

ECE 445

Fall 2026

Senior Design Design Document

Pickleball Paddle Sensor Module

Team 27

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1. Introduction

1.1 Problem

Pickleball is one of the fastest-growing sports in America, with 24.3 million players in 2025, up from 4.2 million players in 2020 [1]. With this explosive growth, the influx of newer players compared to more experienced players is quite large. Many new players are seeking methods of improvement, with classes and coaching being the only option. This creates a problem for the average pickleballer; it's simply too expensive. Similar to tennis, individual coaching or lessons can charge up to \$100 for a single session. This can discourage many players from the sport or rack up a bill that is simply too much for a casual activity. While expensive tracking cameras and proprietary software solutions do exist, there is no cost-effective solution that doesn't require technical setup and data analysis.

1.2 Solution

Our solution is to create an auxiliary device that can universally attach to most any pickleball paddle. We desire our device to communicate with a “host” device via BLE 5.0. This host can be a mobile phone or laptop. The module contains a 9-axis IMU with onboard sensor fusion (BNO085), a piezo disc for contact detection, an ESP32-H2-MINI-1-H2S microcontroller, and a Li-ion power subsystem. The module segments discrete swing events, classifies them into at least three swing classes, detects genuine ball-paddle strikes, and streams a fused orientation quaternion in real time so that a companion app can render a 3D paddle model that mirrors the physical paddle's motion.

1.3 Visual Aid



Figure 2: Mockup of physical module interacting with pickleball paddle.

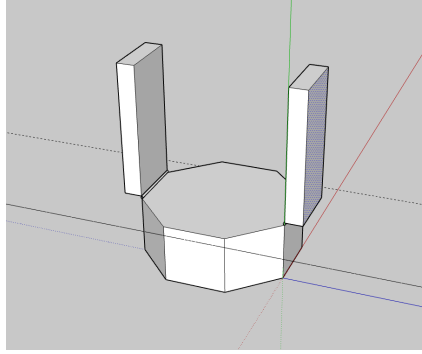


Figure 3: Mockup of 3D-printed C-channel.

The PCBA and battery reside in the grey box at the end of the paddle. There is a c-channel for installation and removal of the module. It will have a USB-C port for charging. If all components cannot fit in the module, size proportions will be modified and the battery may be placed within the pickleball handle.

1.4 High-Level Requirements

The project is successful if all four of the following are demonstrated.

1. **Swing classification and speed.** The module segments discrete swing events and classifies them into at least three swing classes (forehand drive, backhand drive, overhead) with at least 90% accuracy over at least 50 held-out swings per class, and reports peak swing speed within $\pm 10\%$ of a video-derived ground truth across at least 30 trials.
2. **Contact detection.** The module distinguishes a genuine ball-paddle strike from a practice swing or an incidental bump with at least 95% precision and at least 95% recall over at least 100 mixed trials (at least 50 hits and 50 non-hits), with detection latency under 50 ms from impact.
3. **Real-time orientation tracking.** The module streams a fused orientation quaternion over BLE at a sustained rate of at least 60 Hz with end-to-end latency under 50 ms, allowing a companion phone or laptop app to render a 3D paddle model that visibly mirrors the physical paddle's motion with no perceptible lag, verified over at least 10 minutes of continuous operation with no dropped or stale frames.
4. **Wearable-scale operation and offload.** The assembled module weighs no more than 50 g, is no more than 20 mm thick, and mounts to a standard paddle without altering legal play. It offloads a full 60-minute session over BLE at 10 m line-of-sight with zero dropped events, and runs at least 3 hours of continuous active play on a single charge.

Extra goals: dink, volley, and further forehand/backhand separation beyond the initial three swing classes.

