Toward Reproducible XR Research: A Modular Head Worn Sensing Platform

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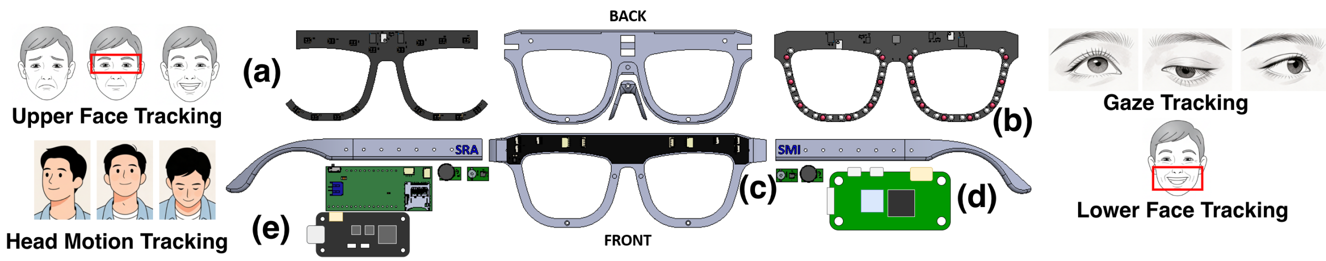

Figure 1: A layout of a modular platform designed for XR sensing research, showing the core mechanics such as the microcontroller interface board, interconnect board, and daughter cards with the data that can be captured. (a) A photointerrupter-based upper facial expression detection solution. (b) A phototransistor-based gaze tracking solution. (c) An audio-based lower facial expression detection solution. (d) A Raspberry Pi-based camera solution for world-facing ground truth data. (e) Inertial Measurement Unit (IMU) data for head motion detection. The application example images are AI-generated.

Abstract

As wearable devices become more prevalent, research into various sensors and their applications on wearables will increase. One such wearable gaining popularity are glasses with prototypes coming in many forms. On one end, there are manually assembled prototypes which offer speed and flexibility, but lack robustness and reproducibility. On the other end, there are polished development platforms that are robust, but are expensive and lack the high degree of flexibility needed for different avenues of exploration. This paper presents the design of a modular hardware platform that serves as a middle ground to fill the gap in the prototyping landscape of head-worn sensing. We describe the system's design with examples of engineering choices made for a research-specific configuration. We demonstrate the platform's flexibility by the implementations and initial feasibility results of use cases, such as head, gaze, and facial expression tracking via daughter cards. Overall, we present an affordable, modular, and robust prototype for head based sensing research that delivers robust construction and reproducible results.

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CCS Concepts

• **Hardware**; • **Human-centered computing** → **Mobile devices**; • **Computer systems organization** → **Embedded and cyber-physical systems**;

Keywords

Modular Hardware Platform, Sensing, Rapid Prototyping, Extended Reality (XR), Augmented Reality (AR), Eye Tracking, Face Tracking

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1 Introduction

Extended reality (XR) has the potential to become the next large consumer electronics market as technological advances enable greater feature integration, but it is still very much in its infancy. Unlike the smartphone market, where architectures have largely matured with the ubiquitous slab design, there is no standard architecture or framework for head-mounted devices (HMDs). Apart from a few core features like WiFi, devices released have largely unique configurations or niche applications [9]. Researchers in industry and academia are actively developing use cases and refining features to produce a device that the general populace will adopt, but the landscape and approach for such development are highly varied.

Even with recent increased interest in developing such devices, research involving hardware often has lengthy turnaround times and higher up-front costs due to the expense of building a physical device. Researchers often need to prototype quickly to test an idea which can lead to implementations that are hard to replicate and not robust enough for multi-user studies. Developing a longer-term use device for such studies can often mean a significant allocation of time and money for the researchers involved. In this paper, we aim to demonstrate how our modular architecture can help researchers develop robust prototypes without incurring excessive costs that also allow for easier to reproduce results.

