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THE EAR BEYOND HEARING: FROM SMART EARPLUG TO IN-EAR BRAIN COMPUTER INTERFACES

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Wearables are everywhere. But in the ears (yet). The research team from the *NSERC-EERS Industrial Research Chair in In-Ear Technologies* (CRITIAS) has been actively developing various in-ear technologies designed to complement the human ear, from "smart" hearing protection against industrial noises, to advanced inter-individual communication systems, to hearing health monitoring devices using otoacoustic emission (OAE), to in-ear EEG Brain Computer Interface (BCI). More fundamental research has also been conducted, particularly on the micro-harvesting of electrical power from inside the earcanal to power future auditory wearables. Current state of the research will be presented in this paper, together with some of recent developments conducted through the CRITIAS industrial research chair to take advantage of the human ear beyond hearing and come up with a truly "bionic" ear.

Keywords: human ear, wearable technology, instrumentation, digital signal processing

1. Introduction

According to the World Health Organization (WHO), not only is the number of people affected worldwide by occupational hearing loss constantly on the rise, from 120 million in 1995 to 250 million worldwide in 2004 and now 350 million in 2015, but the associated personal and societal cost as well [1]. Much of this impairment is caused by exposure to noise on the job, but excessive noise is increasingly encountered in many aspects of day-to-day life. The WHO recently highlighted the very serious threat posed by exposure to recreational noise, estimating that 1.1 billion people are now at risk of losing their hearing [2]. Yet, noise-induced hearing loss is 100% preventable, provided that appropriate hearing protection, communication and entertainment devices are available. This represents a huge challenge for engineers to tackle. Consequently, the first two research themes of the NSERC-EERS Industrial Research Chair, namely "Digital Hearing Protection" and "Communication in Noise", are dealing with hearing preservation and the development of effective communication and entertainment technologies. The human earcanal is currently a largely underexploited area for human sensing technologies, and future market segments, that have yet to be developed in the next 5 to 10 years and yet that are already being referred to as "Wearable Web" and "Healthcare 2.0" [3], are segments where the human ear could play a significant role once it is properly instrumented. As a consequence, the third research theme of the research chair, entitled "In-Ear Sensing" is to deal with the human ear as a "sweet-spot" for non-auditory related research. Finally, the earcanal deformation caused by jaw-joint movement will be considered as a source of energy for the "In-Ear Micro-Energy Harvesting" solutions, and represent a complementary and fourth research theme.

This article will detail the research agenda of the *NSERC-EERS industrial Research Chair in In-Ear Technologies* (CRITIAS) by first stating what the research needs and opportunities are (Section 2), then by reviewing some of the current research activities of the CRITIAS chair (Section 3) to finally conclude, in Section 4, on the potential to use the human ear beyond hearing and come up with a truly “bionic” ear.

2. Research Needs and Opportunities

The following subsections will review the current issues and list the proposed research efforts related to the three research area mentioned earlier: digital hearing protection, communication in noise, in-ear sensing and in-ear micro-energy harvesting.

2.1 Digital hearing protection

2.1.1 Digital Hearing Protection against Occupational Noise Exposure

As a sensory organ, the ear should be protected against potentially harmful and dangerous noises. Noise induced hearing loss is the leading occupational injury in North America. While noise reduction at the source is the ultimate goal, individual hearing protection remains, in practice, the first line of defense in industry [4]. Unfortunately, most hearing protectors are reported to be uncomfortable, firstly because of the physical fitting issues of the hearing protection devices (HPD) to the user's earcanal, and secondly because hearing protectors create a solid psycho-physical barrier, since they block the actual perception of the voice and surrounding warning signals. Not only is this a source of discomfort, but it is also counterproductive for workers, since they become isolated from their working environment, which can also lead to a higher incidence of workplace injuries. To address these individual fit and comfort issues from both a physical and auditory point of view, certain manufacturers, the Canadian company Sonomax Technologies Inc. being the first circa 2000, began to offer HPDs that are based on a custom earplug for increased physical comfort and including a passive acoustical filter for increased auditory comfort: the filter will let some sound energy through, which helps to overcome the problem of overprotection, enabling the wearer to perceive speech and warning signals. Although this “adapted attenuation” approach [5] represents a definite improvement over non-selectable attenuation hearing protectors, it still faces practical, ergonomic and conceptual limitations and issues:

Issue #1 (Practical): Exposure level is often unknown. The level of noise exposure in North American industrial workplaces is rarely available and when it is, it is usually for a group of workers rather than a specific individual. For example, with the Sonomax Solution™ developed during the author's doctoral work, in cases for which the exposure is unknown, the appropriate filter cannot be selected and so the earplug sound-bore that normally receives the filter is simply blocked so that the earplug offers its maximal nominal attenuation, with the risk of “over-protecting” the wearer, hence isolating him from his acoustical environment.