2. Design

2.1 Block Diagram

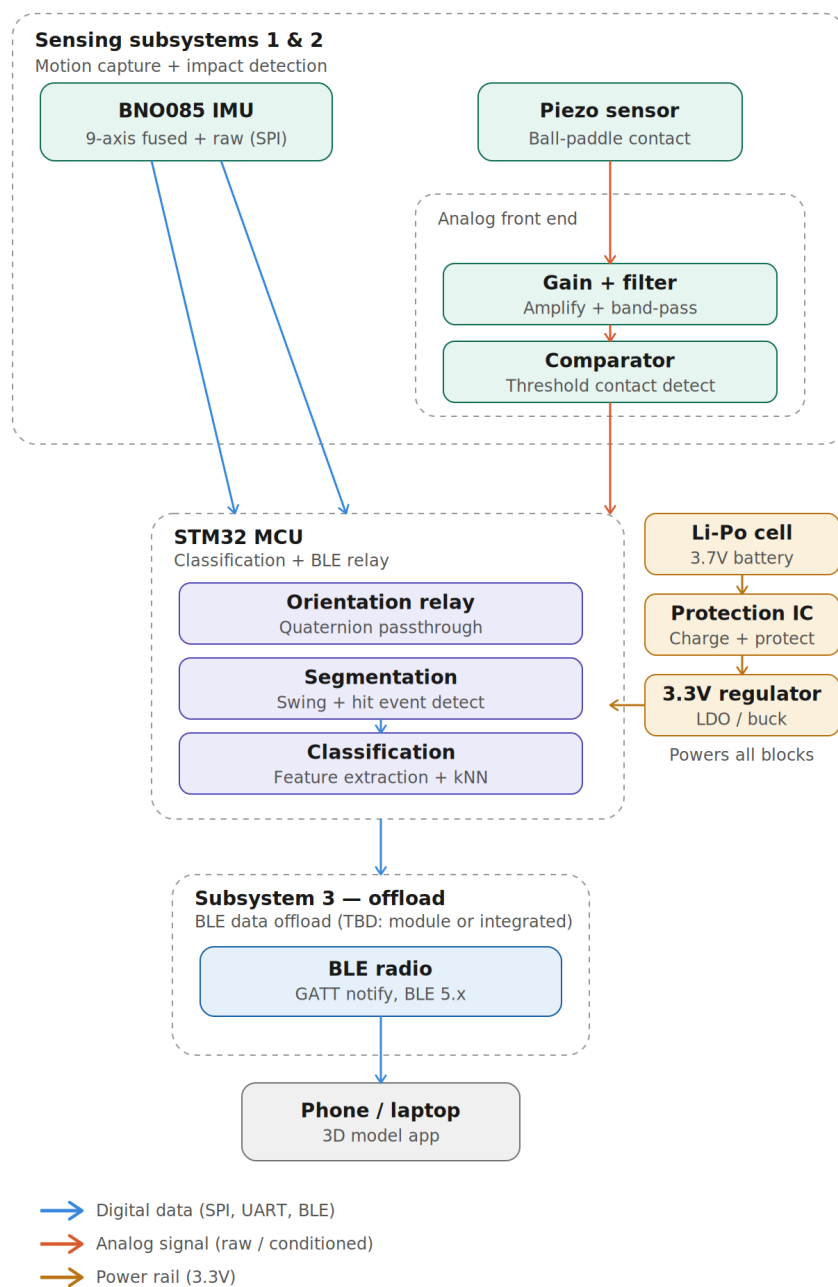


Figure 1: System block diagram. Dashed regions denote subsystem boundaries.

Signal flow:

- BNO085 streams fused orientation quaternion, linear acceleration, and angular velocity over SPI to the ESP32-H2 at ≥ 100 Hz.
- Piezo disc output is conditioned (charge amp + envelope detector + comparator) and sampled by the ESP32-H2 ADC and GPIO interrupt for impact detection.
- The ESP32-H2 runs swing segmentation, classification, and orientation streaming, and transmits over BLE 5.0 to the host.
- The power subsystem provides a regulated 3.3 V rail to all components from a single-cell 3.7 V Li-Po, boosted to 5 V and regulated down through the LM3940 LDO.

2.2 Physical Design

The PCB will sit inside a 3D-printed casing on the bottom of the handle of the paddle. It will be attached via a spring-loaded clasp mechanism. The faces of the clasp are lined with a thin silicone strip so the module grips the handle firmly without marring the paddle's finish, and the clasp can be opened by hand to slide the module on or off without tools. A USB-C port on the module allows charging without removing it from the paddle. The enclosure is budgeted to stay within the 50 g and 20 mm added-thickness limits in the high-level requirements; if the BNO085, ESP32-H2, analog front end, and battery cannot all fit within that envelope, the battery will be relocated into a cavity in the paddle handle itself, connected to the module by a short lead.

