OpenEarable: Open Hardware Earable Sensing Platform

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ABSTRACT

Earables are ear-worn devices that offer functionalities beyond basic audio in- and output. In this paper we present the ongoing development of a new, open-source, Arduino-based earable platform called *OpenEarable*. It is based on standard components, is easy to manufacture and costs roughly $40 per device at batch size ten. We present the first version of the device which is equipped with a series of sensors and actuators: a 3-axis accelerometer and gyroscope, an ear canal pressure and temperature sensor, an inward facing ultrasonic microphone as well as a speaker, a push button, and a controllable LED. We demonstrate the versatility of the prototyping platform through three different example application scenarios. In sum, *OpenEarable* offers a general-purpose, open sensing platform for earable research and development.

CCS CONCEPTS

• Hardware → Emerging technologies; **• Human-centered computing → Ubiquitous and mobile computing systems and tools**; **Ubiquitous and mobile devices**;

KEYWORDS

earables; hearables; open hardware

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1 INTRODUCTION

Earables are defined as "devices that attach in, on, or in the immediate vicinity of the ear to offer functionalities beyond basic audio in- and output." [6]. A broad spectrum of sensors have been used on the earable platform, ranging from motion, audio, and optical to biopotential, environmental, and electrical sensing principles. These have been used to detect a multitude of interesting phenomena that have been used in applications spanning several research areas including health monitoring, activity classification, interaction, and authentication and identification [6]. As a result, the earable platform has attracted attention from several, different research communities, and the number of research publications using the platform is increasing year-on-year.

A wide variety of hardware prototypes have been used in the earable research literature, ranging from commercial offerings such as Apple Air Pods[1] and cosinuss[2], prototype research platforms such as *eSense* developed by Nokia Bell Labs [5], and fully bespoke earable research devices (e.g., [3]). Of particular note is the eSense, which has accelerated the growth of earable research within the academic community. This in part was driven by the devices being freely distributed to academics across the world, providing a platform for which earable research can place and which others can openly contribute to. More recently, Chatterjee et al. [4] introduced *ClearBuds*, which has open hardware and comes equipped with dual microphones that can be used for speaker separation using beamforming. However, these earable platforms lack the extensibility that is required to take full advantage of the wide range of sensors that have been shown to be effective on the earable platform.

We introduce *OpenEarable*, the first fully open-source, Arduino-based earable research platform. *OpenEarable* aims to build upon the success of other earable prototyping platforms by providing a fully transparent and open hardware platform that enables researchers to push the boundaries of earable research. The main objective of *OpenEarable* is to provide an extensible platform that can be easily and cost-effectively manufactured for research and development purposes. In this paper, we present the first version of *OpenEarable* which features a 3-axis accelerometer and gyroscope, an ear canal pressure and temperature sensor, as well as an inward facing ultrasonic microphone and speaker. We provide an overview of the design process and an in-depth walkthrough of the hardware and software systems that make up the *OpenEarable* platform. Based on three exemplar applications from the research literature we highlight how the platform has to the potential to be used for motion-based activity tracking, detection of chewing events, and ear canal shape based authentication.

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[1] AirPods Pro - https://www.apple.com/airpods-pro/
[2] cosinuss - https://www.cosinuss.com/en/technology/

