ECE 445 – Senior Design

Design Document

Sensor Integrated Putter

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Project No. 74

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1 Introduction

1.1 Problem

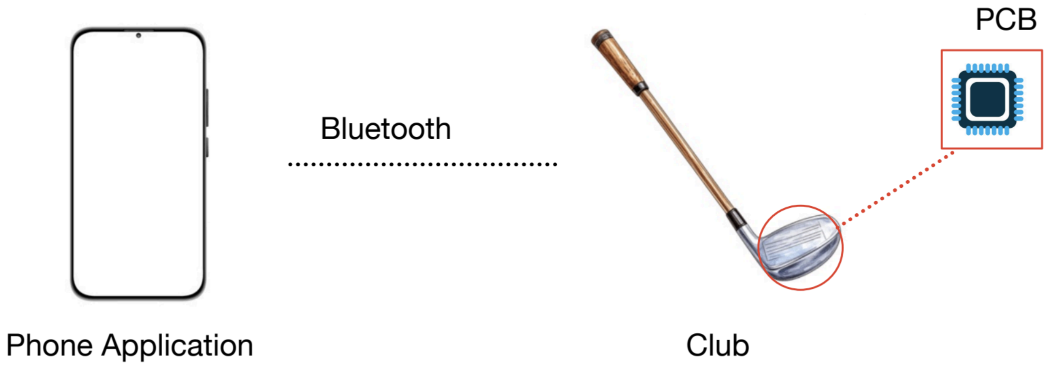
Putting requires a high degree of repeatability and consistency, where small variations in club speed, face angle, and tempo can significantly affect the direction and distance of the ball. That is why the average golfer loses the most strokes in a round on the green. Anyone can hit a ball far, not everyone can consistently get the ball in the hole within par. It is very difficult for golfers to perceive small mechanical differences during practice, which makes it challenging to understand why certain putts hit while others miss. Because putting depends on subtle physical motions, players often rely on subjective feel rather than measurable evidence, leading to inconsistency and difficulty identifying the root cause of errors.

The importance of this problem extends beyond individual performance. Golf is a global sport played by millions worldwide and represents a multi-billion dollar industry, yet performance improvement often comes at a high cost. Inconsistent putting drives demand for private lessons, premium training tools, and top-of-the-line equipment that can be financially out of reach for many players. Developing an affordable data feedback system would help level the playing field by making performance analytics accessible to more golfers.

1.2 Solution

We want to design a sensor-integrated putter that measures and analyzes putting stroke mechanics in real time to provide feedback on individual strokes, consistency, and improvement. By embedding sensing and processing hardware into a putter, the system will focus on capturing physical characteristics of the stroke, regardless of whether the putt goes in or not. A motion sensor will track club speed, acceleration, tempo, face orientation, and rotational behavior of the club throughout the stroke. An impact sensing mechanism will determine the characteristics of contact between the ball and club. Additional optical sensing at the club face will observe ball behavior, most notably ball wobble and roll. These measurements will be processed to quantify repeatability and identify stroke variability. The hardware system will connect with a mobile app via Bluetooth that will show putt metrics, store sessions, visualize trends, and provide users with potential sources of error in their game.

1.3 Visual Aid



1.4 High Level Requirements

- The system must be able to determine putting stroke face angle and timing with consistent results, achieving ≤ ±0.6° face angle error (mapped to a 10-ft putt) and ≤ 5 ms impact timing resolution when tested against high-frame-rate video.
- The system must be able to detect strokes and provide data to the mobile app with ≥ 99% successful stroke packet transmission during a practice session, without any repeated strokes and a maximum end-to-end latency of 500 ms from impact to app display.
- The integrated sensing and power hardware must add no more than 400 g to a standard mallet-style putter and must not measurably restrict the user's ability to perform a natural putting stroke, as verified through repeatable stroke testing.

2 Design

2.1 Physical Design

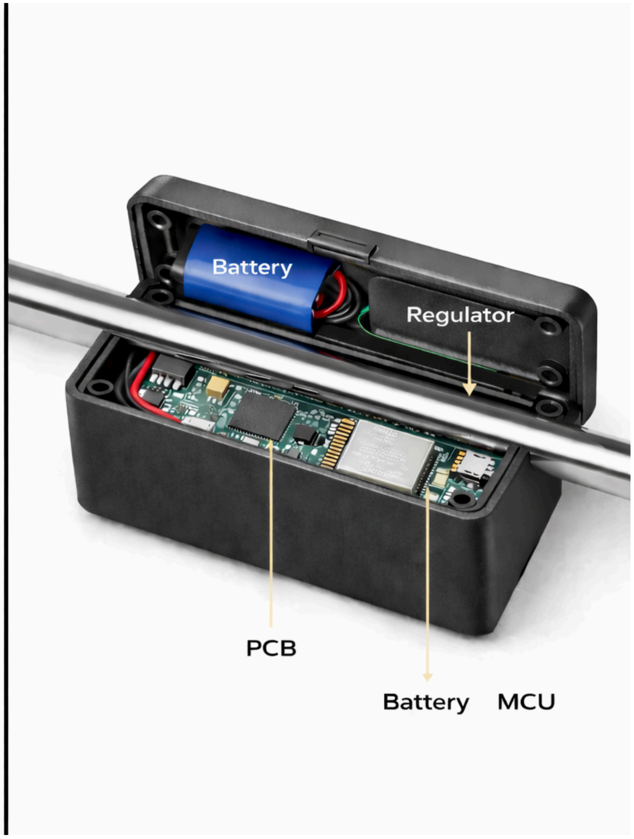
In order to fit our parts flush to the putter, we will have to allocate our parts both along the mallet club face of the putter as well as along the grip. We will mount our PCB inside of a casing from the pollycase on the putter's grip. This container will also contain the battery and regulator modules as well as our MCU, since these components are not required to be on the club head for functionality.

