Audio Engineering Society
Convention
Paper 6026
Presented at the 116th Convention
2004 May 8–11 Berlin, Germany

Application Scenarios of Wearable and Mobile Augmented Reality Audio

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ABSTRACT
Several applications for wearable and mobile reality audio are presented. All applications exploit a headset where microphones are integrated into small headphone elements. The proposed system allows us to implement applications where virtual sound events are superimposed to the user's auditory environment to produce an augmented audio display. In addition, binaural audio-over-IP connections, wired or wireless, are discussed. Finally, some future application scenarios are sketched.

1. INTRODUCTION

The concept of wearable augmented reality audio (WARA) consists of techniques with which real sound environment is extended with virtual or recorded sound events [1]. The concept of mobile augmented reality audio (MARA) is a case of WARA where special attention is paid to the mobility of persons using WARA technology. We use the first concept in this paper. The WARA applications utilize specific microphone-earphone transducers and a real-time audio software system. Virtual sounds may be any signals, e.g., speech from remote talkers, recorded or synthesized announcements, advertisements, instructions, warnings, or music.

For sound capturing and playback a user is wearing microphone-earphone transducers, one of which is depicted in Fig. 1. Such transducers enable creation of augmented auditory environment, in which virtual or recorded auditory events can be superimposed into the user's current auditory environment which is also called pseudoacoustic environment [1].

This article discusses applications the WARA headset enables. We describe several application scenarios and we report implemented prototypes of applications. In addition, a few ideas for the future applications are presented.

The paper is organized as follows. First, the classification of WARA applications is discussed. In Section 2, applications which apply augmented sound events are presented. The WARA headset enables also binaural telephony which is discussed in Section 3. For wearable technology the user interface design issues are discussed in Section 4. Finally, we sketch a few applications that could benefit of the WARA technology.

1.1. Classification of applications

Applications related to WARA technology can be categorized in many ways. Some applications are clearly examples of communications while others can be seen as information services. Applications can also be seen as human-to-human and others as human-to-machine communications. Important division is also the way virtual audio events are connected to the real environment. In some applications created virtual events are *localized* and in others they are *freely floating*.

The idea of *localized acoustic events* is to enhance user's normal auditory scene with additional audio information. The purpose is to connect audio information to real world

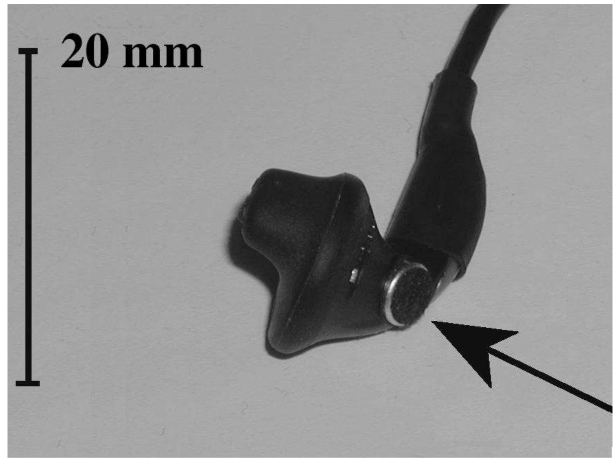

Fig. 1: *A two-way transducer with an open-type earphone (Sony MDR-ED268LP). Position of the electret microphone element is indicated by the arrow.*

objects or places. One application of this category, the Auditory Sticker application, is presented in Section 2.2.

Freely floating acoustic events are not connected to objects or to a certain location in space in the subject's physical environment. The only anchor point relative to which the event is localized is the user's head. Potential applications are information services, such as news, calendar effects, announcements, or many different forms of entertainment such as listening to music. One example of a freely-floating spatial audio event is the calendar application, proposed by Walker et al. [2].

