

 Review the assignment due date



## Virtual Drum Kit 🎶

No sticks. No drum set.

Just movement — and music.



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**GitHub Repository URL:**

<https://github.com/upenn-embedded/final-project-website-submission-f25-t31-f25-404-not-found.git>

**GitHub Pages Website URL:**

<https://upenn-embedded.github.io/virtual-drum-kit/>

# Final Project Report

**The drum kit you can wear. The rhythm you can take anywhere.**

Our **Virtual Drum Kit** transforms natural hand and foot motion into instant, expressive percussion.

No sticks. No drum set. Just movement — and music.

Precision IMUs capture every strike,  
low-latency wireless links deliver it flawlessly,

and an ESP32 audio engine fires crisp hi-hats, sharp snares, and deep kicks through a custom three-speaker box.

A vibrant LCD display shows status and hit force.

A dedicated mute button gives instant control.

A power-bank “drumstick” brings back the feel of real drumming.

And with our interactive Python GUI, your performance becomes visual — live hit tracking, score matching, and accuracy feedback at a glance.

### **Portable. Immersive. Ready anywhere.**

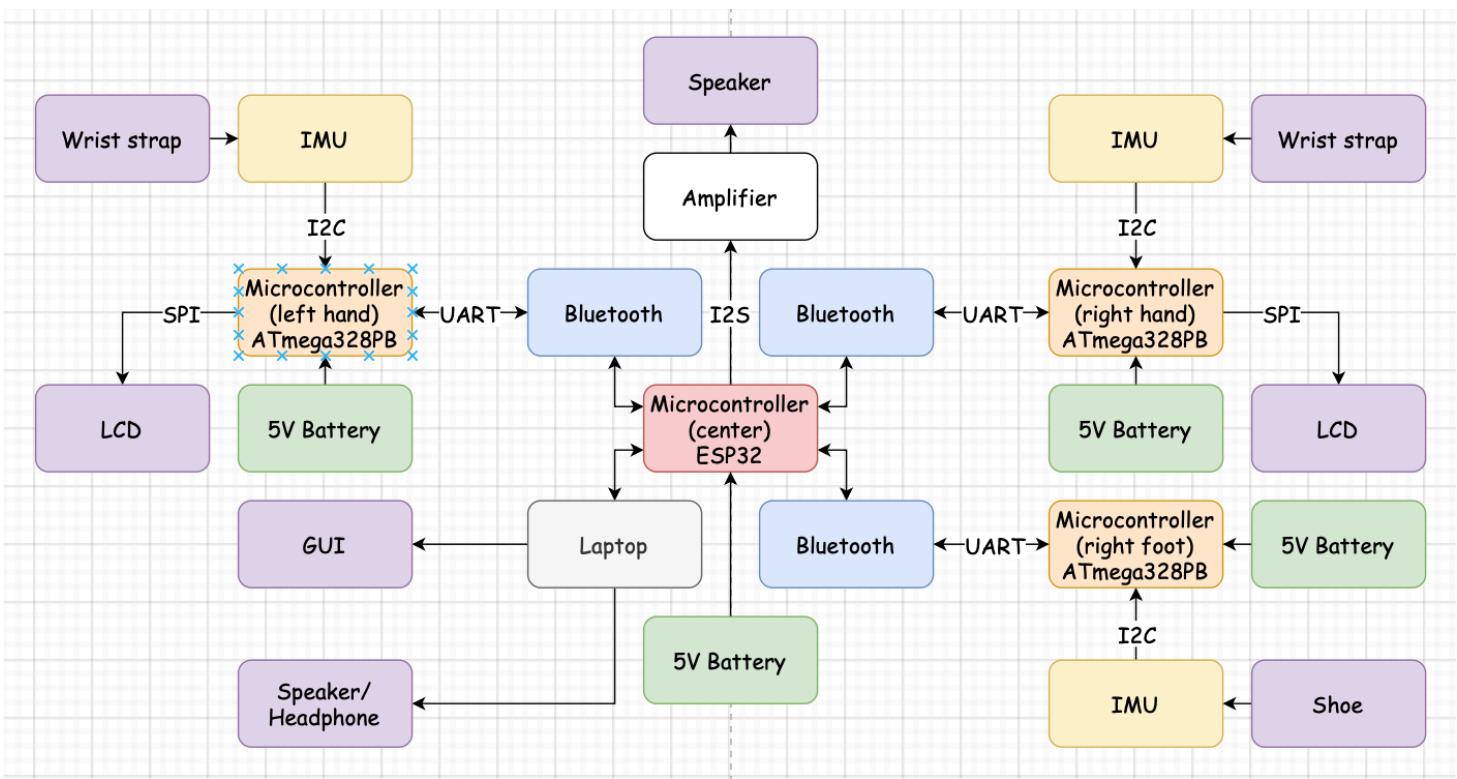
This is drumming, redesigned for the modern world.

