

Pickleball Paddle Sensor Module

ECE 445 Project Proposal

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Introduction

Problem

Pickleball has grown rapidly, with U.S. participation rising from 4.2 million players in 2020 to 24.3 million in 2025, but players at every level still have no easy way to quantify their performance. Coaches and serious players in tennis and baseball have had swing analytics for years; pickleball has not caught up. The smart options that exist today either require a bulky, fully strapped with a sensor paddle or rely on computer vision, or extremely expensive coaching, both of which are impractical for casual everyday play.

Solution

We'd like to propose a small PCBA based sensor module that mounts to any normal paddle and automatically tracks statistics through playtime. A nine-axis IMU (Bosch BNO085) provides a fused orientation estimate that lets a companion phone or laptop app display a live 3D model mirroring the paddle's motion as it's swung, and raw motion data that the onboard MCU segments and classifies into swing type and speed. A piezo element or contact microphone, tuned to the acoustic and/or vibration signature of ball-to-paddle contact, handles collision detection so that a genuine strike can be separated from something like a practice swing or an incidental bump. Classified events are logged on-board and offloaded over BLE to a companion phone application.

The project leans much harder on sensor fusion and signal processing rather than on component count. The bill of materials should stay small, but to extract reliable swing classification and clean contact detection from noisy accelerometer and vibration data will take real iteration across possibly multiple PCB revisions and complex and challenging firmware work.

Following the feedback from the TAs, the scope is going to be limited to three distinct swing classes: forehand drive, backhand drive, and overhead. Dink, volley, forehand/backhand separation beyond the initial three, and on-face strike location estimation are being treated as extra goals so that a partial completion of all objectives still counts as a complete project.