It is obvious that several applications of the WARA technology are based on the knowledge of the location or/and orientation of the user. The tracking of a user's location and orientation takes place at least on two levels. On one hand some applications need information about the global position of the user. Such positioning can be obtained outdoors, e.g., using the Global Positioning System (GPS), but inside buildings no widely available techniques exist. On the other hand, most applications need local positioning in the means of head-tracking, since for successful augmentation of the acoustic environment, estimates on the short-range relative location and orientation of the user's head are needed.

Most WARA applications would need an accurate headtracker for comfortable and convenient use. The headtracker should operate on much larger area than current tracker technology allows. Naturally, tracking equipment should be wireless for easy use. These demands forced us to study head-tracking based on binaural signals. However, this topic is out of the scope of this article, but it is covered in other articles [3, 4, 5].

1.2. Software and hardware for testing application ideas

The testing and prototyping of WARA application ideas is quite tricky since wireless wearable technology with two channel audio I/O is currently not available. However, we have built a testing environment around a normal PC workstation with which some applications can be demonstrated. The PC is equiped with a high quality sound card, a head-tracking device (Polhemus Fastrack), a WARA headset with custom preamplifier, and the WARA software system. The software is built on the Mustajuuri framework which is a plugin-based real-time audio signal processing tool [6]. It is designed for low-latency performance and suits well for our purposes. Due to the plugin structure, different configurations required by applications can be constructed in a very quick and flexible way.

2. AUGMENTED SOUND EVENTS

In this section we discuss applications that can be labeled as augmented sound events. First, we describe a method to render sounds and then we present three applications that have been tested with the WARA prototype system.

2.1. Rendering augmented sound events

The augmentation of user's auditory environment can be performed in two different ways. Either the augmented sound source should stick out from the natural auditory environment or the additional sound source should be embedded in the auditory scene. The first case is usually easier to realize. Sound sources can be rendered with suitable head-related transfer function (HRTF) filters to the desired position related to the user's head. The second case in which additional sound sources are embedded in user's auditory environment, e.g., attached to physical objects is much harder to implement. By applying HRTF filters, the sound sources are often localized inside the head or to the close proximity of the head. For better externalization a simple but useful method is to add some reverberation to the rendered binaural signals [7]. Eventhough the augmented sound source is better externalized with reverb, it is seldom totally embedded in the room in which the user is located.

To obtain natural sounding augmented sound sources in indoor environments, we have applied the widely utilized direct sound plus early reflections plus statistical late reverberation concept (see, e.g., [8]). For a sound source, to be embedded in the user's environment, the direct sound and 14 early reflections are computed with a simple shoe-box room model. The size of the room can be adjusted with user-adjustable wall, floor, and ceiling locations. The 14 reflections consist of six first-order and eight second-order early reflections, consisting only of lateral plane second order reflections. Such a simple room model is computationally efficient and gives nice spatial distribution of early reflections. Each of these reflections is panned to correct direction using FIR filters, the responses of which have been matched to the minimum-phase HRTF functions. The applied filter orders for each of the three virtual sound source groups (direct sound, 1st and 2nd order reflections) can be adjusted individually and the computational burden can thus be reduced [9]. Informal listening tests suggest that early reflections can be rendered with a smaller number of filter taps than the direct sound without degrading the spatial impression.

In addition to the HRTF filtering, each early reflection is low-pass filtered, to simulate material absorption. Such filtering smoothes out the comb-filter-like coloration caused by successive summing of an identical sound source - the fact that $1/r$-law attenuation is implemented and the echoes come from different directions means that the summed sounds are not exactly identical, but close enough for coloration to take place.

The early reflections, although they are computed from a simplified geometry, help in externalization of the virtual sound sources [7], but the rendered sound is still somewhat unnatural. For even better results, some diffuse late reverberation is added to match the length of the reverberation to the reverberation of the room where a user is located. The applied reverberation algorithm [10] is a variant of the feedback delay network (FDN) algorithm. The parameters for the artificial reverberation (reverberation time etc.) are chosen manually. A more sophisticated approach would be to estimate parameters automatically from the binaural microphone signals, but such automatic algorithm has not yet been implemented.