We will have wires running down the club shaft binded tight to ensure no inconsistencies in club motion.

On the head of the club, we will mount our IMU and Piezo strip, The IMU will be mounted on the top middle of the mallet head, while the Piezo strips will rest on the club face itself. This design will ensure an even weight distribution of the club head’s weight, and proper functionality of the IMU as it will read proper club head motion if centered.

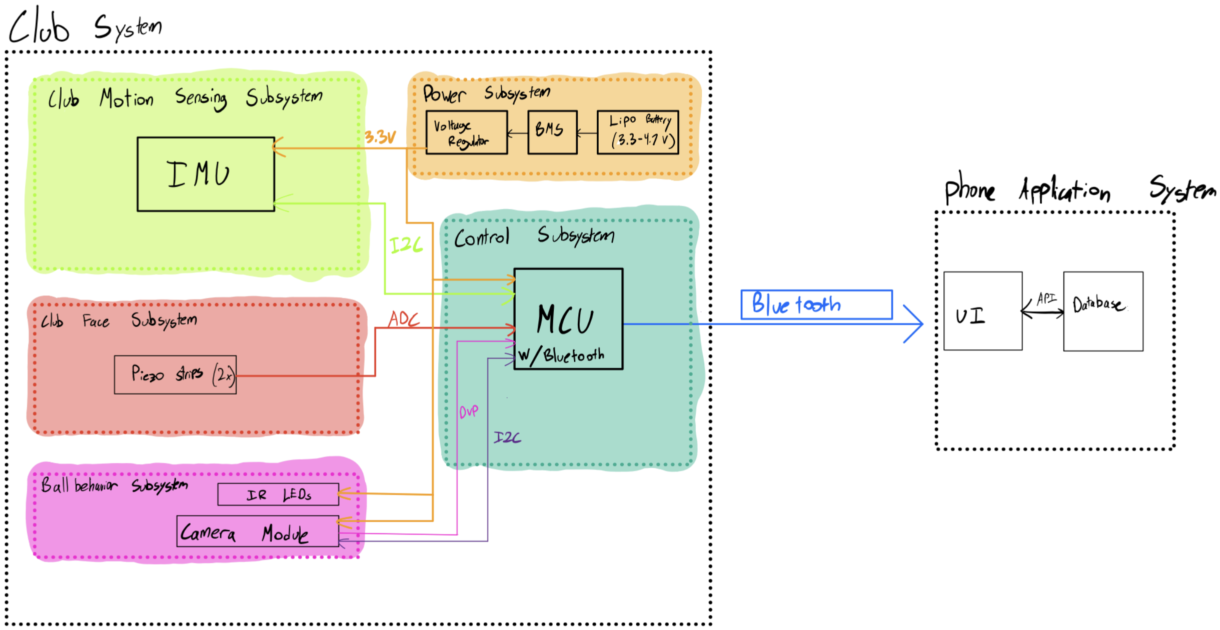
We are not entirely sure if the ideal position for the camera is also on the top of the mallet, or if it might be beneficial to create a mount roughly 8-10cm from the top of the mallet head to hold the Camera/IR module. This may allow for better end over end tracking, however this is a detail we will confirm with physical testing.


Polycase Box
mounted farther down the shaft


Battery
Regulator
PCB
Battery
MCU


Camera Module
- Mounted ~10 cm
above Club Head
- For Visual Tracking
IR
IMU
(Inertial Measurement Uot)
Piezo Strips
- Mounted on Club Face
- For Impact Detection

2.2 Block Diagram



2.3 Functional Overview & Subsystem Requirements

The following sections describe each subsystem in detail, including requirements, a Requirements & Verification (R&V) table, tolerance analysis, and hardware components.

2.3 Subsystem 1 – Club Motion Sensing

Description

An inertial measurement unit (IMU) mounted into the main PCB, located on the back end of the clubhead, is the primary piece of this subsystem. It integrates an accelerometer, gyroscope, and magnetometer which will provide measurements for club speed, acceleration and deceleration, tempo, and rotational motion throughout the stroke. By continuously tracking the putter's movement before, during, and after impact, this subsystem captures the physical characteristics of the user's stroke. The club motion sensing subsystem connects to the control subsystem through I2C and streams continuous data. It is powered by the 3.3 V rail.

Requirements

- I2C communication established between IMU and MCU with communication error < 2% per session.
- IMU measures linear acceleration along three orthogonal axes with range ≥ ±8 g and resolution ≥ 0.01 g.
- IMU measures angular velocity along three orthogonal axes with range ≥ ±500 °/s and resolution ≥ 0.1 °/s.
- IMU measures putter head velocity with accuracy within ±5% relative to reference measurements.
- IMU measures face rotation with error ≤ ±0.6° for putts up to 10 feet.
- Motion tracking operates through the duration of the stroke without interruption or data loss ≥ 95% of the time.

Requirements & Verification Table

Requirements	Verification
● We need to ensure seamless connection between IMU and IC2	● Connect IMU to MCU via I2C. Run 100 continuous putting strokes. Log I2C NACK count. Verify error rate < 2% ● Use I2C logic analyzer to confirm no bus errors during a full 30 minute putting session
● The IMU must measure linear acceleration along each dimension	● We will mount the IMU on a platform such as a treadmill with known acceleration and compare the IMU output to a reference accelerometer. ● Verify reported range and resolution from BNO085 datasheet against measurements on bench, aim for +/- 8 g and a resolution of at least 0.01 g

● The IMU must measure angular velocity along each dimension	● Use a rate table or manual rotation test with known angular velocity reference (bicycle wheel at constant speed). ● Confirm values reported by IMU match reference within specification, and aim for +/- 500 degree/sec and resolution of 0.1 degree/sec
● IMU must accurately measure putter head velocity	● We can place putter on treadmill and check velocity ● Aim for +/- 5% relative to measurements
● IMU must accurately measure face rotation while putting	● Fix putter at known angles and record IMU angle output for 10 ft putts ● Confirm error ≤ ±0.6° across all test angles.
● Motion tracking operates throughout duration of the putt and without interruption	● Have a 30 minute putting session ● Ensure that there are no gaps in data, or at least 98% of data is recorded live