Manufacturing pipelines and options have matured significantly over the last decade, driven by the rise of 3D printing and readily accessible printed circuit board manufacturing. In this paper, we demonstrate how to leverage these low-cost engineering resources to build a modular platform that enables a wide range of research on head-worn sensing. We use established, accessible manufacturing processes and demonstrate that a modular platform fills a gap in the prototyping landscape for head-worn sensing research. The contributions of this work are as follows:

(1) We present a mechanical and electrical framework that enables modularity of sensors, and repeatable construction. We discuss the trade-offs of this solution, and how it can be used to flexibly build repeatable experimental setups at a reasonable cost while retaining the comfort needed for longer user studies.
(2) We demonstrate the modularity of the hardware platform by implementing three sensing designs for XR use cases (gaze, face, head tracking) via interchangeable daughter cards as examples of what can be done with this architecture.
(3) We open sourced the core hardware design files for others to more quickly build upon this platform design [1].

2 Related Work

There is a wide variety of XR-related research devices that integrate sensors to implement features needed for an XR experience. These research devices are typically either an academic prototype designed to address a specific research topic or a fully integrated development kit that feel similar to a real product. There currently lacks an architecture that fills the prototyping gap, enabling robust build quality along with experimental flexibility, which we aim to address in this paper.

Several academic articles involve building glass form factor prototypes as different implementations of gaze [13][11][8][17][22][14], or face tracking [15][12] using sensors that include audio, optical, radio, etc. Prototypes are usually designed around a specific sensing paradigm to implement their respective solutions, but it can be difficult to replicate experiments reliably, which limits generalization across a physically diverse population.

Form-factor integrated development kits for XR research enable higher-quality data collection than academic prototypes, as they are more analogous to consumer devices and provide greater comfort, allowing for longer user studies. Examples of development kits include Meta's Project Aria [6], Microsoft's HoloLens 2 [26], and Qualcomm's Snapdragon AR2 reference design [20], among others. These are all polished systems that enable high-quality data collection, but they are limited to the specific sensors and spatial configurations included in these devices.

Research-oriented ecosystems such as those provided by Tobii [25] and Pupil Labs [19] for eye tracking, Optitrack [16] and Polhemus [18] for motion tracking, or Emteq Labs [10] for face tracking can be incredibly accurate and useful for a specific research domain. These are typically expensive, costing tens of thousands of dollars, and the software stacks are tuned for the specific hardware that those companies have built. Deviating from them or requesting changes is often possible, but typically comes with additional costs for custom work.

This paper presents our work to bridge gaps in this prototyping space by providing a modular framework - shown in Figure 1 - that enables quick, flexible experimentation while allowing for repeatable, robust construction at costs that most research groups can easily afford. Our contribution is similar to other work showcasing platforms and frameworks for applications such as modular wireless sensing [4][28][2], E-Textile sensing [24], and wearable haptics [23]. We go on to demonstrate how a single platform prototype designed around head-worn sensing can be easily applied to different head-worn sensing scenarios such as gaze, face, and head tracking that are critical use cases for XR devices, enabling rapid prototyping at reasonable costs.

3 Modular Sensing Platform

Developing an XR product often involves multiple prototype iterations, including testing different sensor types and configurations to implement features such as head or gaze tracking. This can be very resource-intensive when different researchers test different solutions, since prototypes are often built around a single hypothesis or premise. By developing a modular base, a consistent platform is provided for quickly developing prototypes and conducting one-to-one comparisons of results.

For this XR modular architecture, the device was designed in three sections: the front of the frames and the two leg pieces that fit the temples. Each of these sections can be thought of as an individual design space, connected to the others. To maximize sensor flexibility and balance the convenience of prototyping, we chose the architecture shown in Figure 2.

At its core, the base platform consists of a microcontroller interface that breaks out the connectors from an off-the-shelf microcontroller development board, a system interconnect board that

[1] http://github.com/SamsungLabs/ModularSensingPrototype

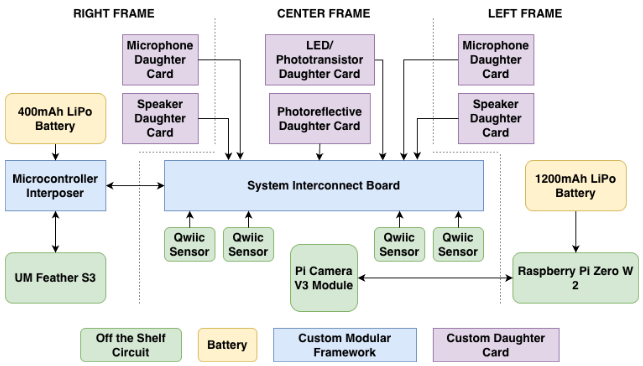

Figure 2: An architectural block diagram showing the framework integrating off-the-shelf (green, yellow) and custom-designed (purple) hardware. The modular framework in blue, along with the mechanical frames, are the core components of this platform, with the other parts being interchangeable per use case.

