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The ear in the age of IoT

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ABSTRACT

At this age of Internet of Things (IoT), wearables are now everywhere, sometimes even in your earcanal. 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 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. The current research activities from CRITIAS and several possible applications are presented in this article, while the corresponding keynote presentation will feature other research groups research and resulting technologies.

Keywords: Acoustics, hearing protection, hearing aid, in-ear biosensing, wearables, internet of things (IoT)

1. INTRODUCTION

This introduction gives an overview of the NSERC-EERS Industrial Research Chair in In-Ear Technologies (CRITIAS) research group, by presenting briefly its history as well as its mission and focus.

1.1 A little bit of history

The NSERC-EERS Industrial Research Chair in In-Ear Technologies (CRITIAS) was created in September 2016 as part of a long-standing and successful partnership between EERS Global Technologies Inc (previously Sonomax Hearing Healthcare Inc) and École de technologie supérieure (ÉTS). The partnership was initiated in late 1999 and led to a unique technology designed to protect industrial workers from noise-induced hearing loss (NIHL). The resulting hardware and software solution, dubbed the Sonomax Solution, was protected by over 50 patents and trademarks and has been marketed all over the world. Following 10 years of collaborative work, the partnership became more firmly established when the author was appointed at ÉTS as professor and founded the CRITIAS Research Chair in 2010, now supported by the National Science and Engineering Research Council of Canada (NSERC) and dedicated to his original quest: to develop a true “bionic” ear that provides effective protection, amplification, communication, monitoring and biosensing within a single in-ear device.

1.2 Mission and Research Focus

CRITIAS focuses on the development of various technologies designed to complement the human ear, from “intelligent” hearing protection and communications in high-noise environments to the integration of in-ear brain-computer interfaces and wearable hearing diagnostics. The research activities focus on three areas: Digital Hearing Protection, Communication in High-Noise Environments, and In-Ear Biosensing. The research activities corresponding to these three themes areas are further described in Section 2 and are illustrated in the Fig.1.

2. CURRENT RESEARCH

Beyond the ubiquitous availabilties of hearing protection and hearing aid, the human earcanal is a perfect place for many applications that span well beyond hearing. While the author and its industrial partner have been early believers of such statement, that shaped all the collaborative

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research work that was conducted within CRITIAS since early 2010, it is exciting to see many new commercial entities now sharing the same vision (1) and are rapidly putting ear-centered wearable products (often called “hearables”) on the market. The market for hearables is considered to be one of the fastest growing (2) as it brings all the smartphones and tablet power one step closer to the human being. While probably not exhaustive, Fig. 1 illustrates the many possible applications and uses of the human earcanal, ranging from digital advanced hearing protection and hearing aid, communication in noise, to in-ear biosensing and even electric and light stimulation.