The rendering of augmented sound sources with or without a room model depends on the application. Obviously, in indoor environments a room model is often applied, but outdoors the modeling of room is unnecessary.

2.2. Auditory Sticker application

The Auditory Sticker is an example of location-based applications. By utilizing Auditory Sticker, the user can leave messages to a specific place in a space or messages can be attached to objects. For example, consider the following situation: The user of the Auditory Sticker application is walking on a street and trying to find his way from place X to place Y. The user comes to a street corner and after checking a map he knows that he should turn to the right from this street corner. The user knows also that his girlfriend is coming later to this same street corner and tries to find her way to the place Y. With the Auditory Sticker application he can now leave a message to her to this specific street corner. When the girlfriend, using a WARA headset, will come to this place, she will hear the message and find her way to the place Y with ease.

In brief, Auditory Sticker is a communication application with which users can leave auditory stickers for each others. It is easy to imagine ways to use it in workplaces, instead of small yellow Post-it stickers.

2.2.1. Implemented Auditory Sticker application in the WARA prototype system

The tracking of the user is a fundamental function in the Auditory Sticker application. In the WARA prototype system, the localization of the user's head is performed with a Polhemus head-tracker device. The operation range of Polhemus is limited being only about 1.5 meters, thus the Auditory Sticker application cannot be used with the current WARA system in a realistic way. However, demonstration of the idea works properly.

In the current Auditory Sticker implementation, recording, playing, and removing messages is possible while the system is running. Recording and playing can be controlled by a cordless mouse with a GUI, depicted in Fig. 2. Naturally, the head-tracker device provides the location of the recorded message to the application. However, the location of the messages (reference point) can also be adjusted manually. The size of the message area or more accurately the radius of the spherical message area can be defined. The reference point is the center of this sphere. Inside the message area the sound of the message is panned to the reference point. Furthermore, the user can select between two playing modes: *Play messages once* and *Play messages repeatedly*.

With the current WARA system the Auditory Sticker application has been demonstrated successfully, but the use of it is quite cumbersome. In order to make the Auditory Sticker application practical, the tracking device should be replaced with a better positioning system, which covers the whole area where the application is meant to be used. It should also be possible to use the Auditory Sticker application with a portable device. Finally, for more convenient use, the sticker application should have a speech user interface or some other user interaction method, discussed in Section 4.

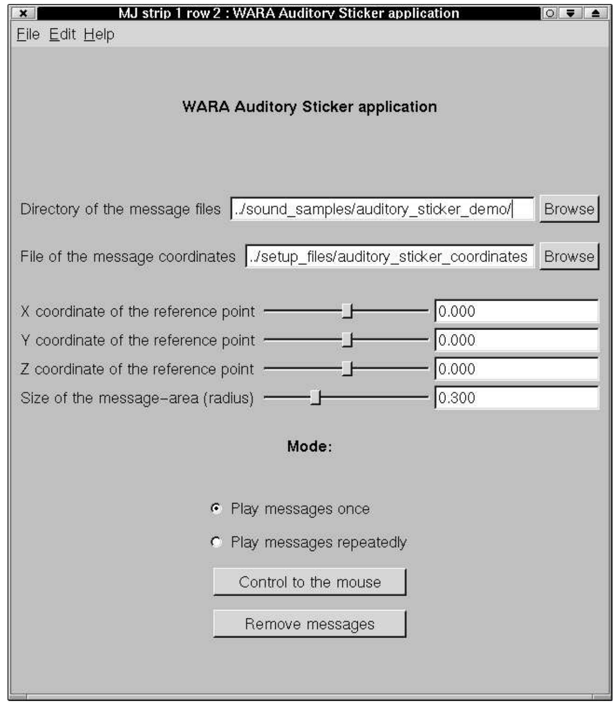

Fig. 2: *Graphical user interface of the Auditory Sticker application.*

2.3. Calendar application

The original idea of the Auditory Calendar application has been presented by Walker et al. [2], and it is an example of application that utilizes freely floating acoustic events. With the Auditory Calendar a user can record calendar entries and place them into directions corresponding to the time of the day. When listening to the daily agenda user hears the calendar entries as coming from different direction at each time stamp.