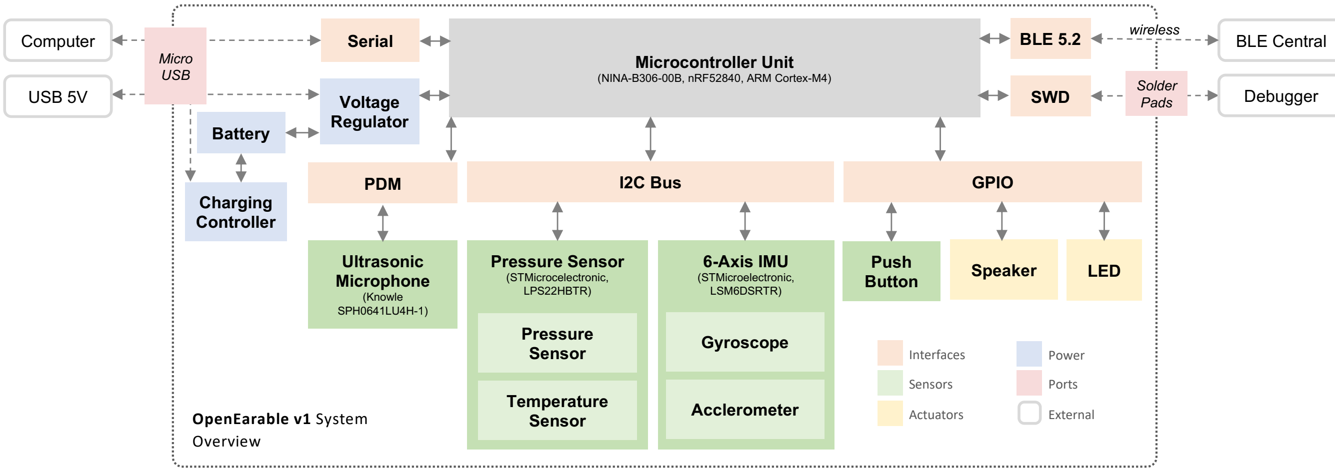


Figure 1: System overview of the *OpenEarable* system architecture. The microcontroller unit is the central hub which communicates with sensors, actuators, and external devices.

2 DESIGN PROCESS

In the following, we describe our guiding design principles and rationalise the sensor selection for the first version of *OpenEarable*.

2.1 Guiding Principles

Our main objective when developing the *OpenEarable* platform was to provide a general-purpose hardware sensing platform for the earable research community that allows for the exploration of state-of-the-art sensing capabilities on the ear. We were guided by the following principles throughout the design and development process:

2.1.1 Openness and Extensibility. The *OpenEarable* platform's hardware and software should be open to, and easily extensible by, others. The *OpenEarable* platform should provide the core infrastructure to enable the exploration of different sensing paradigms. As a result, all hardware design files, firmware, communication interfaces, and data recording tools should be made public and easily accessible so that others can modify and expand the platform in unique and novel ways. We also made a conscious effort to use development tools that are free-of-charge in the design of the hardware and software. We believe that as many people as possible should be provided with the opportunity to develop on, and for, the *OpenEarable* platform.

2.1.2 Manufacturability and Cost-Effectiveness. In order for people to leverage the *OpenEarable* platform for research, they must be able to easily manufacture the device at an affordable cost. To achieve this, we focused on commercial off-the-shelf components that require no specialized tools for manufacture. The PCB was specifically designed to be manufactured, and components assembled, by a self-service PCB assembly manufacturer. Additionally, all plastic parts are designed to be 3D-printable with a standard fused deposition modeling (FDM) printer, commonly available as consumer 3D printers or available to order online. The assembly of an *OpenEarable* should only require minimal equipment, with the first version only requiring a soldering iron, pliers and plastic-compatible power glue. All hardware components should be compatible with the open-source Arduino platform.

2.1.3 Attachment and Comfort. The *OpenEarable* platform, and any extensions, will need to be validated with users and therefore it should be easy to attach yet stable and robust against user movement. In addition, the earable should be comfortable to wear within the limitations of a general purpose prototyping device. For the first version of our design, we use an over-the-ear hook design that wraps around the auricle to encapsulate the electronics whilst providing mechanical stability. This provides an opportunity for sensors to be placed in, on, or around the ear.

2.2 Sensor Selection

For the first version of the *OpenEarable* platform we decided to incorporate both traditional and new sensing capabilities not currently available on other earable platforms. For basic input there is a push button, and a six-axis inertial measurement unit (IMU) for motion-based applications (e.g., gait analysis [2]) and to filter out motion artifacts.

For new sensing capabilities we chose to incorporate an ultrasound microphone and an in-ear pressure sensor combined with temperate sensor. Many earable platforms feature access to an external microphone for voice-based interaction, and most have a microphone inside the earbud for noise-cancellation. However, we could not identify an available platform that provides access to a microphone placed inside the ear canal. Therefore, *OpenEarable* features an inward facing ultrasonic microphone which can be used to detect ear canal shape and deformation based on measured sound reflection. We chose an ultrasound microphone to be able to detect both audible and inaudible sounds which do not disturb the wearer. We also incorporated a pressure sensor for in-ear barometry which provides information about the ear canal shape and deformation. In-ear barometry has gained traction in recent years across a range of applications and have been used to detect jaw and facial movements [1], blood pressure [10], and contraction of the