2.3 Subsystems and Requirements

2.3.1 Motion Sensing & Swing Classification Subsystem (BNO085 + Piezo)

The BNO085 is a 9-axis System-in-Package (SiP) that integrates a triaxial accelerometer, triaxial gyroscope, and triaxial magnetometer with an on-board ARM Cortex-M0+ fusion processor. It outputs stable, fused orientation (quaternion or Euler), linear acceleration, and calibrated angular velocity over SPI or I²C. For this project we use SPI for higher throughput and lower latency. The piezo disc is a passive vibration sensor whose output is conditioned and fed to the ESP32-H2 ADC. This subsystem interacts directly with the Microcontroller & Remote Compute subsystem: the BNO085's SPI bus and the piezo comparator's interrupt line both terminate on the ESP32-H2, which correlates a contact interrupt against the current swing's motion data to confirm a genuine hit.

Requirement	Verification
The BNO085 shall output fused orientation quaternion at a sustained rate of at least 100 Hz over SPI.	• Connect BNO085 to ESP32-H2 via SPI • Log timestamps of each quaternion sample using <code>esp_timer_get_time()</code> • Compute average sample rate over 60 s • Confirm ≥ 100 Hz with no gaps > 20 ms

Requirement	Verification
The module shall segment discrete swing events and classify them into at least three swing classes (forehand drive, backhand drive, overhead) with $\geq 90\%$ accuracy over ≥ 50 held-out swings per class.	- Collect ≥ 150 labeled swings (50 per class) from multiple players - Run classification on held-out data - Compute confusion matrix and accuracy - Confirm $\geq 90\%$ per class
The module shall report peak swing speed within $\pm 10\%$ of video-derived ground truth across ≥ 30 trials.	- Record each swing with a high-speed camera (≥ 240 fps) and a calibrated reference marker - Compute peak paddle-tip speed from video - Compare to the BNO085-derived estimate - Confirm error $\leq 10\%$ for ≥ 30 trials
The piezo-based contact detector shall distinguish a genuine ball-paddle strike from a practice swing or incidental bump with $\geq 95\%$ precision and $\geq 95\%$ recall over ≥ 100 mixed trials (≥ 50 hits, ≥ 50 non-hits).	- Conduct 100+ trials: 50+ genuine hits, 50+ non-hits (practice swings, bumps against hand/leg/ground) - Log detection output - Compute precision = $TP/(TP+FP)$, recall = $TP/(TP+FN)$ - Confirm both $\geq 95\%$
Contact detection latency shall be under 50 ms from impact.	- Use an oscilloscope to measure the time between the piezo signal's threshold crossing and the BLE packet transmission indicating detection - Confirm < 50 ms

Table 1: Motion sensing & swing classification requirements and verification.

Piezo conditioning circuit:

The piezo disc output is a high-impedance, fast transient. It is fed into a charge amplifier / voltage follower (e.g., TL072 or OPA344) with a gain of ~ 10 , followed by an RC envelope detector ($\tau \approx 5$ ms) and a comparator (e.g., TLV3012) with adjustable threshold. The comparator output is a clean digital pulse that the ESP32-H2 can capture on a GPIO interrupt, while the analog envelope is also sampled by the ADC for magnitude estimation. This dual-path approach gives both low-latency detection and impact-strength measurement.

2.3.2 Microcontroller & Remote Compute Subsystem (ESP32-H2-MINI-1-H2S)

The ESP32-H2-MINI-1-H2S is a RISC-V single-core microcontroller with 2.4 GHz BLE 5.0, 320 KB SRAM, 4 MB flash, and a rich set of peripherals (SPI, I²C, ADC, GPIO interrupts). It is responsible for sampling the BNO085 over SPI at ≥ 100 Hz, sampling the piezo envelope over ADC and capturing comparator interrupts, running swing segmentation and classification, streaming fused orientation quaternion over BLE at ≥ 60 Hz, and managing power modes to achieve ≥ 3 hours of active play. This is the only compute and radio subsystem in the design: it both processes sensor data from subsystem 2.3.1 and drives the BLE link to the host app, with no separate radio module.