2.3.1. Implemented Calendar application in the WARA prototype system

In our version of the Auditory Calendar, a user can play, record, and remove single calendar entries while the system is running. The possible times of day for the calendar

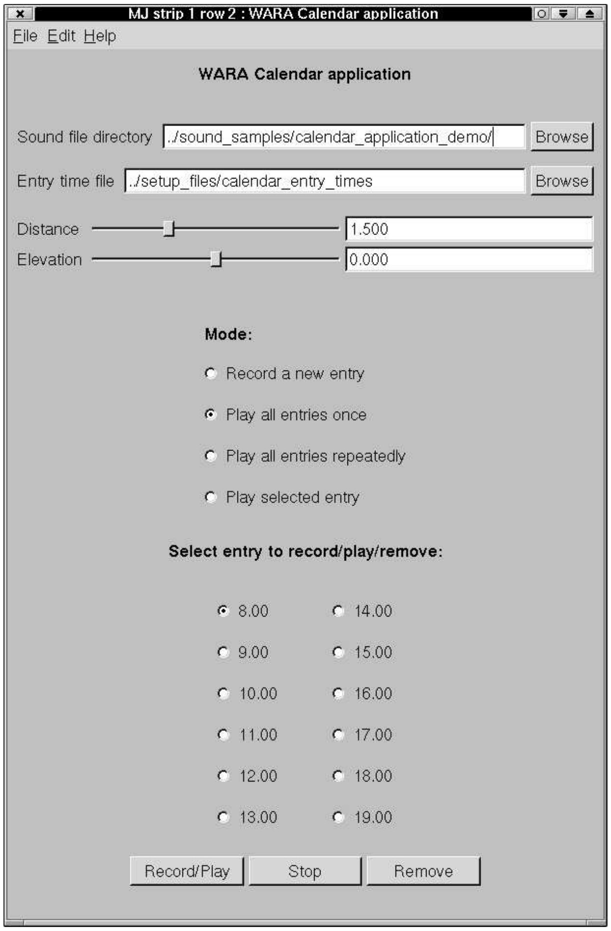

Fig. 3: *The graphical user interface of the Calendar application.*

entries are from 8 A.M. to 7 P.M., from -120° to +210° azimuth, respectively. In total, this makes 12 single entries and the gap between the entries is one hour, which corresponds to 30° azimuth angle.

Both head-tracked and non-head-tracked use is supported. In head-tracked version the calendar events are staying stable at their original places while user turns her/his head.

Some parameters of the WARA Auditory Calendar application can be adjusted with a GUI (Fig. 3). First of all, the directories for calendar entry messages and calendar entry times are defined. For comfortable use of the calendar the user can alter the elevation and distance of the entries. For recording and listening to calendar entries the application has four different running modes: *Record new entry*, *Play all entries once*, *Play all entries repeatedly* and *Play selected entry*.

2.4. Acu-Notch

The Acu-Notch is an experimental plugin that attempts to create an "acoustic hole" (or notch, hence the name) into amplitude-panned stereo signal. This is done by a method similar to the one proposed by Avendano and Jot [11]. The basis of the system is an STFT analysis/synthesis scheme. The short-time spectra of WARA microphone signals are modified by giving less weight to the parts of the signal that are amplitude-panned to a certain direction. An adjustable Gaussian unmixing window is used to calculate the weights. The width of the window determines the size of the area around the desired point on the interaural axis that is to be attenuated in the stereo mix.

The idea is to use this kind of processing in conjunction with a binaural scene analysis system that detects important sound events in the environment and possibly emphasizes them. In a situation where the user is listening to stereo music with the headset, Acu-Notch would be used to attenuate the part of the mix corresponding to the azimuth angle that the detected sound event is localized at. The volume of the real auditory environment of user would be simultaneously increased. A simpler approach would be to automatically turn down the volume of the music when an important sound event is detected.