Tolerance Analysis

A major risk is whether this subsystem can measure putter face angle at impact with sufficient accuracy to provide meaningful feedback. Putting is highly sensitive to directional error. For a 10-foot putt, the allowable lateral miss distance for the center of the ball is the hole radius minus the ball radius, roughly 1.285 inches. Using $x = L \cdot \tan(\theta)$, the maximum angular error is ~0.61°. This shows that the face angle error must be within ±0.6° to reliably distinguish makeable putts from misses. The BNO085 specifies a heading accuracy of ±1.0° RMS in fusion mode; we will evaluate whether additional sensor fusion or calibration is needed to meet the ±0.6° target.

Hardware Components

- Adafruit 9-DOF Orientation IMU Fusion Breakout – BNO085 (for breadboard prototyping)
- CEVA BNO085 IMU ACCEL/GYRO/MAG I2C 32-bit (for PCB integration)

2.4 Subsystem 2 – Impact Sensing

Description

This subsystem detects the time and characteristics of contact between the putter and ball using two piezo film strips positioned near the heel and toe of the clubhead. The sensors generate a voltage signal in response to ball impact, allowing the system to determine the timestamp and relative location of contact (heel, center, or toe). The impact timestamp synchronizes motion data from the IMU. This subsystem connects to the control subsystem via ADC input ports.

Requirements

- Ball impact is detected ≥ 98% of the time during normal putting strokes.
- Ball impact is correctly classified (heel, center, or toe) with ≥ 90% accuracy.
- Impact timestamp captured within ~5 ms relative to true contact moment.
- Abnormal impact signatures (double hits, ground contact) are detected with ≥ 95% accuracy.
- Impacts are sampled at a minimum frequency of 2 kHz during the impact window.

Requirements & Verification Table

Requirements	Verification
● Ball Impact must be consistently recorded each stroke, as otherwise we are unable to make observations about contact’s effect on ball movement.	● We will take 300 putting strokes, and we must detect impact 98% of the time
● Ball Impact being able to classify it as either heel, toe, or center is extremely important for ball path analysis	● To accomplish this, we will put 300 putts again, but fix the ball and putter path such that we have 100 consecutive putts for heel, center, and toe contact ● We need at least 95% accuracy, so no more than 5 slight misreads per location
● In order for seamless interactivity with the data, we need real time access to ball impact data	● Using an external timer and voltage readings, we will test 100 putts and ensure the average impact detection latency is ≤ 5 ms.
● We need to be able to detect mishits and errors	● We will again test 100 putts, and we must be

● Double hits may register only as the first or most recent putts	able to detect the correct abnormality 95% of the time ● We will implement an algorithm that utilizes timing to correctly process a double hit (within .3 ms of eachother)
● We want our sampling to occur with a minimum frequency of 2KHz during our impact window	● We will configure the ESP32-S3 ADC for continuous sampling on both piezo channels ● Verify sample timestamps show consistent ≤ 0.5 ms intervals using a timer

Tolerance Analysis

The impact between ball and putter is a very short event; insufficient sampling can miss the peak and distort metrics. Assuming 5 ms of contact duration, a 2 kHz sampling rate yields a 0.5 ms sampling period, which provides ~10 samples across the 5 ms window. This is sufficient to detect impact reliably and estimate a peak impulse metric. Heel/toe classification relies on the amplitude ratio between the two piezo sensors; this ratio will be characterized empirically using a pendulum impact fixture at known contact locations.

Hardware Components

- 2× Piezo film strip: TE Connectivity Measurement Specialties LDT0-028K (1002794)

2.5 Subsystem 3 – Ball Behavior Sensing

Description

A camera module and corresponding infrared LEDs track ball rotation and wobble immediately after impact. A small hole drilled in the center of the club face allows the camera to be positioned in the back of the head, looking toward the face. Balls will have a line across the equator enabling measurement of roll changes over time. This subsystem provides quantitative metrics for ball rotation rate, roll axis stability, and off-axis wobble. Image data is processed by the control subsystem and key metrics transmitted to the mobile application.

Requirements

- The camera captures video at a minimum rate of 20 frames per second.
- Subsystem detects the orientation line of the ball with ≥ 90% detection accuracy.
- Ball rotation error rate < 10% relative to reference video analysis.
- Wobble detected accurately when > 5° deviation from ideal roll.
- IR illumination and ball-vision maintained throughout the stroke and follow-through.

Requirements & Verification Table

Requirements	Verification
● It is important for analysis that our Camera captures footage at a minimum of 20 fps.	● To do this, we will configure the OV5640 camera via ESP32-S3 and capture a 10-second video clip ● We will count frames in captured video order to verify that the frame rate is at least 20 fps consistently.
● The camera and IR system must be able to tell the orientation of the ball in order to properly track movement.	● To test this, we will place the ball with the equator line visible to the camera in 30 stationary positions at varying angles. ● We will run the detection algorithm, which for 90% accuracy requires the line to be detected in ≥ 27 of 30 positions.
● We want to be able to refine our ball rotation analysis to ensure our measured rotation rates are correct	● We will record both with our camera/ir measurement system, and a high frame camera, and compare machine calculated rotation rate with what we observe from a higher quality camera ● Rotation rates should be within 5% of eachother

• The IR illumination and ball vision must be maintained throughout stroke and follow through.	• Perform 100 full strokes. Review captured video for illumination dropouts or occlusion • Ensure at least 98 putts are followed by camera module (98%)

Tolerance Analysis

The primary risk is whether the camera can maintain a stable line of sight to the ball long enough to measure roll behavior. We need a wide camera angle, and computations must rely on a minimal time window immediately after impact. The OV5640 supports up to 30 fps at QVGA resolution, which exceeds the 20 fps minimum. IR LED placement and intensity will be tuned to provide consistent illumination of the equator line across the expected range of ball positions.

