preferred by unimpaired subjects.

## 7. SOFTWARE BENCHMARK

According to [5] the system latency is divided into three blocks. The first fraction is the data acquisition time of the sensors and the transmission time from the sensor system to the host platform, here there is less possibility for latency minimizations as it is limited by the Xsens sensor system itself. Latency induced by computations on the hardware platform, as PC or TI Integra, is represented by the second part. Finally, the last part consists of delay caused by the minimum required audio buffer size, either by using Microsoft DirectSound or Linux ALSA.

For profiling under Linux gprof was used. This profiler only allows sampling based profiling, which means that the processors call stack is evaluated at distinct sampling intervals. To provide accurate information using this statistical profiling method, a log-file of 28,882 samples was used.

The benchmarked development PC, used for reference value generation, is equipped with an Intel Core2Duo E8400 CPU @ 3 GHz and 3 GB RAM. Software profiling is carried out using the instrumentation profiling method, of the Visual Studio 2010 Ultimate Profiling Tool. This method provides detailed runtime data of every function including external function calls. Elapsed inclusive time values presented here show the time spent in the individual function and sub functions including time spend in calls to the operation.

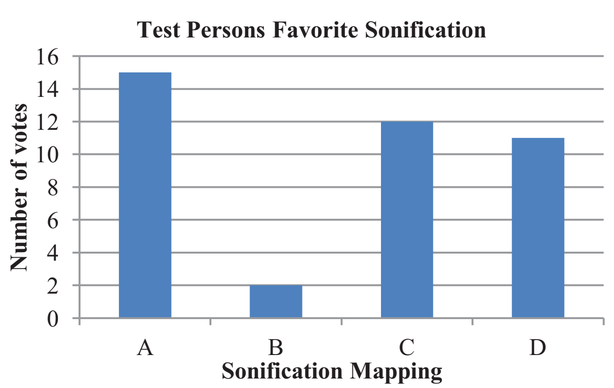


Figure 9: Test person's favorite sonification mapping

$$transmission\ time = \frac{message\ bytes * 9\ (\frac{bit}{byte})}{communication\ baudrate\ (\frac{bit}{s})} \quad (1)$$

In contrast to [5] the communication baud rate was increased to 460800 baud/s, in order to speed up the data transmission between Xsens bus master and computational hardware. The transmission time is calculated according to (1), according to the Xsens XM-B user manual. In sum the data generated per sampling instance consists of 81 bytes, comprising of 36 bytes per MTx sensor and a 7 byte preamble and 2 bytes for sample count. Compared to using a baud rate of 115200 baud/s this is a reduction of about 51 % by increasing baud rate. Xsens sensor system and Blueserial [22] Bluetooth adapters support this increased baud rate. Data acquisition and orientation computation lasts 2.55 ms in worst case. Therefore, sensor data transmission induced latency takes 4.44 ms.

The software caused latency is divided in the functional blocks for data processing according to [5]. Values listed in the Table 7 indicate the time per task to compute an update of the sonification parameters, comprising of enqueueing of sensor data items and calculation of the wrist position and sonification parameters. The usage of the ARM SIMD unit NEON, achieves a considerable latency reduction on the Integra processor for the floating point operation intensive computation of STK instrument generator audio samples, compared to the PC. The NEON unit achieves a speedup by computing up to 16 floating point operations in parallel. The NEON usage is activated by compiler flags. Data independent floating point multiplications are then computed in parallel.

A minimum audio buffer size of 150 audio samples is required, when operating using STK classes and the ALSA audio library. This results in a reduced latency, compared to the PC based approach where the Windows DirectSound library requires an audio buffer of at least 441 samples. In both cases audio buffer sizes below the mentioned limits result in an audio signal interrupted by clicking noise. Using an operation system like either Linux or Windows there is no way to directly access the audio device without using an audio buffer.

| Software sub-block | Latency PC [ms] | Latency Integra [ms] |
|---|---|---|
| Fetch Data | $0.67*10^{-3}$ | $27,90*10^{-3}$ |
| Enqueue Data | $0.76*10^{-3}$ | $0.70*10^{-3}$ |
| Dequeue Data | $0.77*10^{-3}$ | $0.70*10^{-3}$ |
| Position Computation | $1.46*10^{-3}$ | $4.20*10^{-3}$ |
| Display movement features | $51.50*10^{-3}$ | $49.50*10^{-3}$ |
| Compute Sonification Parameters (sine) | $111.60*10^{-3}$ | $68.53*10^{-3}$ |
| Compute Sonification Parameters (beat) | $141.57*10^{-3}$ | $100.09*10^{-3}$ |
| Compute Sonification Parameters (instrument) | 1.23 | $150.14*10^{-3}$ |