houses the majority of the interfacing connectors, and a mechanical frame design that supports repeatable physical mounting. The other daughter cards are designed around the specific sensor configuration under test. Total cost for building a single base unit of the XR platform without any of the daughter cards was less than 150 USD.

3.1 Microcontroller Interface Board

This is the most important component in the base platform as it ties the chosen microcontroller to the rest of the system. The interface board to the ESP32-S3 Feather enhances the development board by extending the interfaces and adding additional features including:

- A micro Secure Digital (microSD) card for long data collection sessions.
- An Inter-Integrated Circuit (I2C) buffer to compensate for the capacitance on the bus due to the wiring and connections.
- Operational Amplifier (Op Amp) buffers for the analog signals so that the Analog to Digital Converter (ADC) has a low impedance source.
- A BNO085 IMU.
- A battery connector that allows us to turn the power on and off. A 400mAh Lithium Polymer (LiPo) battery can fit between the two boards for a more compact design.
- Additional Qwiic/Stemma QT connectors that can be connected to the second I2C bus, allowing for more sensors.

By using the Feather form factor, we can theoretically use a different microcontroller, as many of the pins are common for Feather-based boards, such as power, GND, and I2C. However, not all devices have the internal routing matrix that the ESP32 does, so some peripherals may not be directly compatible.

3.2 Interconnect Board

The interconnect board shown in Figure 3 serves as the primary interface for all sensors. For the XR sensing platform, the interconnect board features 4x Qwiic/Stemma QT connectors, 6x 5-pin FFC connectors for Inter-IC Sound (I2S) devices (4x mic, 2x speaker), and 2x 10-pin headers. This allows support of a myriad of sensor configurations. In most experiments, we use only one or two connectors at a time, so depending on the research direction, this design can be greatly simplified.

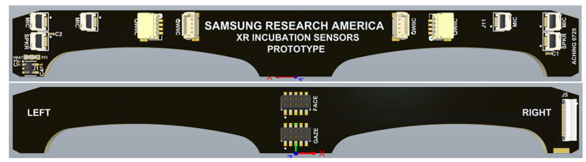

Figure 3: The front and back sides of the interconnect board showing the available connectors.

Designing custom daughter cards or purchasing off-the-shelf breakout boards is at the heart of this modular system. Having a robust framework as a form factor base allows quick integration of existing sensors without wasting time designing an entire system from the ground up, which can be resource-intensive. To implement multichannel sensing schemes that required more than 10-pin connectors, I2C general-purpose input/output (GPIO) expanders were used on the daughtercards, which then controlled analog switches.

3.3 Mechanical Design

The mechanical design of our modular sensing platform facilitates the fast integration of different sensor configurations, enable easy fabrication, and allow for the development of repeatable configurations. In this section, we describe the mechanical design decisions of this platform.

3D-printed frames provide sufficient structural integrity to withstand most use cases and are very lightweight. To enable mounting, heat-set threaded inserts are used to allow high-strength mounting flush with the frames. We used hinges you can buy online as replacements for damaged glasses, screwing them down with M1.2 screws and appropriately placed inserts, as shown in Figure 4.

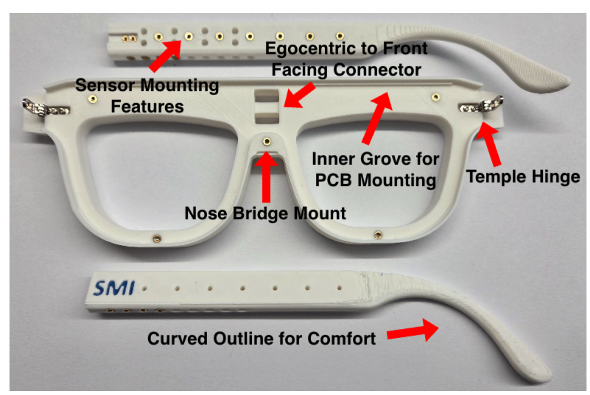

Figure 4: The 3D printed front and temple frames with hinges and heat-set threaded inserts installed.