Hardware Components

- IR LEDs: Vishay TSAL6400
- OV5640 camera module

2.6 Subsystem 4 – MCU and Bluetooth Communication

Description

The ESP32-S3 is the central processing and control unit. It has built-in Bluetooth capability and can interface with the camera module. It collects IMU data via I2C, reads analog inputs from the piezo impact sensors, and receives camera data. All signals are processed to compute stroke and ball mechanics, then transmitted to the application over Bluetooth. This subsystem synchronizes all sensors, manages timing alignment, and handles wireless communication.

Requirements

- Stroke metrics are computed within 500 ms of impact detection.
- Stroke data is transmitted for 100% of strokes.

- All local data and transmitted data are aligned 1-to-1 (no dropped, duplicated, or mismatched packets).
- Bluetooth connection stability maintained for at least 240 minutes.
- IMU and impact sensor data aligned within ±5 ms.

Requirements & Verification Table

Requirements	Verification
● Stroke metrics must be computed as fast as possible so that we can transmit usable data directly to bluetooth	● We must timestamp the impact detection itself as well as and final BLE packet transmission in firmware ● We will log this for 100 strokes, and the mean time between these should be 500ms or less
● We need our MCU to transmit each reading from all of our measurement units	● We will perform a 100 stroke session with phone app logging received packets ● We must verify that for each putt where we record any data that it is transmitted to the app, with a 100% MCU transfer success rate
● It is important that our local and transmitted data are aligned with no discrepancies	● Log stroke IDs on MCU and in app simultaneously for 50 strokes ● Match each data point and ensure identical contents between app and raw data
● Our Bluetooth connection must remain stable while we are using the device	● We will initiate Bluetooth connection and run idle polling for 240 minutes at 10-foot range ● We should have no disconnects
● In order for synchronization of our data transmission and calculations, our IMU and impact sensor data aligned within 5 ms.	● Simultaneously log IMU timestamp and piezo interrupt timestamp for 30 impacts ● Compute time delta for each. Verify all within 5 ms.

Tolerance Analysis

The critical risk is misalignment of the IMU data stream and the impact timestamp. Assuming the IMU samples at Fs Hz, the worst-case quantization error is ±(1/2Fs). At Fs = 200 Hz, worst-case error is ±2.5 ms, within the ±5 ms tolerance. Impact is recorded using an interrupt-driven GPIO/ADC trigger with a microcontroller timer timestamp, keeping total alignment error within the remaining tolerance for interrupt processing latency.

Hardware Components

- ESP32-S3 Microcontroller

2.7 Subsystem 5 – Phone Application

Description

The phone app receives data from the putter via Bluetooth and presents it in an interactive, user-friendly format. Using a local database, the app provides live feedback from the last putt and allows the user to examine trends and observe improvement over time. Users can compare sessions, try different putting approaches, and identify specific sources of error.

Requirements

- The app must display stroke metrics (speed, face angle, impact location, ball roll) within 2 seconds of each putt.
- Stroke data must be stored in the database with 100% reliability and be retrievable for trend visualization.

Requirements & Verification Table

Requirements	Verification

Our App needs to be snappy, and allow a golfer immediately after his putt to see what he did	● We will require that each putt reading is visible on the app within 2 seconds of the putt ● Timestamp BLE packet reception and on screen render time in app logs for 30 strokes ● Ensure average time is within 2 sec
Our app has stroke data stored with 100% reliability and retrievability for in round trends	● We will perform a 100 stroke session. Close and reopen app, navigate to trend view, and verify all 100 strokes appear in history with correct data

Tolerance Analysis

The primary risk is delayed display or incomplete storage of stroke data due to Bluetooth latency. Since metrics are only required within 2 seconds of impact, moderate communication delays are acceptable. Local buffering and acknowledgment of received stroke packets ensure reliable data storage despite timing variability.

Hardware Components

- Mobile phone (iOS or Android)

2.8 Subsystem 6 – Battery and Power

Description

A LiPo battery (~3.7 V nominal, approximately 200 mAh) powers the system. A 3.3 V linear regulator provides a stable supply to the MCU, IMU, camera module, and piezo circuitry. Physical size is a primary constraint given the limited space inside the putter head. A battery management IC will handle safe charging.

Requirements

- Stable 3.3 V supply to all components under full operational load.
- Battery must power the system for at least 4 hours of continuous use (~2 rounds per charge).

Requirements & Verification Table

Requirements	Verification
• We need to be able to provide a stable 3.3V output at all times (under load or no load)	• We will connect regulator output to electronic load set to estimated max current draw. • We will measure output voltage with a multimeter. Verify 3.3 V ± 5% under no load and full load, from full battery (4.2 V) down to cutoff (3.5 V).
• We need our battery to be able to provide power for at least one full round of golf, ideally more	• We will charge our battery to full, and run the system with IMU streaming, BLE active, and camera at 20 fps. • We will do this 3 times, and record time until the system shuts down • The average time our system should run must be at least 4 hours

Tolerance Analysis

The main risk is voltage instability during peak current draw from the MCU and Bluetooth radio. An LDO regulator with sufficient dropout voltage will be selected to maintain 3.3 V during transient loads. Total current draw will be estimated from component datasheets and verified by bench measurement. Battery capacity is sized to support at least 2 hours at the estimated average current draw.

Hardware Components

- 3.3 V LDO voltage regulator (TBD – e.g., LP3985 or equivalent)
- LiPo battery (~200 mAh, 3.7 V)
- Battery management / protection IC (TBD)

2.9 Subsystem 7 – Club Mounting / Physical Integration

Description

A machined or 3D-printed fixture mounts the PCB and battery flush to a mallet-head putter. The mallet head was chosen for its larger surface area and popularity on the PGA Tour. The fixture is designed to be aesthetically clean and may optionally route battery components toward the grip if needed for balance.