Issue #2 (Practical): Exposure level is an average value. Noise exposure values correspond to an 8- hour time-weighted average rather than the worker's actual noise exposure at a given moment. The aforementioned filter can be manually changed, but usually only on occasion, e.g. when a worker changes environments. It would not be feasible to continuously change from one filter to another as the noise levels change.

Issue #3 (Practical): Exposure level is an overall value. The protected exposure level is an overall value that is calculated from the difference between noise exposure and protector attenuation values across frequencies. However, in practice the noise and earplug attenuation frequencies each have their own importance: higher frequencies are critical for speech intelligibility, yet they are the most attenuated by the protector as most passive acoustical filter will show the same low-pass filter characteristics [6].

Issue #4 (Ergonomic): Noise is not interesting, the rest is. An unforeseen human factor has been made clear in a field study conducted by the National Institute for Occupational Safety and Health (NIOSH) on the previous generations of filtered Sonomax custom earplugs [7]: workers do not always need to communicate in loud noise and might often prefer to be over-protected and cut off from uninteresting sounds rather than to be constantly annoyed by them.

2.1.2 Consumer Audio Products Preventing Recreational Noise Exposure

While occupational noise exposure remains the most urgent challenge, it has also been made clear in recent years that recreational noise exposure is a growing concern: either through noisy activities (hunting, shooting, clubbing, snowmobiling, and even lawn mowing) or long and loud periods of music listening over personal music players, more and more people at a younger and younger age are irrevocably putting their hearing at risk. Personal Audio products have been one of the fastest rising segments of the consumer market over the last 15 years. The iPod® was first commercialized in 2001, and today, more than 1.2 billion personal music players (that also includes mobile phone with music playback capabilities) are being used on a daily basis. Similar trends can be observed in the telecommunication business, where hands-free kits and Bluetooth® earpieces are now ubiquitous and are showing continuous sales growth. This massive adoption of in-ear audio products will have dramatic effects on the auditory health of today's citizens and future generations in particular; two important issues must be addressed for the safety of future in-ear consumers of electronic products.

Issue #5 (Health & Safety): Noise isolation is key. Many recent studies (a comprehensive review is available in [8]) make clear that too many users are listening to their personal music player too loud for overly long periods, leading to a dramatic rise in the prevalence of noise-induced hearing-loss. Several studies (see [9] for list of a recent list) show a strong relationship between the ambient background noise and the listening level: the noisier the environment (street noise, transportation noise, etc.), the louder the users will playback their music. Therefore, earphones that would be able isolation the user from the ambient noise would be of immediately beneficial for the very vast majority of users. The only caveat would be that noise isolation for in-ear headphones requires an acoustic seal that can only be achieved by the most well-fitted of earpieces. In most cases, while custom-molded earpieces would provide the best fit, users might resort to a more accessible even though less comfortable generic eartip (foam, flanged or roll-down eartips derived from their industrial earplug counterparts).

Issue #6 (Ergonomic): Occlusion Effect matters. Assuming that Issue #5 above was addressed with an isolating and comfortable eartip, another set of issues remains: when an individual is wearing an intra- aural device (eartip, earplug, in-ear device, etc.) the sound of their own voice is dramatically altered, and body noise is amplified. Usually, the wearer will perceive his own voice and the body-generated noises (footsteps, breathing, etc.) much louder because of his occluded earcanal. The physics of this "occlusion effect" is well understood, as well as its numerous detrimental effects. In industrial hearing protection, the produced voice level of the wearer of earplugs will be reduced because of their false perception of having a louder voice. In consumer applications, the occlusion effect causes such a perceptual discomfort to the wearer of an in-ear device, that currently no manufacturer offers telecommunication products that would occlude both ears (i.e. Bluetooth earpieces are monaural only, headphones with an in-line microphone are not in-ear devices, etc.).