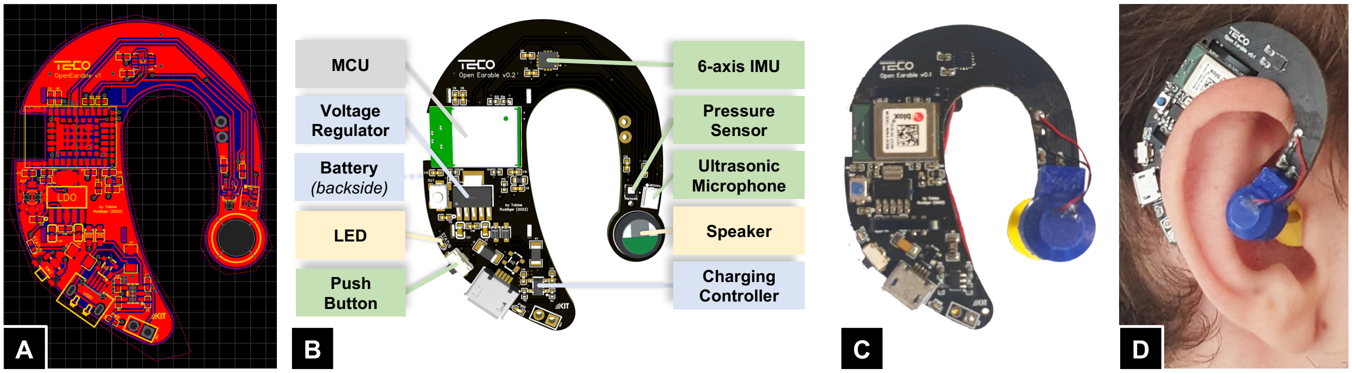


Figure 2: (A) PCB layout of *OpenEarable*; (B) 3D-rendering of the PCB and components; (C) assembled device with 3D-printed parts and battery; (D) a person wearing the device.

tensor tympani muscle (small muscle that actuates the eardrum) which can be used for interaction [7].

3 HARDWARE

The hardware of *OpenEarable* is inspired by existing works in the earable domain. We present the electronics, mechanical design, and production process. Step-by-step manufacturing instructions are available on the *OpenEarable* project's website [3].

3.1 Electronics

The following section describes the circuit layout, microcontroller unit, power architecture and sensors of *OpenEarable*. A schematic system architecture overview is shown in Figure 1.

3.1.1 Printed Circuit Board. We designed the *OpenEarable* PCB in an ear-hook form factor which makes it easy to attach the device to the ear. In addition, the shape of the PCB creates sufficient space to place all components behind the ear comfortably as this location was found to be most acceptable to place rigid components [8]. The PCB is 1.6 mm thick and is designed so that all surface mount device (SMD) components are on the top side only which simplifies assembly and makes it possible to have the components placed and soldered by a self-service PCB assembly manufacturer. Two holes in the PCB are designed specifically to let air and sound pass to the pressure sensor and ultrasonic microphone. In addition, the PCB has four holes for zip ties that hold the battery in place, and one large hole for the speaker. The design files of the PCB are open-source and released under a CC-BY license.

3.1.2 Microcontroller Unit. The microcontroller unit (MCU) of *OpenEarable* is a u-blox NINA-B306-00B module (NINA-B306-01B also compatible) which is based on the nRF52840 Bluetooth Low Energy (BLE) 5.2 system on chip (SoC). *OpenEarable* makes use of the Inter-Integrated Circuit (I2C) interface to communicate with the pressure and temperature sensor as well as accelerometer and gyroscope. The digital pulse density modulation (PDM) interface is used to read the microphone. Programming the MCU is possible using USB Serial or via Serial Wire Debug (SWD) on the backside of the PCB (e.g., to initially flash the USB Device Firmware Upgrade bootloader).