Requirement	Verification
The ESP32-H2 shall sample the BNO085 at ≥ 100 Hz and the piezo ADC at ≥ 1 kHz (or capture comparator interrupts with < 1 ms latency).	• Implement an acquisition routine with <code>esp_timer</code> timestamps • Log sample counts over 60 s • Confirm $\text{BNO085} \geq 100$ Hz, piezo ≥ 1 kHz equivalent
The ESP32-H2 shall stream fused orientation quaternion over BLE at a sustained rate of ≥ 60 Hz with end-to-end latency < 50 ms.	• Connect to the host app • Stream quaternions • Measure the timestamp delta between ESP32 send and host receive • Confirm ≥ 60 Hz sustained for ≥ 10 min with no dropped/stale frames, and latency < 50 ms
The ESP32-H2 shall process and store sensor data from each swing without exceeding 80% of available RAM or flash.	• Use <code>esp_get_free_heap_size()</code> and memory profiling during repeated swings • Confirm RAM and flash usage $< 80\%$ under worst-case load
The ESP32-H2 power consumption shall not exceed 300 mW during active operation (BLE + sensing + classification).	• Measure current draw at 3.3 V during active operation with a power analyzer • Confirm ≤ 300 mW (≈ 91 mA at 3.3 V)
The module shall offload a full 60-minute session over BLE at 10 m line-of-sight with zero dropped events.	• Run a 60-minute session with continuous sensing/classification • Log all events on-device and on-host • Compare counts • Confirm zero dropped events at 10 m

Table 2: Microcontroller & remote compute requirements and verification.

Swing classification approach:

Features are extracted from the BNO085's linear acceleration and angular velocity (peak magnitude, duration, sign of rotation about the paddle's long axis, etc.). A lightweight classifier (e.g., a decision tree or small neural network) runs on-device on the ESP32-H2. On-device classification is preferred for latency and privacy; if accuracy targets are not met, raw features are streamed to the host for classification, and the result is sent back. The $\geq 90\%$ accuracy requirement above will be verified on held-out data regardless of where the classifier runs.

2.3.3 Power Subsystem

The power subsystem powers every other subsystem in this project: the ESP32-H2, the BNO085, and the piezo analog front end. A single-cell 3.7 V Li-Po battery is charged through a TP4056 linear charger with DW01A/FS8205 protection (over-charge, over-discharge, and short-circuit protection), then stepped up to 5 V by a TPS61023 boost converter and regulated down to a clean 3.3 V rail by an LM3940 1-A LDO. The LM3940 accepts inputs from 4.5 V to 5.5 V and outputs 3.3 V at up to 1 A; it requires a minimum 33 μF output capacitor. Boosting to 5 V before the LDO keeps the regulated rail stable and ripple-free even as the battery's own voltage sags over a discharge cycle, rather than relying on the battery's raw 3.7–4.2 V, which would leave the LDO with too little headroom.

Requirement	Verification
The regulated system rail shall remain within 3.3 V $\pm 5\%$ (3.135–3.465 V) under the minimum and maximum expected load.	• Measure the 3.3 V rail with a DMM at idle and while forcing repeated BLE transmissions and sensor acquisition • Repeat at full and low battery states • Record minimum and maximum DC voltage
The 3.3 V rail shall exhibit no more than 50 mV peak-to-peak ripple or transient droop during a BLE transmit burst.	• Measure the rail using an AC-coupled oscilloscope probe placed at the ESP32 supply pins while repeatedly transmitting BLE packets • Record worst-case ripple and droop
The battery shall support at least 3 hours of continuous active operation.	• Fully charge the battery and run a scripted workload that keeps sensing, classification, and BLE activity representative of active play • Log runtime until the battery pack performs its protected low-voltage shutdown
The battery/charger assembly shall prevent unsafe overcharge, over-discharge, and short-circuit conditions.	• Use a battery pack with documented integrated charge/protection circuitry • Verify normal charge termination and protected shutdown using manufacturer-specified indicators and a monitored bench test

Table 3: Power subsystem requirements and verification.