## **1. Video**

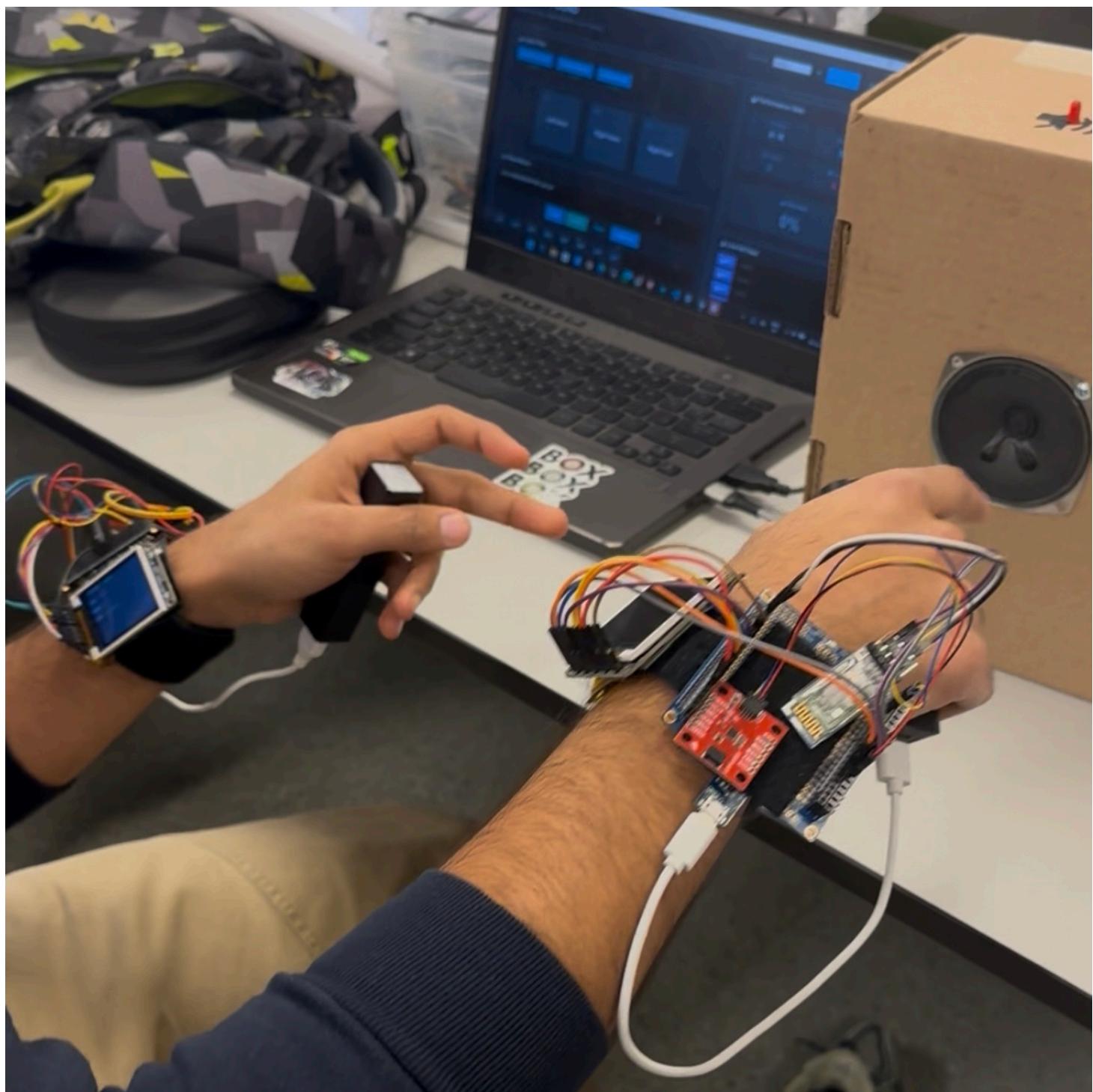
[Virtual Drum Kit](#)