To optimize 3D printing and avoid supports, the front frames are split into two halves: a world-facing and a user-facing half. These two halves are then screwed together using M1.4 screws and threaded inserts. The electronic connection between the world and the egocentric sides is made via an opening for the two 2x5-pin connectors, allowing flexible connectivity to different daughter cards, as shown later in this paper.

The world-facing side has an indented area for the interconnect board, which also houses all the connectors. By placing the connectors on the world-facing side, we do not interfere with the user's field of view through the glasses or the comfort by crowding the space near the eye box with electronics. The egocentric half of the glasses likewise houses an indented area for a daughter card. It also has a nose-bridge mounting screw enabling different nose bridge sizes for comfort while maintaining the same sensor configuration across users.

The temples are modeled after a generic glasses temple for a comfortable fit. This design allows the prototype to easily accommodate different head sizes by just changing the length of the straight sections and printing a new temple. Holes to add M1.4 heat-set threaded inserts were added throughout the temples in a grid to allow for screw-in mounting of additions at different locations.

4 Research Use Case Experiments

The modular framework prototype allowed us to test multiple different research concepts and robustly reproduce research papers [13][15][12] by making daughter cards that attached to our framework. Arduino [1], and ESP-IDF [7] were used for much of the prototyping, with existing libraries enabling quick implementation of sensor streams, allowing more time to focus on signal processing and algorithms development for the desired use cases. The design files and early experimental data for these can be found on our open source repository. [21]

4.1 Gaze Tracking Experiments

Gaze tracking in XR applications is important as it allows the operating system to infer what a user is looking at. This could be in the context of a virtual display or a real-world setting. To perform gaze-tracking experiments, a daughter card shown in Figure 5 was designed with an LED and phototransistors, built upon previous work [13]. Unlike previous work, our emitter/detector pairs are angled towards the approximate center of the eye to maximize signal, using a mechanically designed jig to position the components before final assembly.

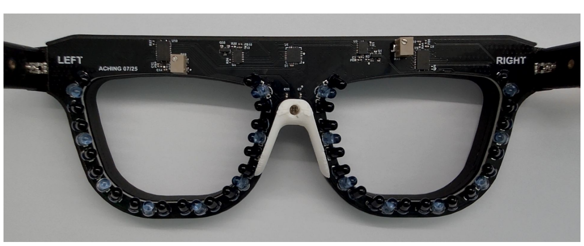

Figure 5: The gaze tracking daughtercard. It contains a pattern of sixteen LEDs and eight phototransistors per eye, allowing us to sense changes in eye position.

We configured a ring of infrared LEDs and phototransistors on a daughter card, allowing us to observe changes in reflected light from the eyes as the user changes gaze. Each LED and phototransistor is controlled via a multiplexer and an analog switch, respectively, allowing us to control everything using just a few pins on our microcontroller via time multiplexing. We buffer the readings from the operational amplifier into the ESP32's built-in ADC, with each eye using a separate ADC. The analog readings are collected by turning on one LED and sequentially gathering sensor readings from each of the 16 phototransistors in rapid succession. We repeat this for each LED, as we collect the left and right eye data simultaneously. The data is stored in a buffer before transmission to minimize the temporal lag between the start and end of each sweep.

Preliminary data collection allowed us to quickly gain insights, such as the need for better diode sensor isolation. The modular platform allowed the team to quickly build multiple copies and test sensors with different parameters, such as lens angle, angling, and placement. After sensor tuning and experimentation, we developed a data-collection pipeline to train a gaze-tracking model.