2.4 Tolerance Analysis

2.4.1 BLE Throughput and Latency

The module must stream a fused orientation quaternion at ≥ 60 Hz with < 50 ms end-to-end latency. A quaternion is 4 floats = 16 bytes; with a packet header and timestamp, call it 32 bytes/packet. At 60 Hz, that is 1,920 bytes/s ≈ 15.4 kbps. BLE 5.0 (2M PHY) supports up to 2 Mbps application throughput, so bandwidth is not a constraint. The dominant latency is connection interval and processing. With a connection interval of 7.5–15 ms and ESP32-H2 BLE stack overhead, end-to-end latency should be well under 50 ms. We will verify this empirically per Table 2.

2.4.2 Sensor Sampling and Data Rate

The BNO085 over SPI can deliver quaternion + linear acceleration + angular velocity at 100 Hz easily (SPI clock up to 3 MHz). At 100 Hz, 3 vectors $\times$ 3 axes $\times$ 4 bytes = 36 bytes/sample $\rightarrow$ 3.6 kB/s. This is trivial for the ESP32-H2. The piezo ADC at 1 kHz (if used) produces 2 bytes/sample $\rightarrow$ 2 kB/s. Total sensor data rate < 6 kB/s, well within SPI and RAM limits.

2.4.3 Contact Signal SNR Margin

To check the feasibility of the 6 dB SNR implied by reliable contact detection, before fully characterizing the selected piezo disc on the bench, we estimate the signal amplitude for a genuine ball strike against the noise floor produced by handle vibration during a practice swing. Assuming a representative peak piezo output of 500 mV for a firm, direct mechanical impulse at the mounting location (typical for commercially available piezo elements used for impact sensing), and a practice-swing noise floor of approximately 50 mV peak from residual handle and grip vibration, the expected signal-to-noise ratio is:

$$\text{SNR} = 20 \cdot \log_{10}(500 \text{ mV} / 50 \text{ mV}) = 20 \cdot \log_{10}(10) \approx 20 \text{ dB}$$

This leaves roughly 14 dB of margin above a 6 dB target. A low-noise op-amp front end (input-referred noise density on the order of 10 nV/ $\sqrt{\text{Hz}}$, integrated over the 200 Hz–2 kHz impact band) contributes only tens of microvolts RMS, confirming the dominant noise source is mechanical rather than electronic. This is a first-pass estimate; the actual sensitivity and noise floor will be measured directly once the piezo disc and conditioning circuit are bench-tested, per the contact-detection verification in Table 1.

2.4.4 Piezo False-Trigger Rejection

The piezo sensor is sensitive to any vibration, including hand grip changes and incidental bumps. The comparator threshold and the envelope detector time constant are chosen so that a genuine ball impact (high-frequency, high-amplitude, short duration) triggers detection, while slower vibrations (hand movement, practice-swing air whoosh) do not. We will tune the threshold empirically over ≥ 100 mixed trials and verify precision/recall $\geq 95\%$.

2.4.5 Power Budget and Thermal

At 300 mW active, the enclosure (approx. 40 mm × 30 mm × 15 mm) has a surface area of ~0.0054 m². With natural convection ($h \approx 10 \text{ W/m}^2\text{K}$), the temperature rise is $\Delta T = P/(h \cdot A) \approx 0.3/(10 \times 0.0054) \approx 5.6^\circ\text{C}$ above ambient. This is safe for handheld use and for the Li-ion battery (max 60°C). No active cooling is required.

2.4.6 Battery Internal Heating

Separately from the enclosure's external temperature rise above, we check the battery cell's own internal heating from discharge and charge current through its internal resistance. For a 500 mAh 3.7 V Li-Po pouch cell (a worst-case stand-in for the 350 mAh cell specified in the BOM, since a smaller cell has higher internal resistance for the same power draw) with an internal resistance of $\leq 120 \text{ m}\Omega$, and an estimated average active-play current draw of 20–25 mA across the ESP32-H2 (5–10 mA), BNO085 (5–10 mA), analog front end (2–5 mA), and BLE radio bursts (5–15 mA):

- Discharge heat: $P_{\text{heat}} = I^2 \times R = (0.028 \text{ A})^2 \times 0.120 \Omega \approx 9.4 \times 10^{-5} \text{ W}$, giving $\Delta T = P_{\text{heat}} \times R_{\theta} \approx 0.000094 \text{ W} \times 100^\circ\text{C/W} \approx 0.0094^\circ\text{C}$ — negligible.
- Charging heat (1C, 0.5 A charge current): $P_{\text{charge}} = I^2 \times R = (0.5 \text{ A})^2 \times 0.120 \Omega = 0.03 \text{ W}$, giving $\Delta T \approx 0.03 \text{ W} \times 100^\circ\text{C/W} = 3^\circ\text{C}$.