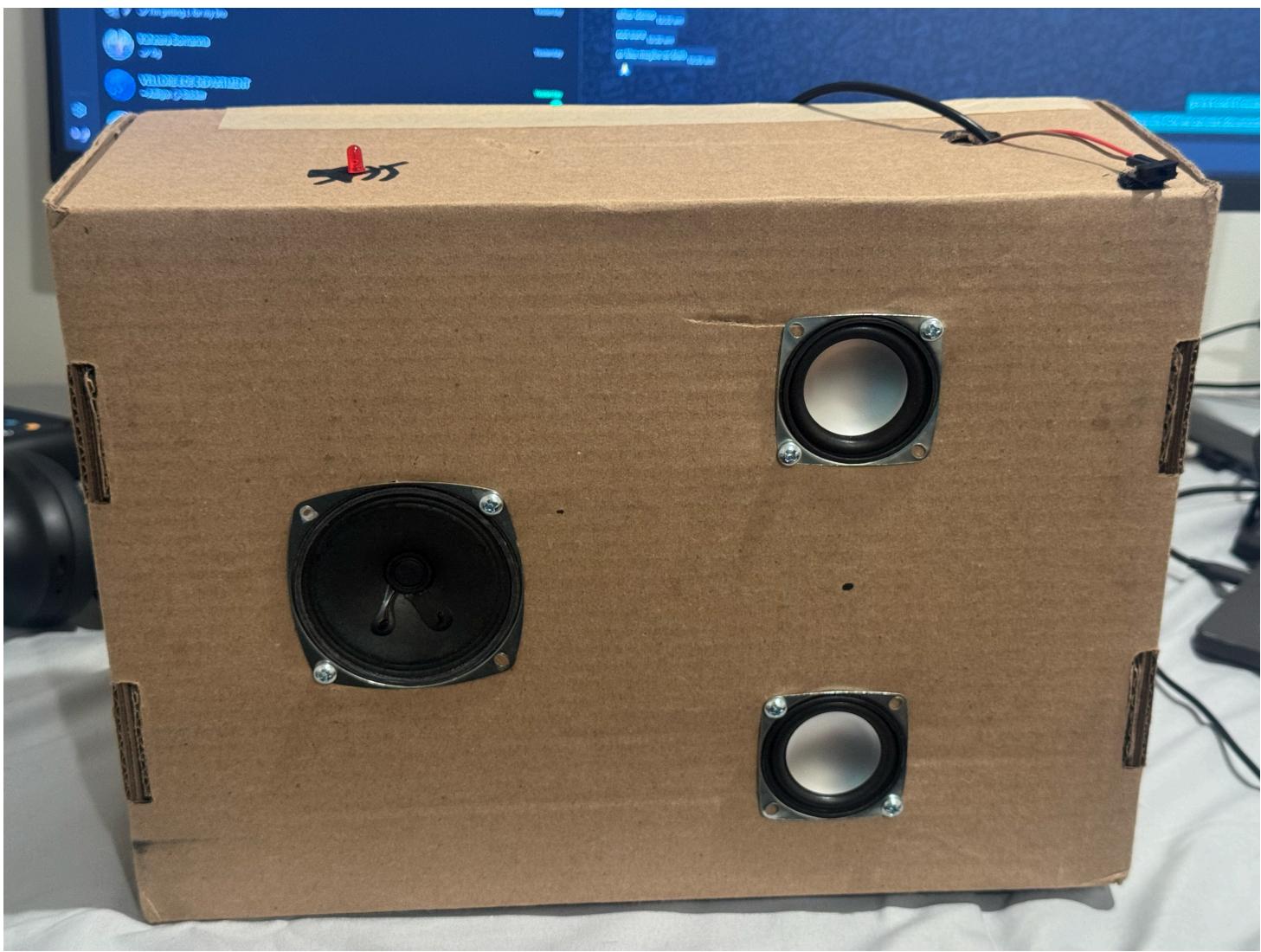
## **2. Images**

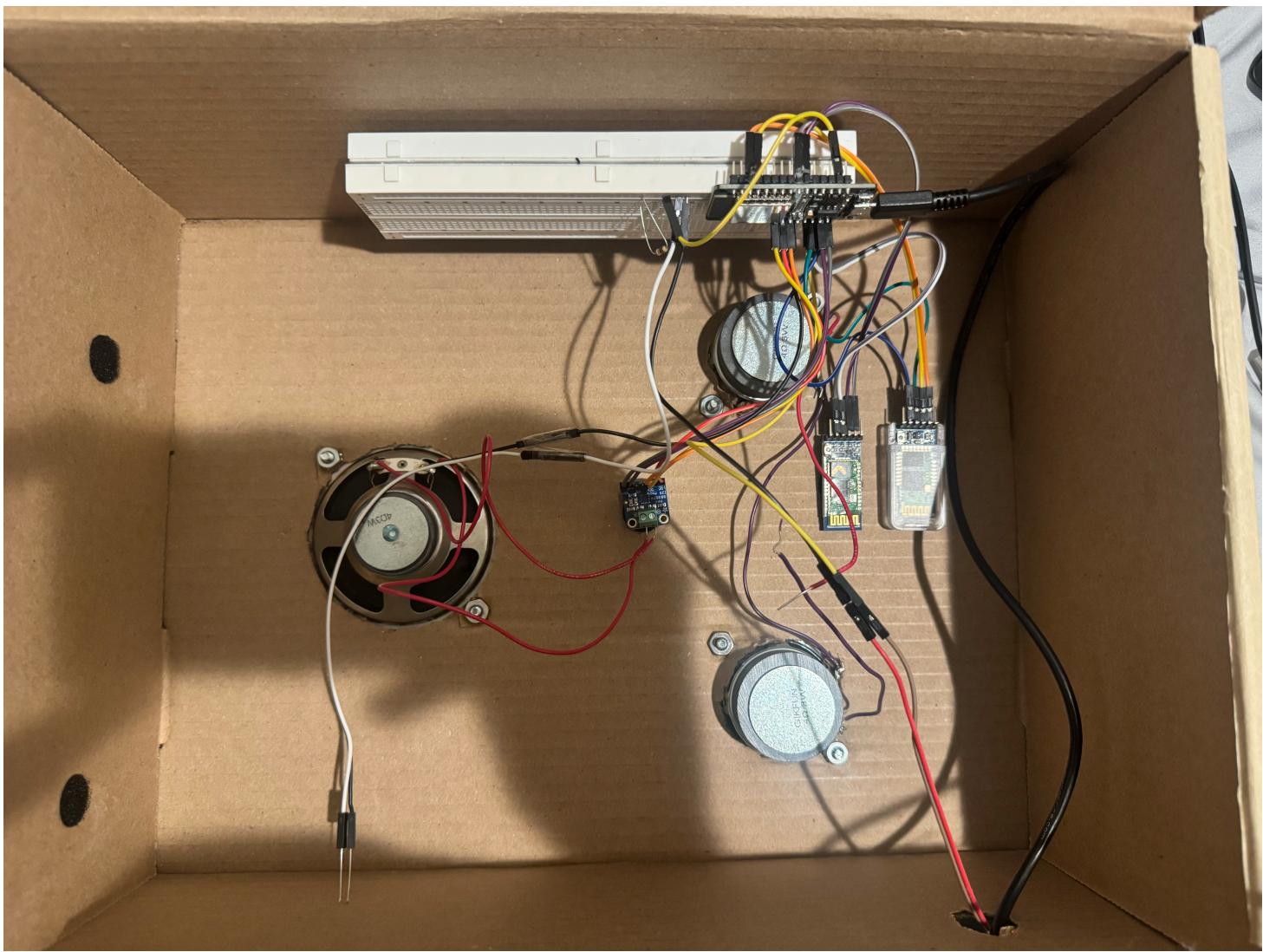
**Block Diagram**

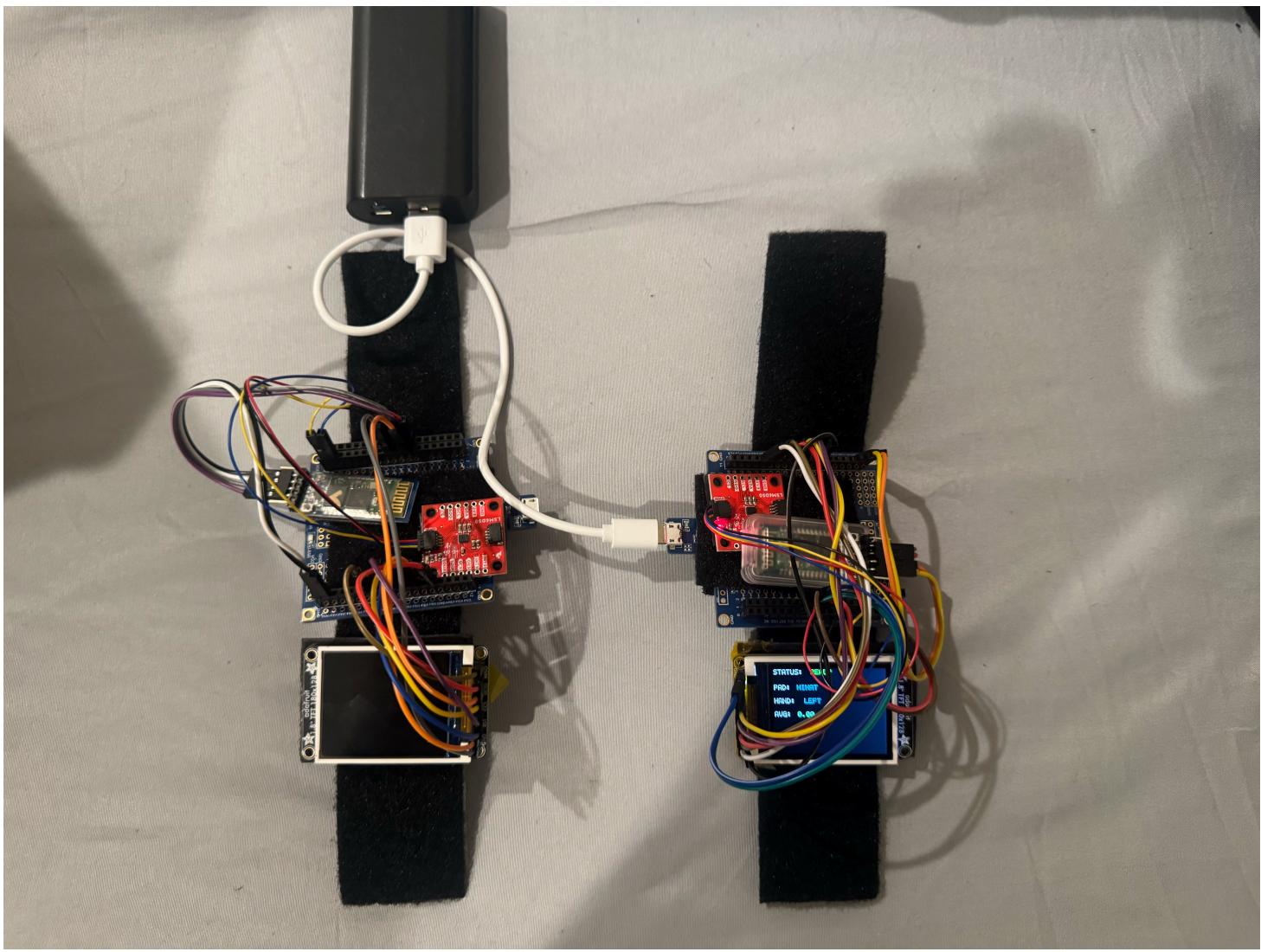