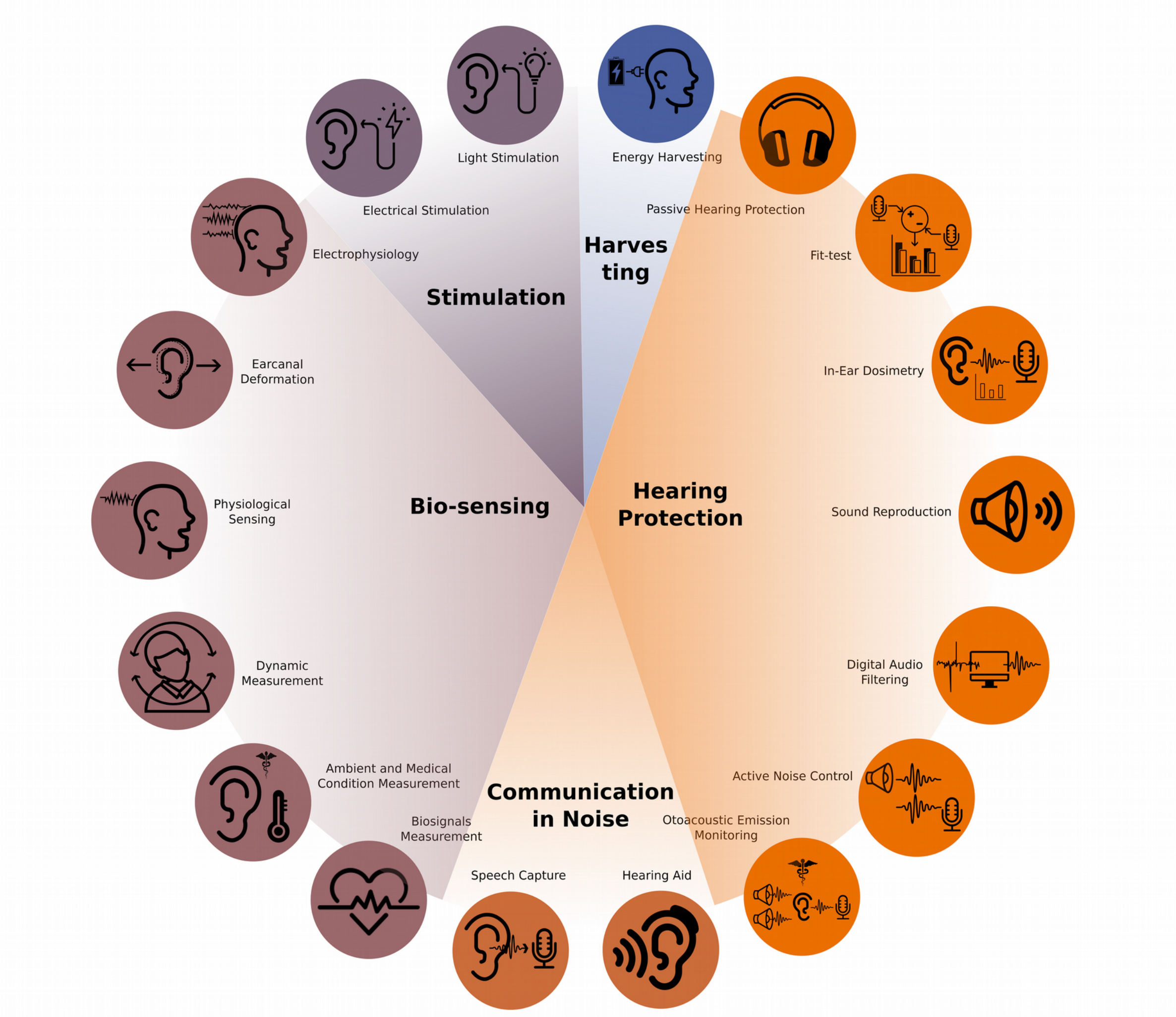

Figure 1: Several of the possible uses of the human earcanal with hearables

The following sections detail several possible uses and present the specific applications that are envisioned within current research activities at CRITIAS. The maturity of that research is rated with the Technology Readiness Level (TRL), a value that ranges from 1 (conceptual idea) to 9 (commercial product), assuming that technologies typically move at TRL 5-6 from academic research activities conducted at CRITIAS to industrial R&D conducted at EERS.

2.1 Digital Hearing Protection

Passive Hearing Protection (TRL 9)

The preferred passive hearing protection device (HPD) used at CRITIAS is an instant custom fitted earpiece, adjusted using SonoFit™ expandable silicone in-ear technology (3). It offers superior comfort, retention and attenuation and is perfect to be further equipped with electronic (digital signal processor, sensors, electrodes, etc.) and electroacoustic components (speaker, microphones, etc.), as illustrated in Fig. 2, to become a “digital earplug”.

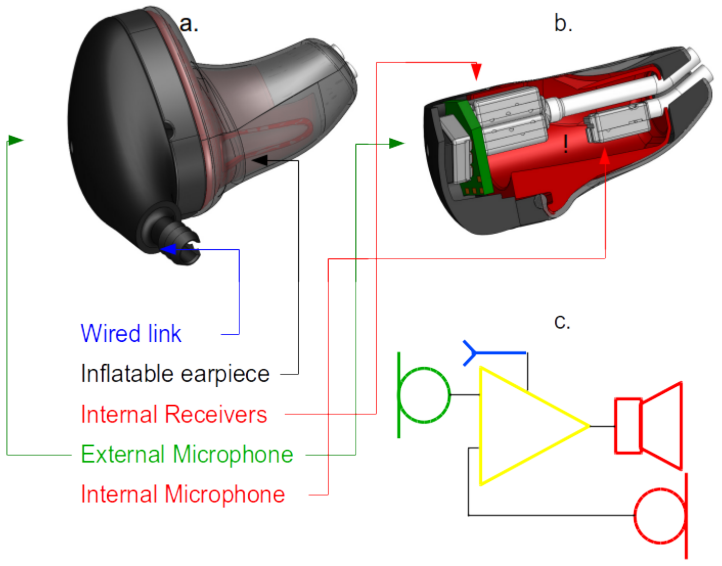

Figure 2 : Illustration of a digital earpiece obtained

First Fit Test (TRL 9)

One of the early technologies developed for the instant custom fit technologies is the individual field fitting testing of HPD. An objective microphone measurement dubbed Field Microphone in Real Ear (F-MIRE) is performed with the digital earplug and checks HPD attenuation for each wearer (4).