Block diagram

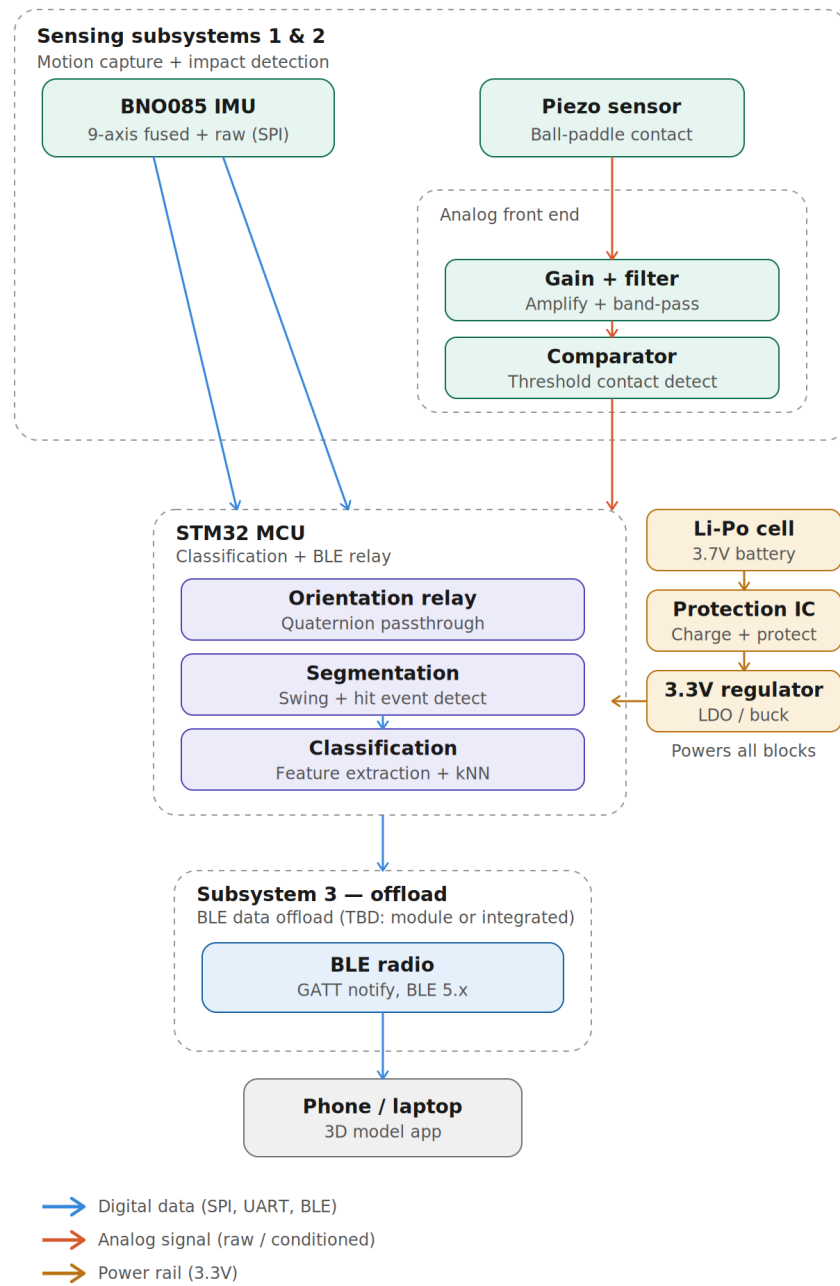


Figure 1: System block diagram. Dashed regions denote subsystem boundaries.

Visual Aid

The pickleball sensor would look like this, with a small 3d printed mount and casing on the bottom of the handle as such:



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

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.

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.

Subsystem requirements

Motion sensing and swing classification

This subsystem captures raw motion data and classifies swing type and speed. It centers on a six-axis IMU mounted rigidly to the paddle handle or throat, feeding an STM32 MCU that performs segmentation, feature extraction, and classification in real time. Swing events are segmented by triggering on peaks in angular velocity and acceleration; each event is aligned on its peak, and hand-crafted features (peak magnitude, rise time, orientation change, dominant axis) drive a lightweight classifier rather than a deep network.

Requirement	Verification
The MCU captures BNO085 accelerometer and gyroscope samples at a sustained rate of at least 400 Hz with zero dropped samples over a 10-minute capture, with no clipping during a maximum-effort swing.	Stream raw samples to a host over SPI during 10 minutes of simulated play. Verify sample count and timestamp monotonicity in a Python script, and confirm no clipping occurs during a maximum-effort drive.
The swing segmenter detects at least 98% of swings and produces no more than 2 false segments per minute of idle, walking, or between-point motion.	Record 100 video-annotated swings plus 10 minutes of non-swing motion. Compare detected event timestamps against the video ground truth within a ± 100 ms matching window.
The MCU completes segmentation, feature extraction, and classification within 100 ms of swing end, on-board and in real time.	Toggle a GPIO pin at segment-end and again at classification-complete. Measure the interval on an oscilloscope across 30 consecutive swings and record the worst case.

Table 1: Motion sensing, orientation tracking, and swing classification requirements and verification.

Contact and collision detection

This subsystem determines whether the paddle has made genuine contact with the ball. A piezo disc or contact microphone is bonded to the paddle face or frame, and an analog front end amplifies and band-pass filters the signal before it reaches the MCU. A comparator stage provides a hardware trigger so the MCU can capture the impact waveform without polling the ADC continuously.

Requirement	Verification
The piezo and analog front end produce an impact signal with at least 6 dB SNR above the practice-swing noise floor, without saturating the 0–3.3 V ADC input range.	Capture raw front-end output on an oscilloscope for 20 hits and 20 practice swings. Compute the peak-to-RMS-noise ratio for each, and confirm no rail clipping occurs on the hardest strike recorded.
The band-pass stage passes the ball-impact frequency band and attenuates handle and grip motion artifacts by at least 20 dB below 200 Hz.	Sweep a function generator through the stage and plot measured gain against frequency, comparing the result to the designed response.
Contact decision logic achieves at least 95% precision and 95% recall against video ground truth.	Run 100 mixed trials including hits, practice swings, paddle taps against the leg and ground, and ball bounces near the paddle. Score the resulting confusion matrix.

Table 2: Contact and collision detection requirements and verification.

Data offload and power

This subsystem logs and wirelessly offloads swing and contact data to a phone or companion application, and powers the module in a compact, low-profile form factor that mounts to an existing paddle. Events are buffered in on-board flash so that a temporary BLE dropout does not lose data.