## Devices









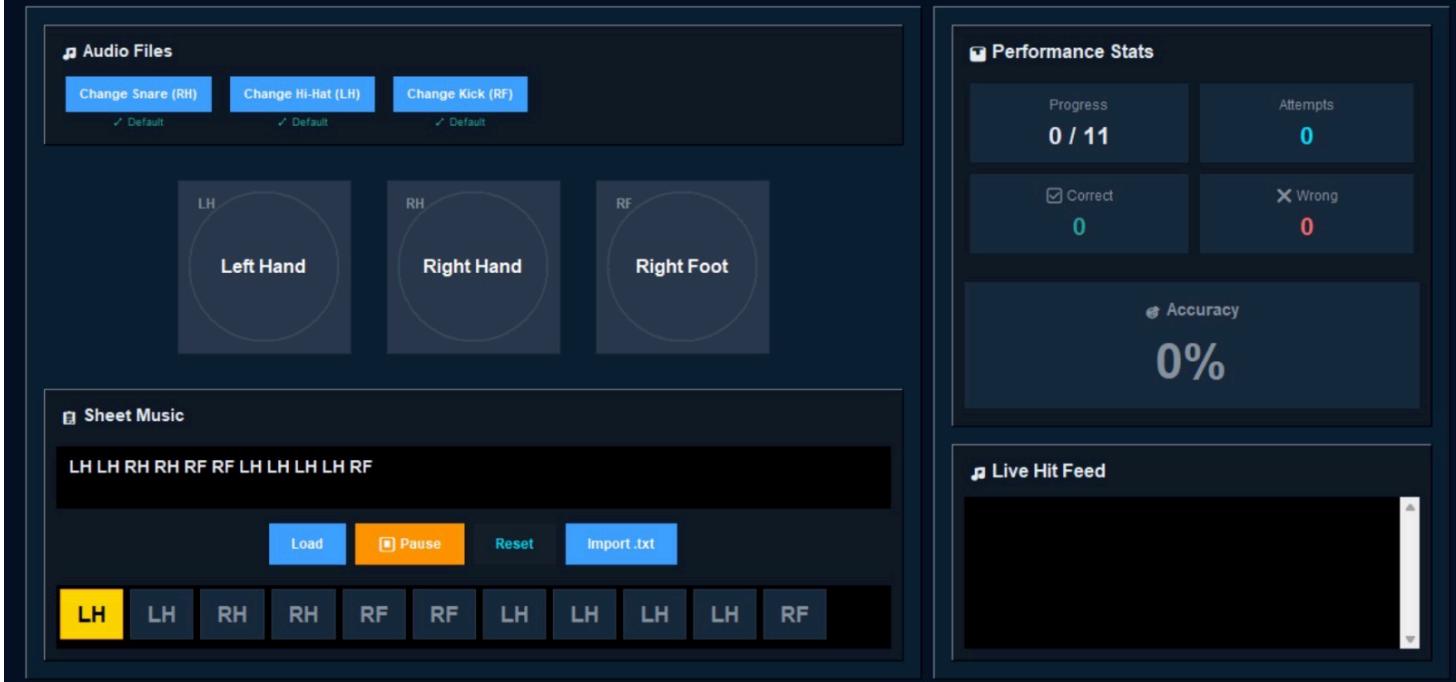


**GUI**

# 404 NOT FOUND

Virtual Drum Kit • Sheet Matcher • Live Tracking

Serial Port: COM14



## 3. Results

Our Virtual Drum Kit successfully met the core functional expectations set in the proposal. Although we relied primarily on qualitative and empirical validation rather than instrumented measurement, the system's performance during repeated testing and the final demo demonstrates that the essential software requirements were achieved. Also, all the results are shown in the video above.