Requirements

- The mounting hardware must integrate flush with the mallet head without exceeding 500 g added weight.
- The putter must maintain acceptable balance as validated by > 90% satisfaction from a sample of 20 golfers.

Requirements & Verification Table

Requirements	Verification
● We need to keep the weight of the putter close to the standard weight of a putter	● We will weigh the complete assembled putter (with all electronics installed) and the baseline putter separately. ● The difference must be less than 500 g, measured with a precision scale.
● It is paramount that our putter keeps a natural feel, and that golfers don't feel it is clunky to move	● Recruit 20 golfers (range of skill levels). Have each hit 10 putts with sensor mounted putter ● Administer satisfaction survey (1–5 scale). Verify ≥ 18/20 rate 3 or higher for putter feel and balance

Tolerance Analysis

The primary risk is relative movement between the sensors and the club head during a stroke, which would reduce measurement repeatability. A rigid, flush-mounted fixture is designed to limit relative rotation to < 0.5°. Added mass is limited to 100 g to preserve balance and user feel.

Hardware Components

- Machine shop machined or 3D-printed attachment fixture
- Mallet-head putter (TBD – specific model to be selected)

2.10 Hardware Design

2.10.1 PCB Overview

The PCB integrates the ESP32-S3, BNO085 IMU, piezo ADC inputs, and camera interface into a single rigid assembly that mounts to the mallet head. Layout priorities are: short sensor traces, clean analog routing for the piezo channels, and robust power/grounding to avoid resets or noisy ADC readings.

We plan a **2-layer FR-4 PCB (1.6 mm, 1 oz copper)** with ground pours and stitching vias to provide a stable return path and reduce EMI. The **ESP32-S3** is placed centrally to shorten runs to the camera interface and power stage. The **BNO085**is placed on a mechanically rigid region aligned to the putter reference frame to reduce error from flex; local decoupling is placed adjacent to its supply pins. Piezo traces route through an analog “quiet” area with a single-point connection back to the main ground plane.

Board interfaces/features:

- **Power input:** JST-style connector for 1S LiPo input placed near the regulator/charger section to minimize IR drop.
- **Camera interface:** short FFC/FPC or board-to-board connection (final connector depends on the chosen camera breakout/module).
- **Debug/programming:** UART/USB access (either via the dev module USB or a small header/test pads).
- **Mounting:** 2–4 mounting holes aligned to the mechanical fixture to prevent micro-slip; keep-outs around fasteners.
- **Test points:** 3.3 V, battery voltage, I2C (SCL/SDA), and piezo channel test pads to speed bring-up.

2.10.2 Operating Voltage & Regulation

The system uses a **1S LiPo (≈3.0–4.2 V operating range)** and generates regulated rails for the MCU/sensors and camera. Power design focuses on stable operation during peak compute/BLE events and camera capture bursts.

Rail plan

- **3.3 V rail:** ESP32-S3 + IMU + piezo front-end reference.
- **Camera rail(s):** depends on the selected module; if the camera board does not provide onboard regulation, additional rails (e.g., 2.8 V analog / 1.5 V core) are generated on the PCB.

Regulator approach (3.3 V)
We use an LDO (or equivalent regulator) sized for worst-case peak draw with headroom. Dropout is checked against the LiPo minimum voltage so the rail remains regulated over the usable battery range. Input/output capacitors are placed per datasheet within a few mm of the regulator pins, and each IC has local 0.1 µF + bulk decoupling as needed.

Current budgeting
At this stage, we maintain an estimated budget to size the regulator and battery; final numbers are validated by bench measurement during bring-up.

Component	Typical Current
ESP32-S3	~100 mA
BLE	~30 mA
IMU	~3 mA
Camera	~50 mA

2.10.3 Signal Conditioning – Piezo Sensors

The piezo film strips produce fast, high-impedance transients that can swing above/below MCU rails. The analog front-end is designed to (1) protect the ESP32-S3 ADC pins, (2) bias the signal into the ADC range, and (3) preserve timing and relative amplitude between channels.

Per-channel front-end topology

- **Series resistor (order: 10–100 kΩ):** limits input current and helps with transient control.
- **Clamp protection:** diodes (or ESD structure) to 0 V and 3.3 V to prevent ADC over/under-voltage.
- **Mid-rail bias:** bias node at ~1.65 V using a high-value divider (order: hundreds of kΩ to 1 MΩ) with a capacitor to stabilize the bias; AC-couple the piezo into this node so negative swings are centered safely.
- **Optional RC shaping:** if needed to reduce ringing; values tuned so the ~ms-scale impact is not smeared.

ADC usage

During an impact window, the firmware samples fast enough to capture the peak and timestamp the event; it records per-channel peak amplitude AL,AR. Impact location is derived from a normalized ratio:

$$r = (AL + AR)/(AL - AR)$$

Thresholds for heel/center/toe are calibrated empirically using controlled hits at known face locations.