The software pipeline allows us to collect data from a user by displaying an action, such as a blink or a point/direction to look at. We then collect the analog readings along with their labels for model training and evaluation. A calibration is done at the beginning of the data collection to zero the readings against ambient light conditions and to a front facing gaze. We collected an early dataset with multiple sessions and users, which we used to train a temporal transformer neural network (NN) to take advantage of the inherent structure in the features. The performance of the model was evaluated on data collections not used in the training. We then empirically tested high-performance models on users using live data to develop inference scripts for more real-world evaluations. You can see an example of a test run in Figure 6 as well as the results of the evaluation in Figure 7. Evaluating on this initial dataset yielded accuracies of over 90% for both the gaze and blinking models. The raw data from some of the users, the model, and the inference code is on our repository.

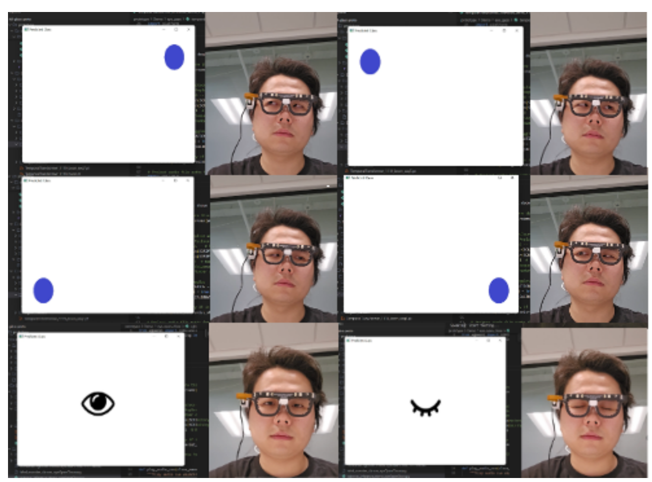

Figure 6: An example of the trained model detecting the gaze direction and blinking of a researcher looking to the upper right, upper left, lower right, and lower left. The gaze is displayed on the screen as a blue circle.

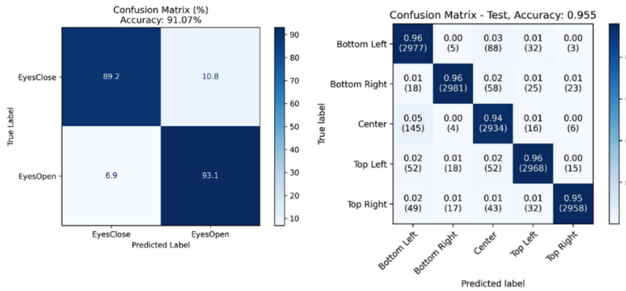

Figure 7: The confusion matrix for the gaze direction and blinking models.

4.2 Facial Expression Sensing Experiments

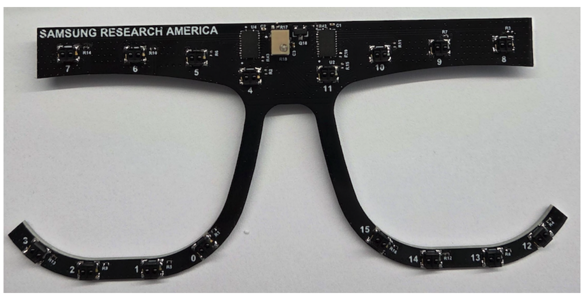

Figure 8: The photointerrupter daughter card designed to plug into the egocentric side of the front frames to enable facial expression tracking.

Facial expression detection has many uses in XR such as avatar mapping, emotion detection [27], diet monitoring [3], and even user-controlled device input [5]. Several research papers have attempted to implement this feature using a variety of sensors including work using photoreflective sensors[15], and acoustic reflections[12]. Optical-based sensors can be highly accurate and fast; however, when mounted egocentrically on a pair of glasses, the field of view will cover only a small region of the face. Acoustic sensors are less affected by ambient conditions because the frequencies used in these applications are much higher than human-audible sounds and targeted to specific frequency bands, but need more distance to operate well. We were able to quickly prototype experiments to enable upper- (optical) and lower- (acoustic) facial tracking with the appropriate sensing modality.

The optical-based sensor daughter card uses 16x GP2S700HCP reflective photointerrupters, as shown in Figure 8 tied to a 16:1 analog switch. Each sensor is an infrared LED and phototransistor pair. These sensors are designed to detect subtle changes in light, such as for encoder wheels, but this implementation uses them to detect movements of the facial muscles as a user changes their expression. In Figure 9, we show the raw ADC readings from the phototransistor. The gain is determined by a potentiometer, allowing us to tune the signals. As the user moves their face into different expressions, the signal will change depending on how close or far the user's face has moved from the sensor. We can see, for example, that as the user changes expression between neutral and anger that the relative levels change for multiple diodes.