Both figures are well within safe thresholds for a cell of this size and chemistry, and confirm that neither active play nor charging poses a thermal risk from the battery itself, independent of the enclosure-level convection result above.

2.4.7 Mechanical Tolerance and Mounting

The C-channel clasp must maintain contact with the paddle handle under centripetal loads. A 50 g module at 10 cm from the handle axis, swinging at 20 m/s tip speed ($\approx 200 \text{ rad/s}$), experiences centripetal force $F = m \cdot \omega^2 \cdot r \approx 0.05 \times (200)^2 \times 0.1 \approx 200 \text{ N}$. The spring-loaded clasp must provide a normal force and friction coefficient sufficient to resist this. We will use a stainless steel spring with a preload of ~50 N and a silicone-lined contact surface ($\mu \approx 0.8$), giving a friction force of ~40 N. The clasp geometry also provides a mechanical interlock (lip) that resists radial motion. We will verify by shaking the paddle vigorously and by instrumenting a swing test with a strain gauge or by video inspection for relative motion.

3. Cost and Schedule

3.1 Cost Analysis

3.1.1 Labor

The estimate for labor is based on an ideal rate of \$50/hour for each team member, assuming 10 hours per week per person over a 16-week semester, multiplied by an engineering development factor of 2.5 to account for overhead:

$$3 \text{ team members} \times \$50/\text{hr} \times 10 \text{ hrs/wk} \times 16 \text{ wks} \times 2.5 = \$60,000$$

3.1.2 Parts

Description & Part Number	Manufacturer / Vendor	Quantity	Price/Unit	Total Price	Datasheet
ESP32-H2-MINI-1-H2S	Espressif Systems / DigiKey	3	\$2.50 (est.)	\$7.50	[2]
BNO085 9-axis IMU (28-TFLGA)	CEVA Technologies / DigiKey	3	\$13.05	\$39.15	[4]
Piezoelectric disc (27 mm)	CUI Devices / DigiKey	3	\$0.85	\$2.55	[7]
TPS61023 boost converter	Texas Instruments / DigiKey	3	\$1.45	\$4.35	[6]
TP4056 Li-ion charger IC	NanJing Top Power ASIC / Amazon	3	\$0.50	\$1.50	[12]
DW01A + FS8205 battery protection IC	generic / Amazon	3	\$0.40 (est.)	\$1.20	—
LM3940 3.3 V LDO	Texas Instruments / DigiKey	3	\$1.20	\$3.60	[5]
3.7 V 350 mAh Li-Po battery	Adafruit	3	\$5.95	\$17.85	—
Custom PCB fabrication	JLPCB	5	\$2.00	\$10.00	—

Table 4: Bill of materials. “(est.)” marks prices not yet confirmed on a live distributor listing.

Parts subtotal	\$87.70
Shipping	\$15.00 (est.)
Tax	\$9.75 (est.)
Total Parts Cost	\$112.45

3.1.3 Total

Team Labor Hours	480 hours
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Machine Shop Labor Hours	10 hours
Total Labor Hours	490 hours

Team Labor Hour Costs	\$60,000.00
Machine Shop Labor Hour Costs	\$500.00
Cost of Parts	\$112.45
Total Cost	\$60,612.45

3.2 Schedule

Week	Task	Person
Week 1 (9/23)	Finalize Design Document & component selection	All
Week 2 (9/30)	PCB schematic & layout design	Peter
Week 3 (10/7)	Order PCB and components (Second Round PCBway submission) & mechanical casing 3D model	Alex
Week 4 (10/14)	Firmware setup & BNO085 SPI integration	Levente
Week 5 (10/21)	PCB assembly & power subsystem testing	Peter
Week 6 (10/28)	Piezo signal conditioning & ADC sampling	Alex
Week 7 (11/4)	BLE 5.0 streaming & companion app 3D model rendering	Levente
Week 8 (11/11)	Swing classification algorithm & data collection	All
Week 9 (11/18)	System integration & high-level requirement verification; Mock Demo	All
Week 10 (11/25)	Fall Break — buffer time for PCB revision or firmware polish	All
Week 11 (11/30)	Final Demo & Final Presentation	All
Week 12 (12/7)	Final paper due; lab checkout	All

Table 5: Project schedule, anchored to the ECE 445 course calendar.