2.11 Software Design

2.11.1 Stroke Detection Algorithm

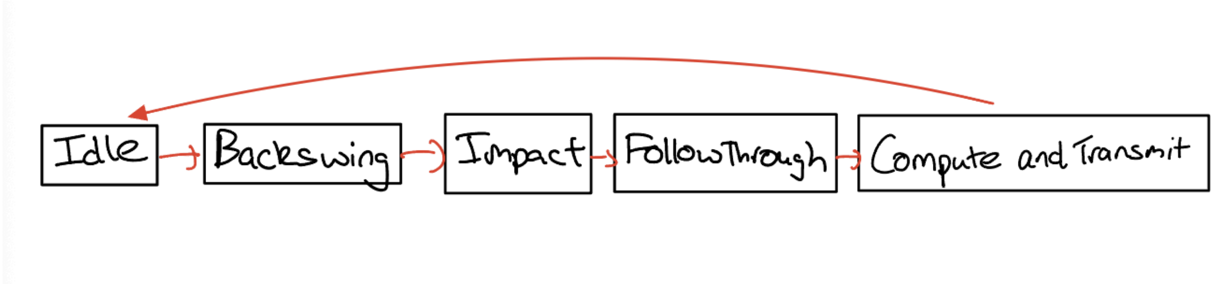
Stroke detection is implemented as a simple state machine driven by IMU motion and a piezo impact trigger. This avoids double-counting strokes and gives a clean timestamp for impact.

States

- **IDLE:** wait for motion above threshold.
- **BACKSWING:** motion detected; buffer IMU data.
- **IMPACT:** piezo threshold/interrupt triggers impact timestamp.
- **FOLLOW-THROUGH:** capture a short post-impact window.

- **COMPUTE & TRANSMIT:** compute metrics, send one BLE packet, return to IDLE.

Initial motion thresholds are treated as tunable parameters (set conservatively at first, then refined during testing). A short refractory lockout after IMPACT prevents ringing from generating a second "impact."



2.11.2 Sensor Fusion & Metrics Computation

The IMU provides fused orientation as a quaternion q(t). We define a calibration pose q0 (static "address" orientation). At impact time ti, the relative orientation is:

$$qrel = q(t_i) \cdot q0^{-1}$$

From qrel, we extract the face-angle component relative to the target line by applying the rotation to a fixed "face normal" vector in the putter frame and computing the signed angle against the target direction in the putting plane.

Impact location (piezo)
Using the two piezo channels, compute $r = (AL + AR)/(AL - AR)$ over the same impact window and classify heel/center/toe using calibrated thresholds.

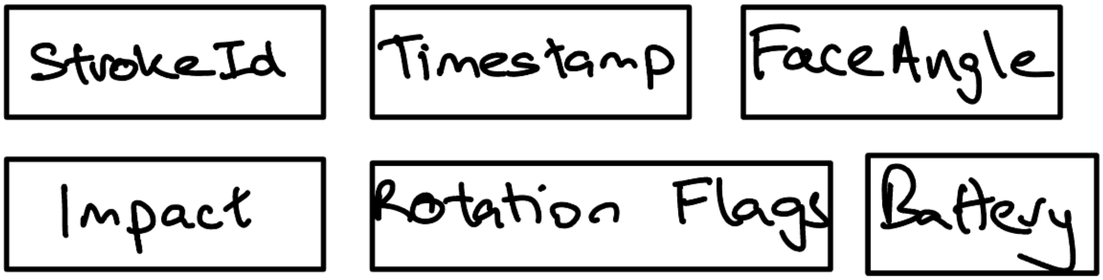
Ball behavior (camera)
After impact, the camera captures a short burst under IR illumination. A lightweight approach is to detect the ball region and track a visible marker/line orientation across frames; rotation is estimated from the change in marker angle over time. Wobble can be flagged if the estimated orientation/centroid shows oscillation or inconsistent rotation progression across the capture window.

2.11.3 Bluetooth Packet Structure

Each stroke produces **one notification** over a custom BLE service/characteristic. The payload is fixed-length to simplify parsing and reduce overhead. Service/characteristic UUIDs are custom 128-bit UUIDs defined in the firmware and mirrored in the app.

Example fixed payload fields (byte layout)

- Stroke ID (monotonic counter)
- Impact timestamp
- Face angle at impact
- Impact location (heel/center/toe)
- Ball rotation estimate
- Flags (e.g., wobble, low battery)
- Battery voltage