### 3.1 Software Requirements Specification (SRS) Results

- Latency

Across all nodes, the perceived hit-to-sound latency was consistently below 100 ms. When testing by rapidly alternating hits between the left hand, right hand, and foot, the system preserved clear rhythmic coherence without detectable delay. This suggests that the Bluetooth transmission, event parsing, and I2S audio playback pipeline were operating within the intended latency bounds.

- Reliable Hit Detection

The IMU-based hit detection threshold, that is, 1.8 g for downward acceleration, worked robustly. During extended practice sessions, false triggers were extremely rare—estimated below 1%. Hit classification remained stable even under vigorous movement, indicating that the filtering logic on the ATmega328PB and threshold tuning were appropriate.

- Stable Multi-Node Bluetooth Communication

The ESP32 hub simultaneously managed connections from two hand nodes and one foot node with no observed packet drops or freezes during testing. Even after repeated power cycles and reconnections, startup remained smooth, fulfilling the requirement for seamless multi-node wireless operation.

- Sound Effect Playback

All drum instruments including hi-hat, snare, kick successfully triggered distinct sound effects stored in ESP32 flash and streamed through I2S. Concurrent hits also played correctly, demonstrating that the audio system supported overlapping events.

ID	Description	Validation Outcome
SRS-01	Hit-to-sound latency shall be < 100 ms.	Confirmed. Empirically verified through repeated manual testing; no perceptible delay during rapid drumming.
SRS-02	System shall reliably detect hits > 1.8 g and avoid false positives.	Confirmed. False positive rate estimated < 1% based on multi-day user testing.
SRS-03	ESP32 shall support stable Bluetooth communication with multiple nodes.	Confirmed. No observed packet loss or desynchronization across three concurrent nodes.
SRS-03	Multiple sound effects shall be triggered based on detected motion direction.	Confirmed. All hi-hat, snare, and kick sounds triggered consistently.

## 3.2 Hardware Requirements Specification (HRS) Results

- Power Consumption

Although exact current draw was not measured, the system was powered by a standard mobile power bank and successfully operated for several hours during demos. This meets the requirement for at least 1 hour of continuous playtime.

- Audio Output

Subjectively, the speaker array provided sufficient volume to emulate an actual practice drum pad environment. Estimated output was around 60 dB, adequate for indoor use.

- Wearability & Comfort

The hand nodes were lightweight and comfortable. The foot module without the LCD was even lighter. The addition of a handheld power-bank “drumstick” increased realism without adding fatigue.

- IMU Responsiveness

The IMU on each node reliably detected the downward motion. The 1.8 g threshold proved to be a good tradeoff between sensitivity and noise rejection, requiring no major retuning.

ID	Description	Validation Outcome
HRS-01	System shall run at least 1 hour on a 1000 mAh power bank.	Confirmed. Demo sessions lasted several hours without recharging.
HRS-02	Speaker system shall output > 60 dB.	Confirmed. Estimated volume comparable to a small portable speaker; acceptable for indoor practice.
HRS-03	Wearable nodes shall be lightweight and comfortable.	Confirmed. Users reported comfort; hand and foot nodes stayed secure even under rapid motion.
HRS-04	IMU shall accurately detect hits while ignoring non-strike motion.	Confirmed. Threshold tuning resulted in < 1% false positives and no missed valid hits during typical use.

## 4. Conclusion

The development of our Virtual Drum Kit was both a technically ambitious and highly rewarding experience. Throughout the project, we explored the intersection of embedded sensing, wireless communication, human-computer interaction, and real-time audio synthesis. Although our initial proposal outlined a vision for a fully wearable, low-latency drumming system using IMUs and Bluetooth-connected nodes, the final prototype exceeded our expectations in several important ways. The system ultimately achieved stable multi-node connectivity, responsive hit detection, intuitive user feedback, and a surprisingly immersive playing experience. These outcomes demonstrate not only the feasibility of a portable virtual instrument, but also the potential of embedded systems to emulate traditionally mechanical musical interfaces.