2.2 Communication in noise

Finding the balance between good hearing protection and communication in noisy environments has been a difficult task. There is no question that workers in noisy environments must be protected to avoid noise-induced hearing loss. However, communication remains a major concern for those equipped with Hearing Protection Devices (HPD). Using personal radio communication in noisy environments is a practical and affordable solution allowing communication between people with HPDs. Bone and tissue conducted speech, such as that captured with a microphone placed in the occluded earcanal, below the HPD, has been used in noisy environments to provide a relatively high signal-to-noise ratio signal.

Issue #7 (Ergonomic): Low quality of in-ear microphone signal. The limited bandwidth of bone and tissue-conducted speech degrades the quality of the speech signal. Moreover, in very noisy conditions, bandwidth extension of the bone and tissue-conducted speech becomes problematic, as residual noise might still be present under the HPD and will be amplified with bandwidth extension techniques.

Issue #8 (Health & Safety): Lack of designated receiver for personal radios. A drawback that has always existed regarding personal radios is that one cannot designate receivers: all those carrying a personal radio (walkie-talkie, etc.) are subjected to the broadcasted signal regardless of whether or not they are the intended listeners. Receiving irrelevant communication is annoying and contributes to the daily accumulated noise dose.

2.3 In-Ear Sensing

The human earcanal is currently a vastly underexploited area, while it definitely represents a “sweet-spot” for biosignal measurement hence offers a unique opportunity for innovative wearable technologies.

Opportunity #1: A “sweet-spot” for physiological monitoring

Aside from being part of the auditory hearing system, the earcanal is a dynamic environment where a several combinations of biosignals can be conveniently measured. For example, reading the temperature of the human body is commonly performed inside the earcanal using an infrared thermometer. Similarly, the earcanal skin tissues contain sweat glands, the humidity of the earcanal, just like its skin conductivity can change over time, as a function of human activity, stress levels and other physiological factors. Obviously, inertial sensors placed inside the earcanal can conveniently measure head position, velocity, and acceleration.

Opportunity #2: Physiological noise is much more than noise

When their earcanal is occluded in silent environment, many people can hear their breathing and heartbeats. This physiological noise is always present and can be captured by the in-ear microphones and further analysed to measure the breath rate and heart rate. Other non-verbal noises can also be captured, such as coughing, swallowing, sneezing, teeth grinding, snoring, etc. Their unique sound signatures enable automated segmentation and monitoring of such events for health, fitness and well-being monitoring. Finally, otoacoustic emissions (OAE) are auditory evoked sounds that are produced by a healthy cochlea in response to audio stimuli, such as pure tones in the case of Distortion Product Otoacoustic Emission (DPOAE) measurements. These very faint emissions are present under the HPD and while they barely emerge from the physiological noise, their presence or absence is a very early indicator of auditory fatigue and pending NIHL and is therefore a very useful tool for auditory health monitoring.

Issue #9: Electrodes are not properly positioned for in-ear electrophysiological recording. EEG is a valuable tool in studying the function of the brain and has been widely used for both medical diagnoses and neuroscientific research. Conventional EEG systems measure the brain's electrical activity by using caps that place electrodes on the scalp (scalp-EEG) and wires transmitting the signals to differential amplifiers connected to a computer. Despite the recent development of a small, wireless and lightweight head-mounted EEG system EEG caps are still uncomfortable to wear and not suitable for daily-life situations. An earcanal-based EEG acquisition system with miniaturized electrodes is a new, complementary approach with user-friendly characteristics [10]: the earcanal is normally hair free and is geometrically asymmetrical. These two characteristics significantly improve the electrical/mechanical contact between the skin and electrode and enhance the repeatability of the experiments. Moreover, the tight fit of an earpiece inside the earcanal applies pressure on the electrodes ensuring fixed electrode positions and a dramatic reduction of motion artifacts that typically obscure the signal quality in conventional EEGs. In all works cited, miniaturized electrodes were placed inside the earcanal either as part of a custom earpiece or on a generic earpiece. Unfortunately, the localization of these electrodes was not carefully studied which resulted in sub-optimal locations, that is, the contact between the electrodes and the earcanal can be altered by jaw-joint movements, thereby affecting the quality of the signals recorded in live and dynamic environments.