[3] *OpenEarable* project website - https://open-earable.teco.edu/

3.1.3 Power Architecture. In general, *OpenEarable* is intended to run from a single LiPo battery cell (*Renata ICP501230PS-03*, 135 mAh nominal capacitiy, 3.7 V nominal voltage). Charging is possible via a micro USB port with electrostatic discharge protection. For battery charging the board uses the *Microchip Technology MCP73831T* charging controller. As the MCU operates at 3.3V, *OpenEarable* also comes with a low dropout voltage regulator (*Texas Instruments TPS73733*). It is possible to also use the device while charging. When sampling all sensors and sending out the data via Bluetooth Low Energy a fully charged *OpenEarable* lasts roughly 10 hours which is well above the threshold for most research .

3.1.4 Ultrasonic Microphone and Speaker. An ultrasonic microphone (*Knowles SPH0641LU4H-1*) with bottom port is placed in close proximity above the speaker. By default, *OpenEarable* samples the microphone at approximately 44 kHz. The speaker inside *OpenEarable* is a standard true wireless stereo (TWS) 8 mm, 16 Ohm resistance earbud component that is available from many consumer electronics stores.

3.1.5 Pressure and Temperature Sensor. Pressure and temperature are measured in close proximity to the speaker and ultrasonic microphone. A hole in the PCB next to the pressure sensors redirects airflow from inside the ear canal. The pressure and temperature information are available from a single package inside the *STMicroelectronic LPS22HBTR* pressure sensor. The sensor can be configured to sample from 1 up to 75 Hz in an absolute pressure range of 260 to 1260 hPa. The temperature sensor supports a similar sampling rate range and has an absolute accuracy of ±1.5 °C.

3.1.6 Accelerometer and Gyroscope. OpenEarable has a 6-axis IMU (*STMicroelectronics LSM6DSRTR*) compromising of a 3-axis digital accelerometer and 3-axis digital gyroscope. Linear acceleration measurement range and angular measurement range can both be configured. By default, *OpenEarable* uses ±4 g linear acceleration range and ±500 dps angular rotation range. In theory, *OpenEarable* supports 1 Hz up to 6667 Hz accelerometer and gyroscope data. Limited by BLE bandwidth, *OpenEarable* currently reliably supports up to 104 Hz.

3.1.7 Light Emitting Diodes. OpenEarable features two LEDs for basic output. One static LED indicates the charging status when the

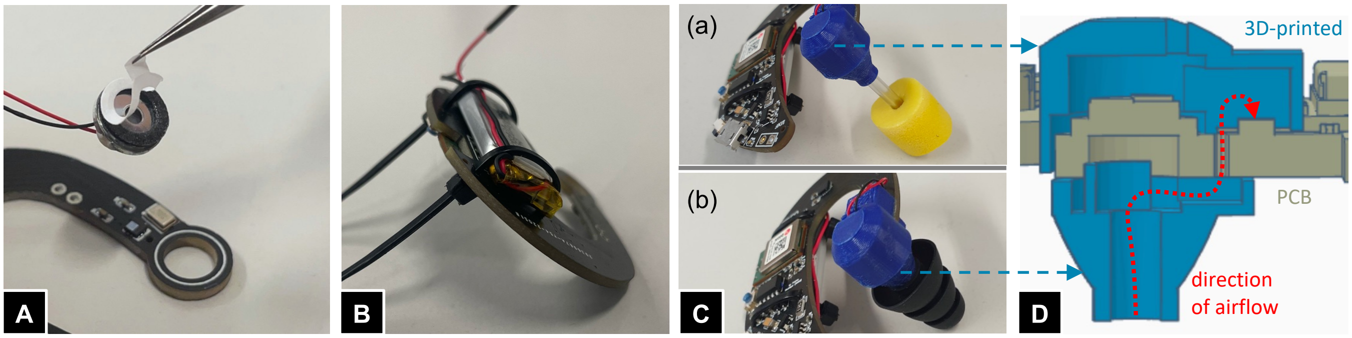


Figure 3: (A) Removing protective layer from adhesive foam of the speaker to glue it on the PCB; (B) Attaching the battery with zip ties through holes in the PCB; (C) 3D-printed shell of the earplug in two different configurations; (D) cross-section view of the earpiece illustrating the redirection of airflow and sound.

micro USB cable is plugged in (on: charging, off: fully charged or not charging). The second LED can be turned on and off or controlled in brightness using pulse-width modulation (PWM).