4. Societal Impact, Standards, Ethics, and Safety

4.1 Societal Impact

Pickleball is the fastest-growing sport in America, with 24.3 million players in 2025, up from 4.2 million in 2020 [1]. This explosive growth has created a large population of new players who cannot afford \$100/session coaching. Our module provides affordable, objective feedback on swing classification, swing speed, contact detection, and real-time orientation, democratizing access to performance analytics. By making improvement accessible to casual players, we hope to increase retention and enjoyment of the sport, and to reduce injury risk from poor technique. The module is designed to be non-invasive, lightweight, and legally usable in play (it does not alter the paddle's playing surface or add significant mass), so it does not confer an unfair competitive advantage.

4.2 Engineering Standards

- **Bluetooth Core Specification 5.0 [11]** — governs the wireless communication between the module and the host.
- **IEEE 802.15.1** — WPAN standard underlying Bluetooth.
- **FCC Part 15, Subpart C [13]** — intentional radiator requirements for the 2.4 GHz BLE radio. The ESP32-H2-MINI-1-H2S is a pre-certified module, but final enclosure integration must maintain antenna keep-out and RF exposure compliance.
- **IEEE 1625 [9]** — rechargeable battery standards for portable computing.
- **IEEE 1725 [10]** — rechargeable battery system design and qualification.
- **USB Type-C Specification 1.4** — charging port.
- **IPC-2221 / IPC-7351** — PCB design and footprint standards.
- **RoHS / REACH** — hazardous substance restrictions for consumer electronics.

4.3 Ethics

We adhere to the IEEE Code of Ethics [8], particularly:

- **Tenet 1: Hold paramount the safety, health, and welfare of the public.** Our module is lightweight, rounded, and securely mounted; the battery is protected against overcharge/overdischarge/overcurrent; the enclosure is designed to remain attached during aggressive play.
- **Tenet 4: Reject bribery in all forms.** We have no undisclosed sponsorships or conflicts of interest.
- **Tenet 5: Improve the understanding of technology and its appropriate application.** We will document our design, verification methods, and limitations honestly.

- **Tenet 9: Avoid injuring others, their property, reputation, or employment by false or malicious action.** We will not misrepresent our accuracy or reliability claims; all high-level requirements are verified empirically.
- **Data privacy:** the module streams sensor data to a host app. We will not collect or transmit personal data without user consent, and all session data is stored locally on the user's device by default.

4.4 Safety

- **Battery safety:** Li-ion cells are used with a protection IC (DW01A + FS8205) and a compliant charger (TP4056). The battery is physically isolated from the user's hand and from the paddle's playing surface. Users are instructed to dispose of batteries at certified recycling centers per IEEE 1625/1725 and local regulations. Damaged or swollen batteries must be removed and isolated immediately.
- **Mechanical safety:** the enclosure has no sharp edges. The C-channel clasp is spring-loaded but cannot pinch the user during normal installation/removal. The module is secured against centripetal loads up to 200 N (see Tolerance Analysis).
- **RF safety:** the ESP32-H2-MINI-1-H2S is a pre-certified module with a maximum output power of +10 dBm. At 10 m distance, the power density is far below FCC limits. The antenna keep-out zone is maintained in the enclosure design.
- **Thermal safety:** worst-case temperature rise is $\sim 6^{\circ}\text{C}$ above ambient (see Tolerance Analysis), well within safe handheld limits.
- **Lab safety:** during development, all batteries are stored in protective casings, monitored for overheating, and handled in accordance with IEEE 1725. The soldering iron, reflow oven, and 3D printer are used with standard PPE and ventilation.
- **Play safety:** the module does not alter the paddle's playing surface, weight distribution (≤ 50 g), or thickness (≤ 20 mm) in a way that would affect legal play or player safety. It is mounted at the butt end of the handle, away from the hitting surface.

5. References

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