2.4.1. Acu-Notch in the WARA prototype system

The Acu-Notch was not found to perform perfectly. The window width parameter is a critical factor affecting the performance of the system. A window too wide will cause more artifacts to appear (the wider the window the more severe modifications to the spectra will be made). A suitable window width also depends on the particular music signal and preferences of the user.

Our version of Acu-Notch is based on the assumption that the input signal is purely amplitude-panned. However, many recordings have delay-panned and diffuse components, resulting in non-optimal performance of the Acu-Notch application.

3. BINAURAL AUDIO OVER IP

The WARA technology enables the transfer of a 3D auditory environment to a remote location. Such auditory telepresence makes several interesting applications possible. In this section two prototypes, the binaural tele-

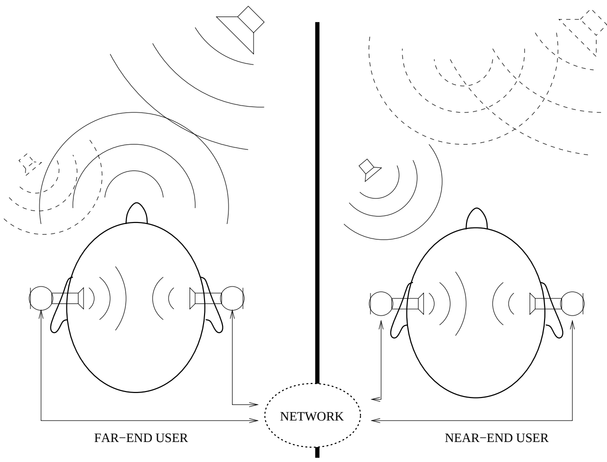

Fig. 4: *Binaural telephone. The far-end user's voice should be rendered outside the near-end user's head.*

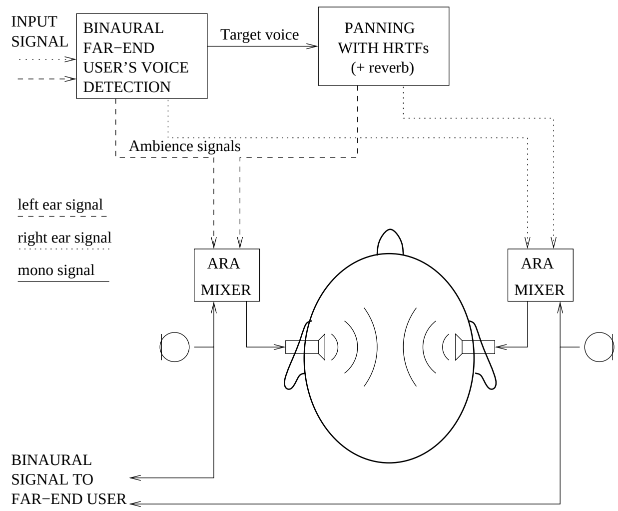

Fig. 5: *Rendering of binaural signals in the near end.*

phone and the binaural wearable telephone are discussed in more detail.

3.1. Binaural telephone with WARA workstation

A binaural telephone prototype is a two-way voice-over-ip (VoIP) application. In addition to voice transmission, it transmits the whole 3-D auditory environment to the receiving end. The basic idea of binaural telephone is illustrated as follows: Consider a situation where a far-end user, wearing a WARA microphone-earphone headset is listening to the conversation around her/him. The near-end user hears the conversation where speakers are distributed in a space as in a real situation, see Fig. 4. This effect can be called the auditory telepresence.

One major problem occurs in binaural telephony when the local speaker in a far-end starts to speak, since her/his voice is much louder than others and the voice is localized inside the near-end listener's head. This, of course, sounds unnatural. For convenient use of the system the far-end local speaker has to be rendered so that the sound seems to come from outside the head, as illustrated in Fig. 4. In order to enable this, it is necessary to automatically detect when the far-end user is talking.