3.1.8 Push Button. A push button on the lower backside of *OpenEarable* can be used for simple, binary input. Another push button next to the MCU serves as reset button and can be used to enter the device firmware updates mode of the microcontroller by double pressing the button.

3.2 Mechanical Design and Assembly

The *OpenEarable* PCB is an integral part of the design as it functions as earhook. The assembly of the PCB was done by a contract manufacturer, see subsection 3.3. The parts that have to be self-assembled are described below.

3.2.1 Speaker and Battery. The speaker is an adhesive foam ring pre-installed so it can be glued onto the PCB while also sealing off the speaker (see Figure 3 A). The battery is attached onto open earable using 2 mm wide zip ties (see Figure 3 B).

3.2.2 Earplug. The *OpenEarable* earplug consists of two 3D-printed parts which are glued together and sealed off with PLA-friendly glue (Pattex instant glue). The front part sits above the speaker and the PCB through-hole and seals it of. Either, a foam type sealing earplug with plastic tube (*Etymotic Research* disposable eartip ER1-14A, 13mm diameter, see Figure 3 C (a)) to maximise ear canal sealing, or a triple flange conical silicone standard eartip can be put on the earplug (see Figure 3 C (b)). The backside separates the speaker cables and pressure sensor as well as microphone. Together, the 3D printed parts ensure that the ear canal is sealed for pressure sensing.

3.3 Production and Costs

OpenEarable was designed with the JLCPCB [4] parts library in mind. Therefore, almost all components are available as standard self-service SMD parts assembly order. The MCU and microphone have to be ordered specifically for assembly which, from our experience with JLCPCB, can two weeks lead time (depending on supplier availability) following which PCB manufacturing and assembly require an additional working week. For the 3D-printed parts we used an *Ultimaker 3*, however, there are also many inexpensive online 3D-printing services available that could be used to manufacture the earpiece plastic parts made-to-order.

The total costs excluding shipping for ten *OpenEarable* is roughly \$400 (≈ \$40 per device). The costs per device are split as follows: \$0.50 PCB, \$36.50 electric components, \$0.10 zip ties, \$4.10 foam earpieces (incl. 4 replacements), and \$0.10 3D-printed parts. One-sided PCB assembly is free of charge.

4 SOFTWARE

All *OpenEarable* software is open-source and available on the project website under the MIT license.

4.1 Firmware

The *OpenEarable* firmware is implemented in C++ using the Arduino framework based on the implementation of the *Arduino Nano 33 Bluetooth Low Energy (BLE) Sense*. This makes it easily possible for others to change the firmware running on the device. The firmware reads out all sensors and makes them available via BLE. Due to bandwidth limitations, at least BLE 4.2 has to be supported by the device connecting to *OpenEarable*.

4.1.1 Generic Attribute Profile Specification. OpenEarable's main interface for data transfer is a custom-defined Generic ATTribute Profile (GATT). Based on the profile, various functionalities of the earable can be controlled as well as sensors can be configured and read out. Table 1 gives an overview of the GATT specification for *OpenEarable* for regular data recording, as well as for recording and sending audio data. The sensor service is responsible for enabling sensors, configuring sampling rates and sending out sensor data. Using the device info service, a unique name and the device generation can be read out. The dedicated audio service sends out bursts of audio samples of roughly 1 second duration sampled at 62.5 kHz. At the moment, continuous audio streaming is not supported, however this is a software limitation that will be fixed in a future iteration (see subsection 5.4).

[4] JLCPCB - https://jlcpcb.com/

Table 1: BLE GATT profile services and characteristics overview of *OpenEarable*. A detailed documentation including UUIDs of the BLE API can be found on the project's website. The specification follows the schema for usage with edge-ml.org.

Service	Characteristic	Read / Write / Notify	Description
sensorService	sensorDataCharacteristic	Read / Notify	timestamped data of the different sensors
	sensorConfigCharacteristic	Write	enable sensors and configure sampling rate
deviceInfoService	deviceIdentifierCharacteristic	Read	unique identifier name of the device
	deviceGenerationCharacteristic	Read	generation of the device
audioService	audioCharacteristic	Read / Notify	burst chunks of ultrasonic audio data
	packageInfoCharacteristic	Read / Notify	info about total package amount and sending state

4.2 Recording Tool

Two options are available to record data with *OpenEarable*, a custom-built dashboard and an open-source and browser-based toolchain for machine learning on microcontrollers.