Issue #10: Traditional wet electrodes are ill-adapted for in-ear recording. Traditional Ag/AgCl wet electrode preparations reduce the skin–electrode interface impedance by abrasion of the Stratum Corneum (SC), and the use of electrolytic gel. The requirement for skin abrasion, the use of gel, and the risk of a short circuit, are known limitations [11]. Developing dry electrodes technology that would be compliant with the human earcanal is therefore required.

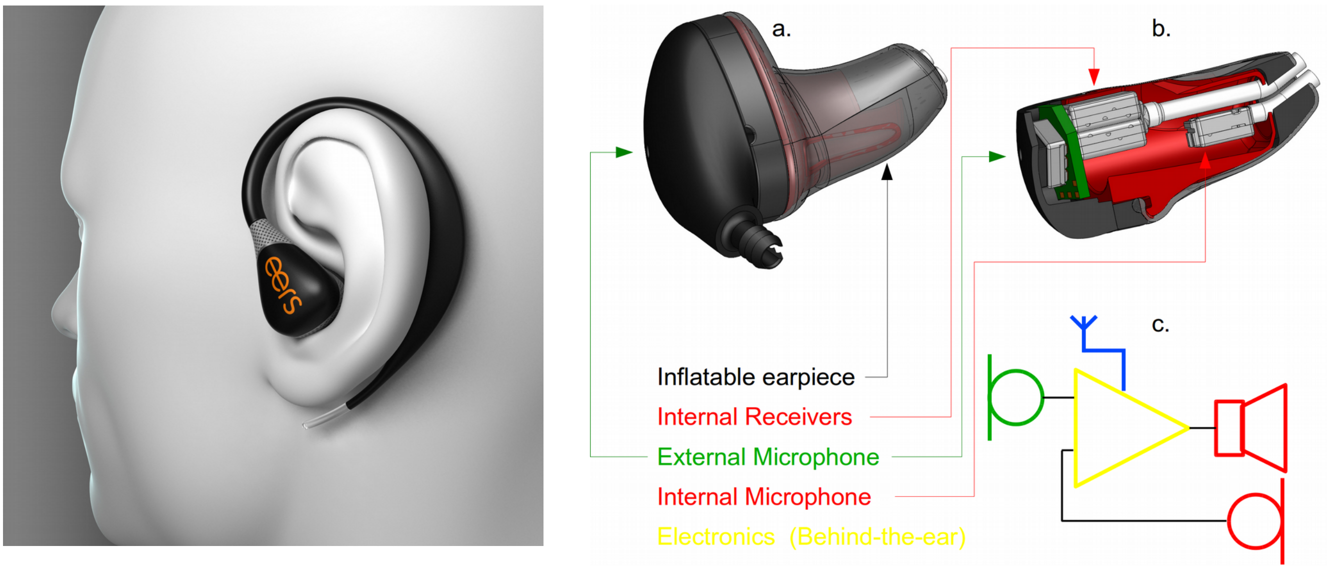

Figure 1: Auditory Research Platform (ARP V2.0) developed for real-time audio signal processing: overall design (left); instrumented earpieces (a), electroacoustic components (b) and equivalent schematic (c) (right)

2.4 In-Ear Micro-Energy Harvesting

On a weekly basis, hundreds of millions of users worldwide must replace the button cell batteries in their hearing aids. Unfortunately, batteries are a source of environmental waste, a financial burden and somewhat time-consuming and requiring good dexterity to change. What if hearing-aids could be self-powered?

Opportunity #3: Using the jaw-joint movement as a source of mechanical energy. As mentionned earlier, the jaw-joint movement caused by daily activities such a eating, chewing, speaking, etc. creates distortions of the earcanal shape. One of the complementary research axis from the CRITIAS research chair aims to develop an energy harvester for all kinds of in-ear devices using the mechanical power of jaw movement. The challenges of the proposed strategic research proposal are first to find ways to capture a sufficient amount of energy from the low-frequency and small-amplitude movements of the earcanal walls, second to store the intermittent captured power in an appropriate energy storage device to supply continuous power to the in-ear device, and third to integrate the system components into the in-ear device as an embedded system without creating wearer discomfort nor interfering with device's functions.