In the WARA implementation the detection and segregation of far-end user's voice is carried out with a modified version of a sound segregation algorithm for reverberant conditions [12]. The purpose of the original algorithm was to separate two simultaneous speakers from each other by analyzing signals of two microphones. The same idea, which is based on the directional processing of binaural signals, was applied here. The detailed description of the algorithm is reported in another article [13].

The implemented binaural telephone is working between two WARA prototype systems. The binaural audio is transmitted with the UDP protocol over the Internet. With the aid of sound segregation algorithm the transmitted sound signals are divided into three signals at the receiving end, see Fig. 5. Two of these signals are the original left and right ear signals from which the possible far-end user's voice is removed. The third signal is the segregated one. In the WARA prototype system the segregated voice is panned with HRTFs in front by default but the user can adjust the position of the segregated voice with a GUI.

3.1.1. Discussion about the implemented algorithm

The original algorithm proposed by Shamsoddini and Denbigh [12] was used as a front end to a speech recognition system or as an aid for the hearing-impaired. In these contexts it is not required that the quality of segregation result should be perfect. This is not the case when the algorithm is applied to binaural telephone in the WARA prototype system. In our implementation the quality of segregated sound alone is not perfect. However, when the segregated sound is panned in front of the near-end listener's head and mixed together with left and right channel binaural signals (from where the local speaker's voice has been removed), the result sounds quite good.

The binaural telephone prototype works well and indeed gives a feeling of real telepresence. When a person is listening a meeting remotely (if only one participant of the meeting is wearing the WARA headset), there really is the feeling of being present in the meeting. Difficulties occur if the listener wants to participate in the meeting, since comments are only heard by the person who wears the WARA headset. However, the binaural telephone could be useful in many situations, e.g., in net-meetings.

3.2. Binaural wearable and portable telephone

The implemented binaural telephone application works only between two WARA prototype workstations. However, it is desirable to have a wearable system with which auditory telepresence can be experienced, e.g., while walking in the street or while sitting in the bus. For that purpose we implemented a thin WARA system client to a PDA device which is connected with WLAN to the network. Such a setup would enable testing of the basic two-way communication scheme, where both users are wearing a WARA headset, and stereo audio would be transferred to both directions. Unfortunately though, the PDA that was utilized, Compaq iPAQ 3630, did not have a stereo line-in jack. This means that it was not possible to record the binaural signal of the mobile user and make the system truly binaural full-duplex. Instead, we had to settle for an internal microphone and try to auralize recorded mono signal (using HRTFs) at the non-mobile end.

The portable binaural telephone works well as long as the WLAN connection can provide all audio packets to the mobile user. Unfortunately, current WLAN networks are seldom designed for reliable streaming audio. Nevertheless, our demonstration showed the potential of portable device, since it is really fun to walk in the lobby of a big building and at the same time listen to the other sound environment.

4. USER INTERFACES

Conventional and visually oriented user interfaces that we have used in the WARA prototyping workstation cannot be applied anymore when the mobile and wearable technology is available. The optimal user interface should be "eyes-free" and preferably also hands-free meaning that communication between a user and a machine should be performed with, e.g., speech or gestures. Suitable gestures could be head nods to different directions or simple drawings to the PDA screen as studied by Brewster et al. [14].

The user interaction problems concern both input and output. The latter seems easier problem to solve, since with good text-to-speech synthesizer most required information could be presented to the user. Menus and lists can be presented to certain extend with 3D sound [14, 15]. Also information about time, e.g., spatialized audio progress bar has been proposed [16]. In addition to sound output, tactile output could be useful in the form of tactons, tactile icons [17].

The input for user interaction might be harder to implement. Speech input from the user is an important feature in order to make WARA systems hands-free. Speech-based control through speech recognition may be used by simple commands to start and stop functions of communication or to operate machines and systems, or by more advanced man-machine communication by natural language. In the future WARA headsets provide the user interface that is available any time, anywhere, for persons wearing such a system.

As mentioned earlier head nods and hand gestures could be a good choice for picking items from auditory menus. For example, accelerometers attached to a wrist watch could detect many different hand gestures that are easy to use without visual display.