4.2.1 OpenEarable Dashboard. To make it easy to get started with recording sensor data, we have developed a dedicated dashboard for *OpenEarable* (see Figure 4). Users can connect to the device via their browser, configure sampling rates, enable sensor streams and record as well as export sensor data as CSV files.

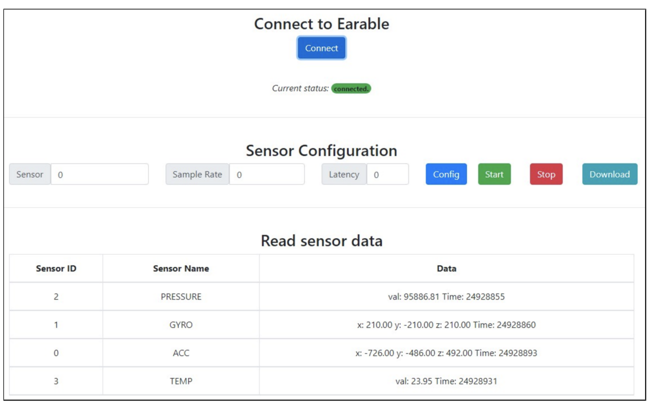


Figure 4: *OpenEarable* dashboard that lets users configure sampling rates, enable sensors, and record data via WebBLE.

4.2.2 edge-ml. Out of the box, the *OpenEarable* firmware supports edge-ml[5], which is an open-source and browser-based toolchain for machine learning on microcontrollers. It offers recording, dataset management and labeling features. Using the default firmware installed on *OpenEarable*, users can simply connect to the device via WebBLE in their browser via edge-ml. In addition to data collection and labeling, it is also possible to train, validate, and export embedded machine learning models for *OpenEarable* using the edge-ml toolchain.

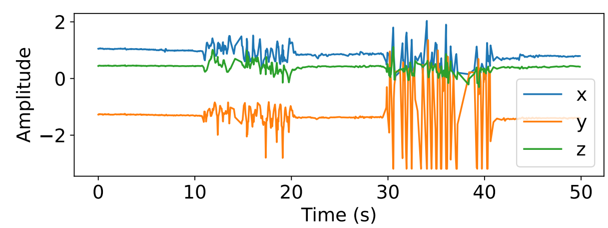
5 APPLICATION EXAMPLES

To gain an understanding that the *OpenEarable* platform is outputting valid data we used three example application scenarios from the earable literature.

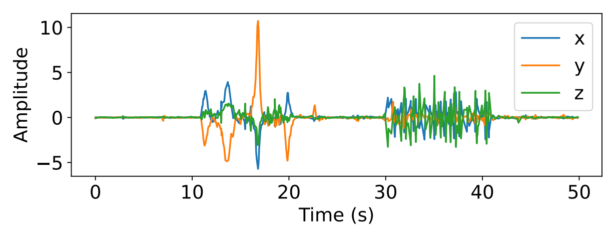
[5] edge-ml - https://edge-ml.org

5.1 Motion Tracking

Measuring motion on the ear is a common application in the earable space which can be used for a number of applications [6]. Figure 6 shows accelerometer and gyroscope readings for a test in which we recorded data from a single subject performing a sequence of three activities: (1) standing still, (2) walking, and (3) jumping jacks. We chose these activities to elicit distinct patterns, and the jumping jacks allow us to validate the mechanical stability of the *OpenEarable* during vigorous motion. The activities were performed for 10 seconds in the following sequential order: stand, walk, stand, jumping jacks, and stand.



(a) Data obtained with the integrated accelerometer.

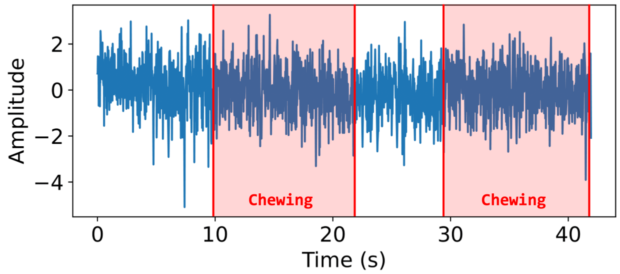


(b) Data obtained with the integrated gyroscope.