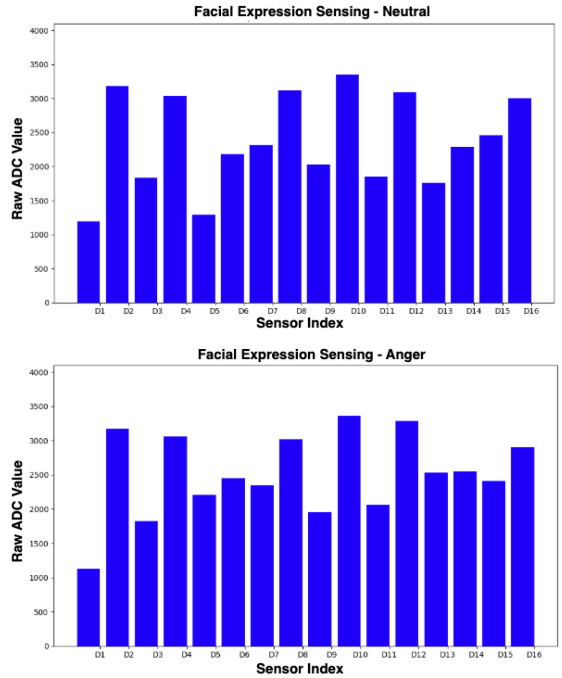

Figure 9: The raw analog data from the 16 phototransistor sensors for two expressions, neutral and anger.

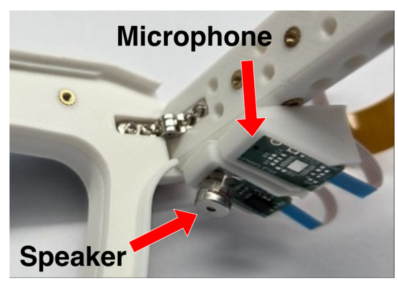

Figure 10: A custom breakout for a 16 ohm speaker driven by a class D amplifier, and an I2S digital microphone mounted to the temple frames aimed at the user's face to detect lower facial expressions.

For acoustics-based sensing of facial expressions, the frequency modulated continuous wave (FMCW) technique is used to measure changing distances as the face moves. A chirp (a signal with increasing frequency over time) is emitted from a speaker aimed at the lower face, and a digital microphone records the reflected audio signal. The sensor pair mounted on the right temple is shown in Figure 10. The emitter and sensor are angled to point toward the lower part of the face at 30 degrees when the user wears the device. The angle is fixed by the 3D-printed mount, but because of our platform's modularity, it can be easily adjusted to optimize based on experimental results.

By correlating the reflection with the emitted signal, a feature map of different facial expressions can be generated. In order to validate that our setup was receiving sensor signals, we plotted the preliminary test data in Figure 11 with the recorded reflection from the microphone along with the spectrogram representation of that signal in real-time. The spectrogram of this signal is in Figure 11 and shows that the most intense frequency increases linearly over time, which is characteristic of the chirps emitted by the speaker. For these early experiments, we are using relatively low-frequency emitter/receiver pairs as they are readily available off-the-shelf. Commercial applications would use more customized, higher-frequency ultrasonic devices for higher resolution.