Requirement	Verification
The BLE link transmits a full session record of at least 500 events (type, speed, contact flag, timestamp) with zero loss at 10 m line-of-sight.	Generate 500 synthetic events on-board with known sequence numbers. Transmit to a phone or laptop at 1 m, 5 m, and 10 m, and verify sequence completeness on the receiver.
The power subsystem supplies 3.3 V $\pm$ 5% with no more than 50 mV ripple under worst-case load (IMU, analog front end, MCU active, and BLE transmit burst).	Measure the rail with an AC-coupled oscilloscope probe while forcing a BLE transmit burst, and confirm ripple and droop remain within limits.
The battery supports at least 3 hours of continuous active operation, and the system shuts down cleanly below the cell's minimum safe voltage.	Run a scripted duty cycle to depletion while logging runtime. Verify the undervoltage cutoff triggers at the designed threshold using a bench supply voltage sweep.

Table 3: Data offload and power requirements and verification.

Tolerance Analysis

The focus will be on making sure the battery of this size is able to handle the power draw without overheating or setting on fire. In order to be sure, we can see through this analysis that there should be no safety concerns:

We're making a battery selection based on the energy needed and the physical size of the module. A 500 mAh, 3.7 V Li-Po cell most like what we might end up using. It provides 1.85 Wh, and weighs around 12 to 18 grams, and is also available in even smaller sizes. A 1000 mAh cell offers more for us to work with at the cost of size and weight. For this, we'll assume a 500 mAh cell as the worst case for thermal safety, since a smaller cell has higher internal resistance for the same power draw.

Some assumptions:

- Ambient temperature is around 25 °C to 40 °C.
- The module is supposed to be mounted at the paddle handle end, with the battery inside a small 3D printed shell.
- The battery is a single pouch cell with an internal resistance of " $\leq 120 \text{ m}\Omega$ " which should be typical for a 500 mAh battery of this type.
- The system duty cycle is continuous active play: the MCU runs at a reasonably low clock, the IMU then also samples at 400 Hz, and BLE would transmit only when offloading data, basically in bursts.

Estimated current consumption during active play:

STM32L4 (MCU): 5–10 mA

BNO085 IMU: 5–10 mA

Analog front end (op-amp, comparator): 2–5 mA

BLE radio: 5–15 mA

LDO quiescent < 0.1 mA

Total average $\approx 20\text{--}25 \text{ mA}$

Heat Generation in Battery:

$P_{\text{heat}} = I_{\text{batt}}^2 \times R_{\text{internal}}: (0.028)^2 \times 0.120 = 0.000784 \times 0.120 \approx 9.4 \times 10^{-5} \text{ W} = 0.094 \text{ mW}$
(negligible temperature rise)

Thermal Resistance and Temperature Rise:

$\Delta T = P_{\text{heat}} \times R_{\theta}: 0.000094 \text{ W} \times 100 \text{ }^{\circ}\text{C/W} = 0.0094 \text{ }^{\circ}\text{C}$

Charging Heat Generation:

$P_{\text{charge}} = I_{\text{charge}}^2 \times R_{\text{internal}} = (0.5)^2 \times 0.120 = 0.25 \times 0.120 = 0.03 \text{ W}$

$\Delta T = 0.03 \times 100 = 3 \text{ }^{\circ}\text{C}$

This should show that the battery usage should be well within the safety thresholds of most batteries of this size and type

Impacts and Standards

Ethics and Safety:

The module includes a rechargeable Li-Po cell mounted on equipment that is swung at speed and occasionally dropped or struck against the court surface. The design includes a dedicated battery protection IC (over-charge, over-discharge, and short-circuit protection) and follows safe Li-Po handling practices consistent with IEC 62133 (safety requirements for portable sealed secondary lithium cells) and UN 38.3 (transport testing for lithium batteries). The enclosure is designed so the battery is not a load-bearing element and cannot be crushed under normal paddle use.

Societal Impact:

Performance analytics of this kind have historically been available only through expensive coaching or bulky, tethered sensor systems. A low-cost, unobtrusive module lowers the barrier for recreational and intermediate players to access objective feedback previously limited to well-funded athletes, consistent with the accessibility that has driven pickleball's rapid adoption.

Data Privacy:

Swing and contact event data (type, speed, timestamp) is transmitted over a point-to-point BLE connection to the user's own phone or laptop and is not associated with any personally identifying information, uploaded to a third party, or stored off-device by default.

Applicable Standards:

The BLE radio operates in the 2.4 GHz ISM band and is subject to FCC Part 15 (rules for unlicensed intentional radiators) in the United States; a pre-certified BLE module or SoC will be used to inherit its existing FCC/CE certification rather than requiring independent radio certification of the full board.