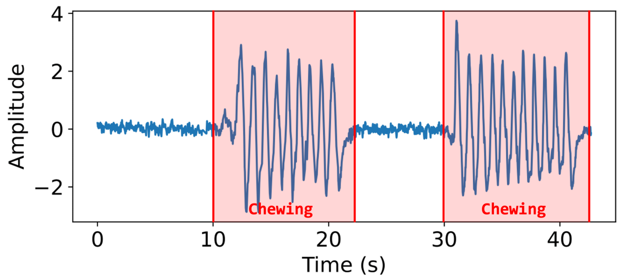
Figure 5: Motion activities recorded with *OpenEarable*. The following events can be seen in chronological order: Standing still, walking, standing still, jumping jacks and standing still. The data was z-normalized before plotting.

5.2 Ear Canal Pressure

A popular ear canal pressure application is the detection of jaw motions [1]. Figure 6a shows two sequences of chewing activities, with a break in-between. The importance of an air tight ear canal can be seen with the chewing events clearly visible when using the sealed ear buds. The distinct pressure signal demonstrates the feasibility of in-ear barometry using the *OpenEarable* platform.



(a) No sealing is applied to the earpiece of *OpenEarable*.



(b) Sealing is applied to the earpiece of *OpenEarable* so that the pressure sensor is air tight with the ear canal.

Figure 6: A sequence of ear canal pressure changes including chewing and not chewing with (a) a triple flange conical silicone standard eartip, and (b) *Etymotic Research* disposable eartip ER1-14A. The data was z-normalized before plotting.

5.3 Ear Canal Sound Reflections

It is possible for the ultrasonic microphone to pick up an inaudible signal from the speaker. This information can be used to understand the shape of the ear canal because the sound is reflected differently depending on the shape, a principle which can be used for authentication [9]. While more detailed evaluations are necessary to assess generalized authentication performance based on *OpenEarable*, Figure 7 shows the spectogram of a 18kHz tone played in the ear canal for 1 second.

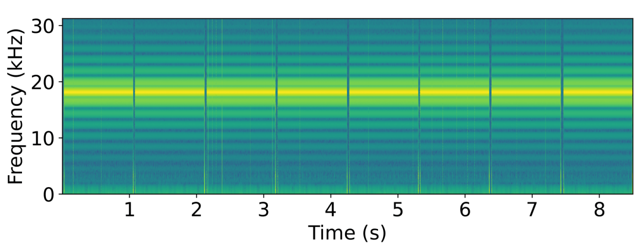


Figure 7: Spectrogram of a reflected ultrasonic signal which was emitted into the ear canal with multiple 1s long probings.

5.4 Future Work

As this is the first version of *OpenEarable*, there are a number of limitations with the prototype and improvements to be made. The current 6-axis IMU was selected due to stock limitations, and future versions will feature a 9-axis IMU with magnetometer. The earable is currently designed to be worn on the right ear only and can not be paired with a second device. So far, there are no libraries available for recording data from the *OpenEarable* platform on either Android or iOS devices which is a high priority item considering popular use cases of earable devices. While transferring a continuous audio signal over BLE is technically feasible, it is not yet implemented in the current *OpenEarable* firmware and the speaker only supports playback of a constant frequency. The Bluetooth classic advanced audio distribution profile (A2DP) is not yet supported. The standard ArduinoBLE library with current configuration achieved a transmission rates of 6.5 kB/s for the audio signal, we intend to use the NimBLE library, however, just recently support for the nRF52840 was added and compatibility with the bootloader of *OpenEarable* is pending but under active development. *OpenEarable* does not support reading out the battery level

6 CONCLUSION

OpenEarable is the first-if-its-kind open hardware initiative for earable research. In this paper we introduce a new device that features a series of sensors and actuators: a 3-axis accelerometer and gyroscope, an ear canal pressure and temperature sensor, an inward facing ultrasonic microphone as well as a speaker, a push button, and a controllable LED. We have shown the validity of the hardware based on three example application scenarios. Regarding the future development of *OpenEarable*, we are looking for feedback from the community and hope to bring parties together that are interested in pushing the platform further as a joint research effort. To stay up-to-date about the latest developments around *OpenEarable* we ask readers to refer to our project's website.

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