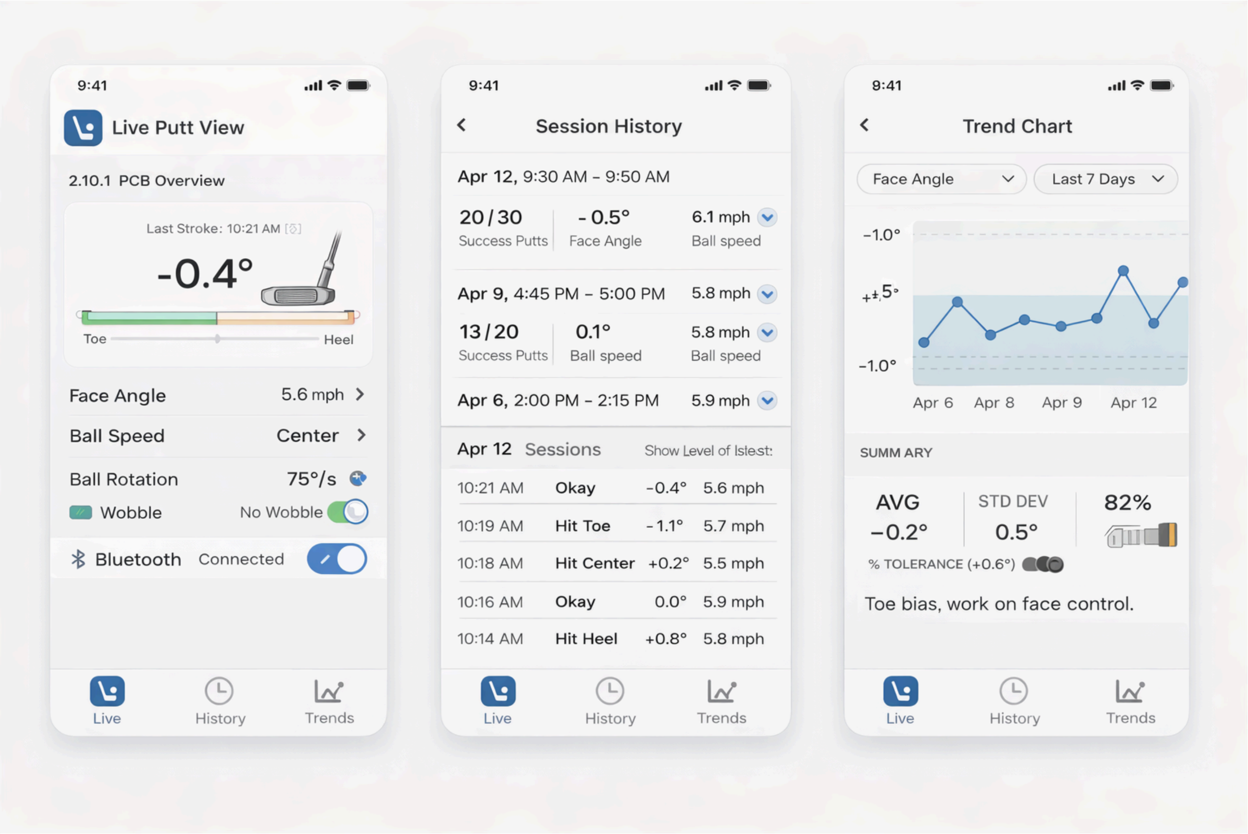
2.11.4 Phone App Architecture

The phone app handles BLE connection, packet parsing, and session logging/visualization. A cross-platform implementation (or a single-platform prototype) is acceptable; final stack depends on time constraints and team preference.

Core app responsibilities:

1. Scan/connect to the putter device and subscribe to stroke notifications.
2. Validate and parse each stroke packet.
3. Store strokes locally by session (timestamped).
4. Display:
    - **Live view** (most recent stroke metrics)

- ○ **Session history** (list of strokes)
- ○ **Trends** (simple plots of face angle consistency / speed consistency over time)



2.10.1 PCB Overview

Last Stroke: 10:21 AM

-0.4°

Face Angle 5.6 mph

Ball Speed Center

Ball Rotation 75°/s

Wobble No Wobble

Bluetooth Connected

Apr 12, 9:30 AM – 9:50 AM

20 / 30 Success Putts · - 0.5° Face Angle · 6.1 mph Ball speed

Apr 9, 4:45 PM – 5:00 PM 5.8 mph

13 / 20 Success Putts · 0.1° Ball speed · 5.8 mph Ball speed

Apr 6, 2:00 PM – 2:15 PM 5.9 mph

Apr 12 Sessions Show Level of Islest:

10:21 AM	Okay	-0.4°	5.6 mph
10:19 AM	Hit Toe	- 1.1°	5.7 mph
10:18 AM	Hit Center	+0.2°	5.5 mph
10:16 AM	Okay	0.0°	5.9 mph
10:14 AM	Hit Heel	+0.8°	5.8 mph

SUMM ARY

AVG −0.2° · STD DEV 0.5° · 82%

% TOLERANCE (+0.6°)

Toe bias, work on face control.

2.12 Tolerance Analysis

2.12.1 Face Angle Accuracy (Subsystem 1)

For a 10-foot putt, the allowable lateral miss for the center of the ball is hole radius minus ball radius ≈ 1.285 inches. Using x = L·tan(θ): θ_max = arctan(1.285 in / 120 in) ≈ 0.61°. The BNO085 specifies ±1.0° RMS heading accuracy in free fusion. Achieving the ±0.6° target will require static calibration and evaluation of drift during a full stroke. This is the primary technical risk of the project.

2.12.2 Impact Timestamp Resolution (Subsystem 2)

Contact duration is approximately 5 ms. At 2 kHz sampling (0.5 ms period), ~10 samples are captured within the contact window. This provides sufficient data to identify the peak impulse and timestamp it to within 0.5 ms, well within the ≤ 5 ms requirement.

2.12.3 IMU–Piezo Timing Alignment (Subsystem 4)

IMU sampling at 200 Hz introduces a worst-case quantization error of ±2.5 ms. The piezo interrupt adds negligible latency via interrupt-driven GPIO. Total worst-case alignment error is approximately ±3 ms, within the ±5 ms requirement.

2.12.4 Battery Life (Subsystem 6)

Battery life is estimated in two ways: (1) a conservative “upper bound” assuming high current draw, and (2) an expected duty-cycled profile where the camera/IR are only active briefly after impact. Because current draw depends heavily on camera duty cycle and BLE settings, the design doc’s estimate is treated as provisional until bench measurements are available.

During bring-up we will measure current in key modes (BLE idle connected, IMU streaming, camera burst, full stroke capture → transmit). Using measured values and an assumed practice cadence (strokes/min), we compute average current and select the smallest battery that meets the session-length target with margin. If needed, we reduce average draw via duty cycling (camera window length, BLE parameters, and MCU sleep between strokes).

3.1 Cost Analysis

Description	Manufacturer	Quantity	Extended Price	Link
IMU ACCEL/GYRO/MAG I2C 32BIT	Adafruit	1	$24.95	Link
SENSOR PIEZO FILM VIBRA TABS	TE Connectivity Measurement Specialties	3	$15.03	Link
ADAFRUIT OV5640 CAMERA BREAKOUT	Adafruit	1	$19.95	Link
ESP32-S3-WROOM-1-N8R8 DEV BRD	Espressif Systems	1	$15.00	Link
EMITTER IR 940NM 100MA RADIAL	Vishay Semiconductor Opto Division	2	$0.96	Link
IMU ACCEL/GYRO/MAG I2C 32BIT	CEVA Technologies, Inc.	1	13.05	Link
OV5640 CAMERA XIAO ESP32S3 SENSE	Seeed Technology Co., Ltd	1	$11.99	Link
RF TXRX MOD BT WIFI PCB TH SMD	Espressif Systems	1	$6.56	Link
IC REG LIN 3.3V 500MA SOT-223-3	Microchip Technology	1	$0.69	Link
IC REG LIN 2.8V 500MA SOT-223-3	Microchip Technology	1	$1.16	Link
IC REG LINEAR 1.5V 1A SOT-223-3	Microchip Technology	1	$1.61	Link
CONN FFC VERT 24POS 0.5MM SMD	GCT	1	$0.62	Link