5. OTHER APPLICATION SCENARIOS

5.1. Augmented sound events

When the technology is ready for a real mobile and portable WARA system (consisting of a headset and a PDA device which handles wireless networking, tracking, preamplifier, etc.) there are a whole world open for augmented sound event applications. Such applications could be announcements, advertisements, instructions, warnings, etc. The main benefit of the WARA headset is that all these applications can be customized to one single user. In other words, while you hear your natural auditory environment, you can hear augmented sound events that are meant only for you. Consider for example a situation that you go to a shopping mall and you have a list of goods to buy. You give the list to your PDA and it optimizes your way through the mall, just as current navigation systems do in cars. While walking on your shopping track, with the WARA headset on, you hear your navigation aids with 3D sound but also (if you want) some advertisements from different stores, warnings, etc. When you are close to the item that is on your shopping list, you can localize it easily, since the Radio Frequency Identification (RFID) tag attached to the item provides you a cue about its location with a 3D sound event.

5.2. Binaural audio networking

Wearing the headset which is connected to the mobile communications system or a network, the user may be turned to a mobile binaural real-head recording unit. Therefore, we may consider many different types of applications based on the same idea as the popular webcam concept. The user may voluntarily provide other users of the network an access to the binaural real-time recording captured using his/her headset. This service could also be locked to a certain location. For example, a user planning to travel to some place could check if there is another user with 'open microphones' in the place and experience the live audio scene of that user, who may be anonymous. The signal could be routed through a server which holds the database of locations of 'open ears' users and relays the audio streams to users who want to subscribe to the transmission from a specific location. This could also facilitate, among other things, listening to a free concert or theater performance remotely from the headset of another user or even the performer. In some cases, the same concept could also be used for remote audio surveillance of public spaces.

5.3. A potential game for WARA technology

The WARA headset would open a totally new area of applications applying binaural audio. In this paper we have only little scratched the surface of this application world. However, one major problem is to develop mobile and wearable WARA technology so that equipment are widely available for reasonable price. To boost the research and development a so called killer application should be invented. One such application could be a game in which the WARA headset plays a significant role. For example, let us consider the following game scenario.

The game environment is an abandoned office building or factory in which two teams are playing. The goal of the game is to steal a flag from the base of the other team. Every single player is wearing a WARA headset and a wearable computer. Both teams have their own radio channels for communication. In addition, binaural signals (team mates auditory environments) can be delivered and players can co-operate by leaving Auditory Stickers to their team mates. The WARA technology enables augmented reality for each player without blocking the sight of players.

6. OTHER FUNCTIONALITIES OF WARA HEADSETS

WARA technology makes it possible to include such hearing-related features as hearing protection and hearing aids. Hearing protection can implement passive and/or active noise control by blocking and canceling too loud signals entering through headset earplugs. Hearing protection may be also selective in an intelligent way so that informative and harmless sounds are passed while harmful and annoying sounds are attenuated. For very noisy environments special headsets allow speech communication, for example by capturing speech of the subject inside the ear canal.

Hearing aid functions are easily integrated in WARA headsets which include all components needed to process the pseudoacoustic sounds from the environment as well as augmented sounds according to the hearing abilities of the subject.

7. CONCLUSIONS

In this paper different applications for WARA technology, which utilizes specific microphone-earphone transducers, are presented. A few applications have been implemented with the WARA prototype system and those are described in more detail. Practical issues related to prototypes are pointed out and usability issues are discussed.

The WARA headset enables a new way of human-to-human and human-to-machine communications. The WARA headset allows hands-free and eyes-free communication with a user and a portable computer, e.g., a PDA. When the WARA technology is widely available it will enable many applications that are hard to imagine today. In conclusion we'll see a bright future for mobile audio and speech through wearable and mobile augmented reality audio applications.

8. ACKNOWLEDGMENTS

This work has been carried out in collaboration between Helsinki University of Technology and Nokia Research Center. Härmä's work was partially supported by the Academy of Finland.

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