In-ear Dosimetry (TRL 9)

Typical noise dosimetry is performed by picking up the sound exposure of a worker with a microphone placed on the shoulder. With the In-Ear Dosimetry approach, the microphone is placed in the occluded earcanal, measuring what noise level actually reaches the eardrum through the wearer's HPD, but discarding wearers induced disturbances (such as speech, coughing, teeth grinding etc.) that are not to be accounted for in the cumulated noise dose, as they are non-hazardous for the user's hearing (5,6).

Sound Reproduction (TRL 9)

By including a miniature loudspeaker in the earpiece, signals can be played back to the protected ear. In-ear acoustics modeling recreates sound like it feels with an open ear, creating a more natural sound experience (7).

Digital Audio Filtering (TRL 9)

With the miniature loudspeaker inside the earpiece and a microphone outside, useful external sound is transmitted to the protected ear. Using Modulation-Based Digital Noise Reduction (MBDNR) voice and warning signals passed through while the rest of the ambient noise is passively blocked (8,9).

Active Noise Control (TRL 9)

The amount of attenuation provided by the passive HDP can be further increased using active-noise control (ANC). The residual noise is picked up via the in-ear microphone, inside the occluded earcanal, dephased by 180 degrees and played back to local cancel the initial sound disturbance. ANC can also be very useful for cancelation of the so-called "occlusion effect". Normally, all wearers induced disturbances (own voice, footsteps, friction noise, etc.) as well as physiological noise (swallowing, coughing, breathing, etc.) would be perceived under the occluded ear and could become very annoying. With ANC, those low frequency noises are all canceled out, making the experience more natural and comfortable. The benefits of such technology were recently studied for musicians and performers, who need to protect their hearing while singing or playing instruments and would otherwise be disturbed and even annoyed by the occlusion effect (10,11).

Otoacoustic Emission Monitoring – Ear Fatigue (TRL 6)

Physiological fatigue originating from over-exposure to sound creates a gradual reduction in auditory capabilities. Rather than relying on subjective testing, such as hearing threshold testing using audiometry, a change in hearing sensitivity -often refered to as temporary threshold shift (TTS)- can be assessed using otoacoustic emission. By stimulating the ear with 2 pure-tone stimuli, a distortion product otoacoustic emissions (DPOAE) can be generated by the outer hair cell of the inner ear and picked up by the in-ear microphone. It recently became possible to monitor theses DPOAEs in high level of ambient noise, using adaptive filtering and denoising techniques (12–14).

2.2 Communication in Noise

Hearing Aid (TRL 3)

Using the existing in-ear loudspeaker and an outside microphone it is possible to add a hearing aid feature to the digital earplug. By selectively amplifying speech and warning signals, it is possible to assist industrial workers, who sometimes have significant existing hearing loss (15).

Speech Capture (TRL 9)

Speech produced by the wearer can be captured within the occluded earcanal. Since that signal is picked up underneath the HPD, it benefits from its passive isolation and offers a superior signal-to-noise ratio (SNR). Recent work has been conducted to further reduce the residual noise and enhancing the intelligibility of the picked-up speech by increasing its high frequency content (16).

2.3 In-Ear Biosensing

Biosignals Measurement (TRL 5)

The in-ear microphone can pick up many signals present inside the occluded earcanal. This signals is often referred to as physiological noise, but contains useful information, including heartbeat and breathing sounds from which it is possible to extract the wearer’s heartbeat and breathing rate (17). It has been also shown that other non-verbal signals could be picked up (coughing, teeth grinding, teetoh or tongue clicking, sneezing, etc.) and could be used for a wide range of hand-free and silent man-machine interface or as well for continuous health monitoring application (18).

Ambient and Medical Conditions Measurement (TRL 4)

The ear is a perfect place to measure temperature, as traditionally done in medical diagnostics. Using commercialy available sensors inside the occluded earcanal, ambient temperature and humidity levels are easily recorded and monitored. The combination of these two measurements detects workers’ physical involvement or overexertion (such as heavy lifting, levels of sweating) and combined with prior biosignals measured can be very reliable indicator of the health and condition of the wearer.

Dynamic Measurement (TRL 6)

Head movement can be recorded with 6-axis Inertial Measurement Unit (IMU) using accelerometer and velocimeter sensors. These measurements of head’s dynamic are suitable for monitoring fatigue (like head nodding down, etc.) or for musculoskeletal troubles induced by repetitive movements or activities (such as using a jackhammer, long-distance driving, etc.). The addition of a magnetometer (packaged as an 9-axis IMU) enables applications with 3D audio processing, which must account for head position in azimuth and elevation (gazing, etc.). A man-down detection (fall or injury detection) has recently been developed at CRITIAS using this same technology (19).