CRYSTAL 32.7680KHZ 12.5PF SMD	Abracon LLC	1	$0.69	Link
Capacitor - 0.1µF / 50V (0805)	Yageo	12	(E-shop SMD)	Link
CAP CER 18PF 50V X8R 0805	KEMET	2	$0.20	Link
Capacitor - 0.001 µF / 50V (0805)	Samsung	3	(E-shop SMD)	Link
Capacitor - 10µF / 50V (0805)	muRata	6	(E-shop SMD)	Link
Connector - Micro USB-B	Amphenol FCi	1	(E-shop SMD)	Link
Diode - CDBA540-HF (DO214AC)	Comchip	2	(E-shop SMD)	Link
Diode - CDBA540-HF (DO214AC)	Comchip	3	(E-shop SMD)	Link
Resistor - 10KΩ 1%(1/8W) (0805)	Stackpole Electronics, Inc.	14	(E-shop SMD)	Link
RES 1M OHM 1% 1/8W 0805	TE Connectivity Passive Product	5	$0.50	Link
Resistor - 22Ω / 1% / (1/10W) (0603)	Yageo	1	(E-shop SMD)	Link
Switch - Tactile	Littelfuse	2	(E-shop SMD)	Link

3.2 Schedule

Week of	Tasks	Owner
Feb 23–Mar 1	Design Doc finalized. Order breadboarding components. PCB design draft completed.	All
Mar 2–8	Design Review week. Breadboard prototype of IMU + piezo. ESP32-S3 BLE test.	All
Mar 9–15	Breadboard Demo. Piezo signal conditioning. Camera module integration test.	All
Mar 23–29	Third PCBway order deadline (3/9). PCB layout complete. Machine shop drawings.	All
Mar 30–Apr 5	PCB assembly. IMU calibration. Stroke detection algorithm prototype.	All

Apr 6–12	Progress Demo week. Integration of all subsystems. R&V testing begins.	All
Apr 13–19	Full system test. App data display verified. Balance user study.	All
Apr 20–26	Mock Demo. Final bug fixes. Presentation preparation.	All
Apr 27–May 3	Final Demo (4/27). Final Presentation (4/27). Final Paper due (5/4).	All
May 4	Best Projects Ceremony. Lab Checkout.	All

4 Risk and Ethics + Safety

4.1 Risk Analysis

Risk	Mitigation	Likelihood	Impact	Priority
BNO085 face angle accuracy does not meet ±0.6° target	Evaluate sensor fusion modes; add static calibration; if insufficient, investigate higher-accuracy IMU alternatives.	Medium	High	HIGH
Camera loses line-of-sight to ball during stroke	Use wide-angle lens; limit required measurement window to 50–100 ms immediately post-impact.	Medium	Medium	MED
Battery capacity insufficient for 2-hour session	Bench-measure actual current draw early; upsize battery if needed; add sleep modes.	Medium	Medium	MED
PCB design errors require multiple respins	Thorough design review; use breakout modules for first prototype; order early.	Medium	High	HIGH
BLE connection drops during practice session	Use BLE connection parameter tuning; implement auto-reconnect in app firmware.	Low	Medium	LOW
Machine shop / 3D print fixture causes sensor drift	Design rigid fixture; verify with dual-IMU comparison test (see Subsystem 7 R&V).	Low	High	MED

4.2 Ethical Considerations

A primary ethical concern is data privacy and integrity. The system collects performance data that may be considered personal or sensitive to users. In accordance with IEEE principles related to protecting public welfare and avoiding harm [1], all collected data will be stored securely, transmitted only with user consent, and used solely for performance analysis. The system will avoid misleading claims about guaranteed improvement and will present feedback transparently, with clear explanations of uncertainty and limitations.

Another ethical consideration is honest representation of system capabilities. The ACM Code emphasizes avoiding deceptive claims and ensuring that users understand how systems work [2]. Our design will clearly communicate what metrics are measured, how they are computed, and what conclusions can be drawn from the data.

4.3 Safety Considerations

From a physical safety standpoint, the system operates at low voltages and currents, minimizing electrical risk. The Bluetooth subsystem will operate under FCC Part 15 regulations governing unlicensed radio frequency devices [3]. Battery selection and regulation will follow industry best practices and align with IEC 62133 battery safety standards to prevent overheating, short circuits, or leakage [4]. Mechanical integration will ensure that no sharp edges, exposed wiring, or loose components pose a risk during normal use.

The system does not alter the putter's structural integrity or introduce high-energy actuation, reducing the risk of injury. Any modifications to the club will comply with relevant sports equipment safety norms and campus fabrication policies.

4.4 Societal, Economic, and Environmental Impact

Societally, this project contributes to the growing field of wearable and embedded sports analytics, promoting data-driven skill development and accessibility to high-quality feedback tools. Economically, it aligns with trends in consumer sports technology and has potential applications in coaching, rehabilitation, and performance training.

Environmentally, the system is designed to be reusable and rechargeable, minimizing disposable components. Battery life considerations and durable mechanical integration reduce waste associated with frequent replacement.

References

[1] IEEE, "IEEE Code of Ethics," Institute of Electrical and Electronics Engineers.

[2] ACM, "ACM Code of Ethics and Professional Conduct," Association for Computing Machinery.

[3] Federal Communications Commission, "Code of Federal Regulations Title 47, Part 15 — Radio Frequency Devices," FCC.

[4] International Electrotechnical Commission, "IEC 62133 — Safety requirements for portable sealed secondary cells and for batteries made from them, for use in portable applications," IEC.

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