Table 7: Detailed computational latency

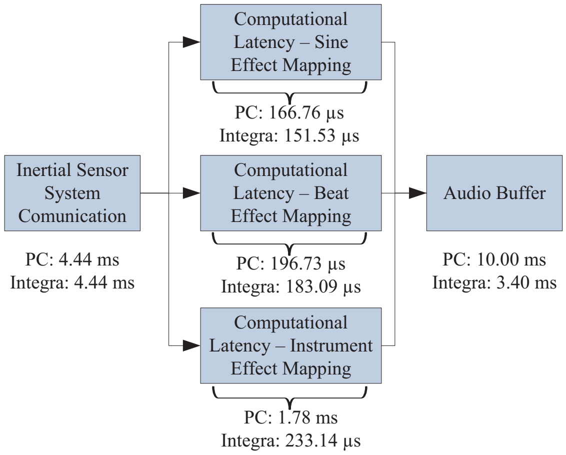


Figure 10: Hardware and software latency overview

The influence of data transmission, audio buffer size and computation, dependant on the hardware platform, is evaluated in Figure 10. In summary the overall system latency for the Integra processor sonification is about 8.07 ms, in contrast to a latency of 14.61 ms to 16.22 ms when operating on a PC. Major latency reduction is achieved by audio buffer minimization.

Figure 11 gives a comparison of computational costs of the required software tasks performed on PC and Integra platform. According to profiling the application allows a throughput of 4.28 kHz on the single core Cortex A8, as computation tasks last 233.14 µs at maximum. However, the maximum sampling frequency of the attached MTx sensor system will limit the application to an operating frequency of 100 Hz, when using two MTx sensors. Audio data rate was set to 44.1 kHz.

## 8. CONCLUSION

Implementing a mobile sonification system, the design goal is to achieve a sonification with an overall latency of 30 ms at maximum. The evaluation performed here clarifies that continuous, real time, low latency sonification of human arm movements can be achieved on low power, mobile platforms like the ARM Cortex A8 processor.

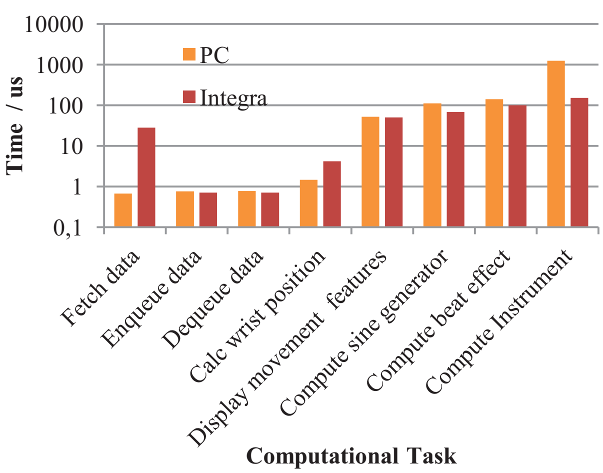


Figure 11: Computational latency distribution in comparison

Due to software optimization the overall computational latency keeps almost constant while performing with a significantly reduced clock frequency of 1 GHz compared to the 3 GHz PC.

Additionally, it is shown that depending on the operating system the audio buffer size can be significantly decreased. As the audio buffer size mainly influences the overall system latency this optimization step would also allow computing on processors with even lower clock rates and thus lower power consumption. Still the audio buffer causes one of the main latency parts. The second main inherent part is the MTx sensor data acquisition and data transmission time. In sum ≈98 % latency are caused by these two aspects.

In general, the overall latency of 7.99 ms of the proposed continuous sonification demonstrator meets the requirements and contains margin for operating it on platforms with further reduced clock rates and thus less power consumption.

The profiling results presented here also clarify, that more complex audio signal generation including mixing different fundamental or instrumental sound generation blocks would not significantly increase total latency. This enables further research in designing more comfortable and medical effective parameter mappings for audio synthesis.

The subjective test series performed here showed that all four evaluated parameter to sound mappings were significantly understandable. This is a convincing result, as none of the test persons had experience in designing or using movement sonification. All of the proposed mappings turned out to be intuitively usable, as the test persons had to rate the mappings after only 45 seconds of experience.

In overall rating, after performing free trials with all four sonification mappings, test persons rated the instrument based sonification to be best understandable. These mappings base on stereo effect in contrast to the beat effect in the competing two mappings. This shows that for unimpaired persons it is easy to correlate wrist position and sound source displacement.

In summary, the proposed Integra processor based system enables real-time low latency sonification. Additionally, it provides the required flexibility for adoptions in movement feature calculations and sound synthesis and enables further research in sonification design for upper arm movements. The hardware demonstrator will be used in studies to determine benefit from a continuous synthetic sonification in reach and grasp motor learning tasks. Studies will be used to figure out further significant motion parameters for relearning of movements and the design of an effective parameter to sound mappings, as well as an ambient and motivating sound design. The demonstrator is a research platform for designing a more effective and pleasant sonification for usage in home based stroke rehabilitation.

## 9. ADDITIONAL FILES

The attached "beat_sonification.wav" file represents an arm moving from the right to the front, then grasping a cup, moving it to the left and back to front. After that, the cup is raised for drinking and put back on to the table on the right. The file is available for download at http://www.ims.uni-hannover.de/fileadmin/www/files/forschung/sonification/beat_effect.wav

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