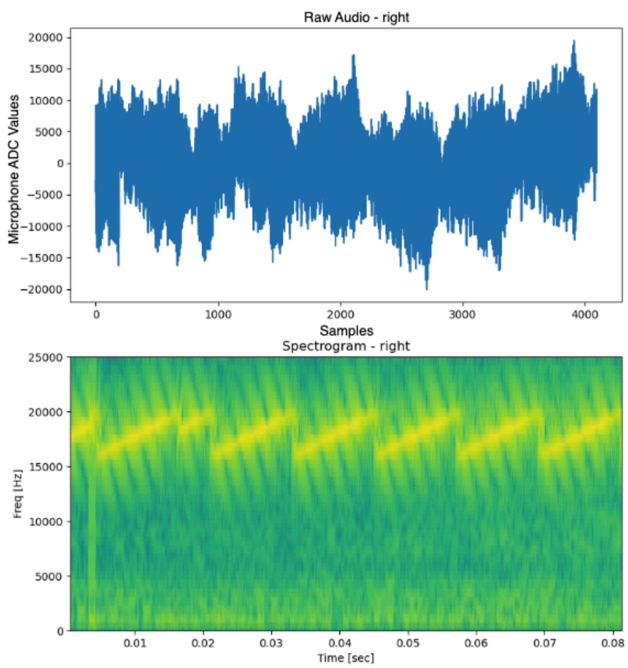

Figure 11: (Top) Raw microphone data from the right channel of a chirp from 16-20kHz. (Bottom) The resultant spectrogram shown on the bottom clearly shows the core frequency linearly increasing, following the profile of a chirp.

4.3 Head Pose Experiments

One of the most common sensors is the IMU. It is present in all XR devices because it enables high-frame-rate updates to forces, which are necessary for head tracking.

By simply swapping out the front mount, as shown in Figure 12, we can quickly add an IMU breakout board that supports the Qwiic interface, such as the Adafruit ICM-20948 breakout. Because most of these off-the-shelf breakout boards have library support, a researcher can quickly prototype use cases such as nod detection. For this example, we simply collected raw data from the IMU's nine channels, representing acceleration, angular velocity, and the local magnetic field along the X, Y, and Z axes.

As shown in Figure 13, the plots of the raw IMU data against time (represented by samples gathered) show the signals for a nod,

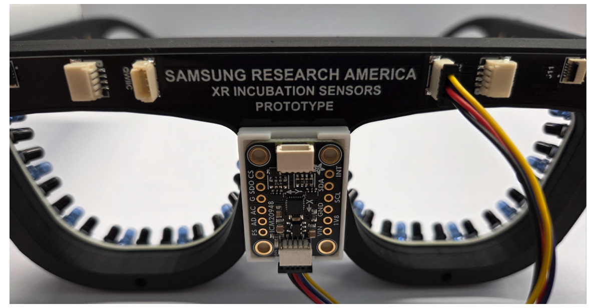

Figure 12: The ICM20948 IMU breakout board mounted to our frames.

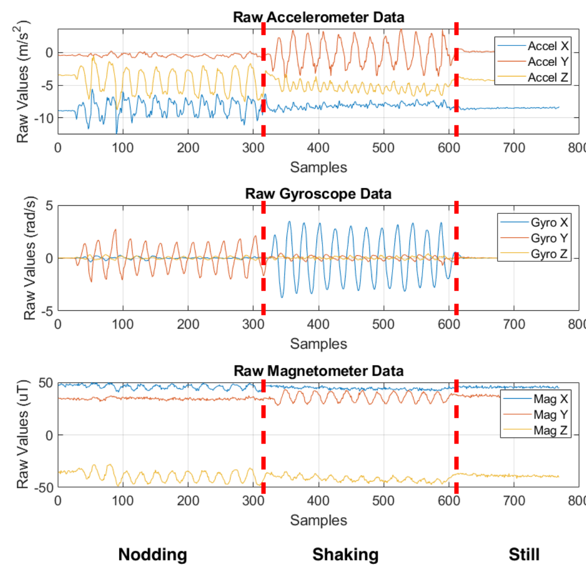

Figure 13: A plot of the raw data from an IMU when the head nods up/down, shakes left/right, and is still.

shaking left to right, and stationary. There are clear differences in the signals between these motions, which can be easily classified by a model or even by basic heuristics. While data from an IMU alone can be limiting, combining it with other sensors can yield more accurate insights by providing context to resolve ambiguities.

5 Conclusion

This paper presented a modular sensing platform aimed at enabling academic-level head-mounted sensing and XR research to be more robust, allowing the researchers and the community to better reproduce and verify results. We detailed the use of 3D printing to create a robust mechanical framework around a core ESP32-based microcontroller development board. Using this core platform as a common base, we demonstrated three use cases: gaze tracking, facial expression tracking, and head movement tracking. Overall, we showed that a modular platform can be used effectively to bridge the gap between manually assembled hardware prototypes and polished development kits for head-worn sensing research.

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