3. Ongoing Research Activities

Addressing all the issues presented in prior section is the first goal of the CRITIAS research chair. To accomplish this, the research program will focus on two interconnected research themes, “Digital Hearing Protection” (presented in section 3.1) and “Communication in Noise” (presented in section 3.2), with the objective of developing the required knowledge and technology for a unique in-ear device merging hearing protection and communication features. Taking advantage of the physiological monitoring and energy harvesting that is possible within the human earcanal, the third goal of the proposed chair is to develop the technology required for continuous “In-Ear Sensing” (presented in section 3.3) whereby enabling applications ranging from simple physiological monitoring of workers, to more advanced research tools for auditory cognitive neuroscience or even the development of integrated audio-capable Brain Computer Interface (BCI) and the fourth goal is to develop in-ear energy harvesters (Section 3.4).

The ability to make an instant custom-fitted earpiece equipped with electro-acoustic components and integrated electronics is crucial for the proposed research program. The self-fitted custom earpiece developed by *Sonomax Technologies Inc*., using the proprietary SonoFit™ process, and now available through the industrial partner EERS, constitutes an excellent platform, dubbed the *Auditory Research Platform* (ARP). It is illustrated in Fig. 1 in its current configuration suitable for hearing protection and communication devices, but is under development, as ARP V3.0 to use the human earcanal for in-ear sensing applications.

This section details the research conducted over the last years within the former *Sonomax-ÉTS Industrial Research Chair in In-Ear Technologies* that led to the development of several prototypes of digital hearing protectors able to protect their wearers while enabling normal communication in noisy environments. It also details the ongoing research efforts within the industrial research chair.

3.1 Digital hearing protection

Over the recent years, several innovative audio processing algorithms have already been developed, namely to detect voice activity in low signal- to-noise ratios [12–14], design alarm and warning signal detectors [15] and use modulation-band filtering to remove noise while conveying speech and warning signals [16]. Other “smart” hearing protection algorithms have also been developed, such as those for professional musicians, with active noise control of the occlusion effect [17, 18], or for hypersensitive subjects [19]. While promising, these technologies now require further optimization and actual implementation of the ARP digital signal processor, so that their actual real-life benefits may be assessed. Several other audio processing algorithms also need to be investigated, such as embedded continuous fit-testing of an in-ear device based on prior developments on field-attenuation measurements [20–22], in-ear dosimetry [23–27], loudness-based uniform attenuation, level-dependent attenuation, and specialized audio processing algorithms able to combine hearing aid and hearing protection to address the issue of the protection of hearing impaired workers [28].

3.2 Communication in noise

Workers need to be able to communicate in noise. When the acoustic speech signal is overly disturbed, an in-ear microphone can be used [29], the speech signal can be denoised with adaptive signal processing and its intelligibility improved using spectral extension techniques [30–33] then transmitted using personal radio communication systems. Natural and robust two-way communication systems have been proposed [34, 35] and through a coding of the vocal effort of the speaker and a model of the intended communication distance, so-called Radio-Acoustic Virtual Environments (RAVE) [36] are now being envisioned. Further research is now required to better understand auditory processes involved in speech production under hearing protectors in noise and build the corresponding psychoacoustic model, to validate RAVE systems in real-world situations for industrial and tactical applications.

3.3 In-ear sensing

“Wearable technologies” is a generic and trendy expression that includes more than a dozen market segments, with “Smart Watches”, “Smart Glasses” and “Fitness and Activity Tracking” devices topping the list. In 2015, the global market of wearable technologies was estimated at $22.7 billion, a mere 2.3% of the $1 trillion market potential [37]. Many experts, including the author [38, 39], believe that the human earcanal is an ideal place to collect several types of high quality biosignals. Using the ARP’s discrete sensors, instruments used for physical and physiological monitoring applications will be developed, ranging from man-down detection and gaze detection using the 9-axis inertial unit, to body temperature and earcanal humidity monitoring using the ad hoc embedded miniaturized sensors, to the measurement of galvanic conductivity using in-ear electrodes. Biosignals such as heart beat and breath rate will be extracted from the in-ear microphone signal using time-frequency analysis coupled with the adaptive filtering previously proposed [40, 41] for low to medium noise applications. Algorithms have recently been proposed by the author [42–44] to measure otoacoustic emissions (OAE) and can be used to continuously monitor the auditory fatigue of a worker in medium to high noise environments.