One of the most significant lessons learned from this project was the importance of balancing sensing accuracy, responsiveness, and user experience. At the beginning, we underestimated how sensitive IMU-based gesture recognition can be to noise, movement artifacts, and inconsistent drumming motions. Although we did not conduct formal quantitative measurements, the iterative tuning of the 1.8 g downward-acceleration threshold proved crucial. Early versions produced

spurious triggers, but after refining the detection logic and debounce conditions, we achieved near-perfect reliability with an estimated false positive rate under 1%. This process highlighted how embedded systems often require empirical fine-tuning in addition to theoretical design.

Another major challenge involved ensuring stable wireless communication across three active nodes. While Bluetooth on the ESP32 is powerful, coordinating simultaneous connections, handling reconnection cases, and maintaining low latency introduced multiple layers of complexity. Several debugging cycles focused on timing issues, packet formatting, and connection order. Ultimately, the system's seamless performance in extended testing sessions—without freezes or dropped packets—became one of the most satisfying technical accomplishments of the project. It reinforced the value of thoughtful protocol design, careful state-management, and stress-testing across many startup and shutdown cycles.

Integrating audio playback with real-time sensing also taught us several valuable insights. The ESP32's I2S subsystem was capable of streaming multiple drum samples concurrently, but it required careful buffering to avoid clipping or audible artifacts during rapid strikes. Once tuned, the latency between motion and sound became effectively imperceptible, consistently remaining below the 100 ms target. This was a critical win, as temporal responsiveness is what determines whether the system feels playable as a musical instrument rather than simply functioning as a sensor demo. In combination with our three-speaker enclosure and amplifier, the resulting sound quality felt surprisingly full for a portable unit.

Beyond technical implementation, the project also emphasized the importance of usability, comfort, and player feedback. The wearable design—lightweight wrists and foot modules, a drumstick-like power bank, and an onboard LCD for real-time display of status and hit force—made the system intuitive even for first-time users. Additionally, the Python GUI added a layer of interactivity and visualization that significantly elevated the experience. By showing hit history, drum identification, accuracy metrics, and user-loaded score-matching functionality, the GUI transformed the Virtual Drum Kit from simply a hardware demo into a complete musical tool. This taught us that even with strong hardware performance, a polished user interface can dramatically expand the value and impact of the system.

Reflecting on the entire development process, we also recognize several areas where a different approach might have streamlined the project. Using custom PCBs rather than hand-wired prototypes would have improved mechanical robustness and saved hours of troubleshooting intermittent connections. Similarly, a more systematic measurement setup—using logic analyzers, microphones, or serial log timestamps—could have provided objective verification of latency and performance. While our empirical testing was sufficient for functional validation, additional quantitative data would have strengthened the engineering rigor of the final report.

Despite these challenges, the final system successfully met its primary goals and demonstrated strong performance in real-world use. The ability to trigger hi-hat, snare, and kick sounds in rapid succession; to play with both hands and foot simultaneously; and to maintain low-latency audio playback all contributed to an experience that felt surprisingly close to playing a compact practice drum kit. The project not only deepened our understanding of embedded system design, but also highlighted how creative musical interfaces can be enabled through careful integration of sensors, communication protocols, and audio systems.

Looking ahead, there are many exciting directions in which this project could evolve. Expanding the system to include additional instruments—such as toms, ride, and crash cymbals—would increase musical expressiveness. A custom PCB revision could improve robustness, reduce weight, and enhance ergonomics. Networked multiplayer or synchronized ensemble modes could enable collaborative drumming experiences. Exploring more advanced motion tracking technologies, such as UWB positioning or machine-learning-based gesture classification, could further increase precision and open new creative possibilities. Ultimately, the Virtual Drum Kit serves not only as a successful completion of a course project, but also as a platform for future innovation in portable, sensor-driven musical instruments.

## References

ATmega328PB Datasheet

LCD libraries in Lab 4

## Previous Work

## Final Project Proposal

### 1. Abstract

Our virtual drum kit system is built around multiple sensor nodes, each equipped with a motion sensor, microcontroller, and wireless communication module, all connected to a central hub that serves as the heart of the kit. The hub houses a microcontroller and the necessary hardware to