Physiological Sensing (TRL 3)

By making the earpiece conductive, for example by integrating a electrode or by using metal-coated or conductive polymer, skin contact electrical impedance can now be measured. This unique marker tightly related to how the custom earpiece is fitting inside the earcanal, enables the unique verification of the wearer’s biometric information. The same conductive earpiece can record much of the electro-dermal activity, capturing muscle and heart activities, thereby enabling a wide range of activity tracking and man-machine interface application.

Ear Canal Change Detection (TRL 2)

The conductive earpiece can easily detect movement in the earcanal induced by temporomandibular activities. Monitoring such activities (jaw movement, opening and closing the mouth, stretching, grinding teeth, etc.) creates some interesting applications. Examples include dentistry temporomandibular jaw-joint (TMJ) pain from jaw clenching, or linguistic research to understand jaw-joint activity during speech production. Leveraging on other biosignals detection provides great insight for wellness and sports tracking solutions. Cardiovascular activity inside the earcanal distorts the ear canal. Blood flow pulse can be measured by monitoring the conductive earpiece electrical properties (impedance, charge, voltage, etc.) while in contact against the earcanal, possibly opening new ways to monitor cardiovascular activities and diseases.

Electrophysiology (TRL 5)

By adding additional miniaturized electrodes on the earpiece, inside of the ear (intra-aural) and other around the ear pina (circumaural), brain wave signals can be recorded and monitored. While such electrophysiological signals (EEG) are not as specific as the ones obtained with a full scalp EEG with a much higher density of electrodes, they are easy to record in a non-invasive way, making them suitable for real-world applications. Auditory evoked potential (ERP) can be conveniently measured with a device that combined these electrodes on the audio digital earpiece (20, 21).

2.4 In-Ear Stimulation

The following two research activities are not currently taking place at CRITIAS, nor are they on the short-term research agenda of the CRITIAS team but are possible innovative applications.

Electrical Stimulation

Instead of receiving signals, the electrodes can act as actuators, to send modulated electrical signals, for example using the direct current stimulation paradigm. This can slightly alter the behavior of the nervous system and could have promising applications, given the proximity of the vagus nerve, which comes close to the surface of the earcanal tissues. This pneumogastric nerve has a tight parasympathetic control of the heart, lungs, and digestive tract and offers. There is research using this stimulus to alters motion sickness, appetite and nausea stemming from radiation therapy. There is another line of research where such stimulation, combined with sound signals, can alter auditory perception and mood for therapy or entertainment (22).

Light Stimulation

Instead of sending electrical signals, visible light can be shined inside the occluded earcanal. There is recent research that shows that some photoreceptor-proteins in the brain can receive that light and that similar benefits as the one provided by light therapy have been observed, affecting the generationmolecules regulating circadian rhythmicity. This offers convenient and discrete means to treat jet lags, seasonal mood and affective disorders (23).

2.5 In-Ear Energy Harvesting

Energy Harvesting (TRL 3)

Many of the “hearable” applications mentioned above require a continuous electrical power supply. One possible approach, rather than relying on disposable or rechargeable batteries or capacitors is to harvest the energy directly from the wearer itself. Amongst the many possible sources (head movement, head heat, solar radiation, etc.) a promising source appear to be the mechanical distortion of the earcanal induced by the jaw-joint movement. Prototypes of piezoelectric micro-energy harvesters have been developed and were proven to be able to recharge a battery over regular daily movements of the jaws (from eating, swallowing, yawning, speaking, or chewing gum, etc.) (24–28).

3. CONCLUSIONS

At the dawn of the 4th industrial IoT 5G revolution, it is clear that the interconnection between the human being and machine (or network) is getting more real every day. The human earcanal appears, at least in the views of the researchers from CRITIAS, as a perfect place to achieve this interconnection and the many possible applications that have been highlighted in this paper. While some of these applications may be years away, it is worth noting that several disruptive technologies developed by CRITIAS have already been integrated into innovative products brought to market by EERS Global Technologies, the industrial partner. For example, the most recent version of the "digital earplug", commercialized by EERS under the name "SonX", won in 2016 the first prize for the "Hear and Now" Noise Safety Challenge, a joint initiative by the US Department of Labor (DOL), the National Institute for Occupational Safety and Health (NIOSH), the Mine Safety and Health Association (MSHA), and the Occupational Safety and Health Association (OSHA) for technologies that uniquely reduce work-induced hearing loss.

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