3.4 In-ear Micro-Energy Harvesting

Over 300 million users change their hearing aid batteries on a weekly basis. Not only is this inconvenient and costly, but battery disposal has a negative impact on the environment. Several rechargeable battery technologies exist, but their low efficiency and power capacity require larger-sized hearing aids or more frequent recharges. Ideally, hearing aids should be self-powered, harvesting energy from their environment. Studies conducted within CRITIAS since 2010, show that the mechanical energy from jaw-joint movement could be harvested to power such electronic in-ear devices. Since the earcanals’ shape and geometry as well as their attributed deformations are unique to individuals, a test setup was then developed to measure on a group of test-subjects the extreme of their earcanal deformations. the earcanal energy capability based on the pressure changes in an inflatable earplug filled with water. The test results showed that the earcanal dynamic movement is capable of powering current hearing aids for more than 2 hours in average [45]. This duration would be obviously made longer if more jaw-joint movements were considered, such as the ones resulting form speaking or chewing gum, or for more power-savy hearing aids.

The promising results for the energy capability of the earcanal deformations led to the development of two energy harvesting prototypes, electromagnetic and piezoelectric, that were subsequently designed, fabricated and tested [46, 47]. The results successfully proved the concept of in-ear energy harvesting and demonstrated the capability of the earcanal to be considered as a sustainable source of kinetic energy in the body. Nevertheless, the design of optimized in-ear energy harvesters remains very challenging, as the exact deformation of the human earcanal is still poorly understood and as inadequate group data is available on earcanal deformations among individuals.

Besides, the small size and very unique geometry of each earcanal make the design of a generic energy harvester difficult, as recently highlighted in the chair most recent work [48, 49]. Also, the choice of energy conversion between piezoelectric, electromagnetic, electrostatic and triboelectric remains unsettled.

In addition to earcanal dynamic movements, other kinetic energy sources in the region of the head have been already investigated in CRITAS research group : from the jaw movements using a piezoelectric chin strap [50], from the head movement using a combined piezoelectric and magnetic device installed on an eyewear [51], or even from breathing airflow, using an electromagnetic energy harvesting device that could power the end-of-life indicator of respirators cartridges [52]. It is believed within CRITIAS research group that wearable devices of the future, be it augmented reality glasses, bionic ears, etc. will be self-powered and that there is a real need to develop a miniaturized in-ear micro-energy harvester that uses the jaw-joint movement resulting from eating and speaking activities, to provide electrical power to all kinds of electronic in-ear wearable devices, such as hearing aids, digital hearing protectors but also new auditory wearables currently being developed within the *NSERC-EERS Industrial Research Chair in In-Ear Technologies*.

4. Conclusions

While wearable technologies are everywhere, they have not (yet) been configured for the ear. According to the WHO, more than 1.1 billion people daily put their hearing at risk either at work or leisure. The *NSERC-EERS Industrial Research Chair in In-Ear Technologies* (CRITIAS) will face this challenge by developing leading edge technology combining in-ear instrumented hardware platforms with audio signal processing and biosignal extraction algorithms to enable its Canadian industrial partner, EERS Technologies Inc., to commercialize in-ear wearables for hearing protection, hearing aid, two-way communication and brain-computer interfaces for industrial, military, consumer and medical markets. The first objective of the Chair will be to develop a versatile in-ear hardware platform with the team at EERS, using its SonoFit proprietary instant custom molding technology. The envisioned in-ear platform, dubbed Auditory Research Platform (ARP), will be instrumented with several discrete sensors, electroacoustics transducers, electronic circuitry and a digital signal processor. The processor will run audio signal and biosignal processing algorithms to be developed within the proposed research program. The core research activities will include 4 areas of expertise: a) digital hearing protection, b) communication in noise c) in-ear sensing and d) in-ear energy harvesting. The activities of this research chair will further strengthen and sustain this successful industrial-academic 15-years old collaboration and create an innovative ecosystem able to retain this unique expertise on Canadian soil.

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