ECE 445
Senior Design Laboratory
Design Document

Real-Time Golf Swing Tracker

Team No. 15
Tamir Battsogt
(**tamirb2@illinois.edu**)
Ryan Leuba
(**leuba2@illinois.edu**)
Ki Jung (Ben) Kim
(**kijungk3@illinois.edu**)

TA: Sanjana Pingali
Professor: Arne Fliflet

October 3, 2024

Contents

1 Introduction

1.1 Problem

Mastering the golf swing is a complex challenge with nuances that can be difficult to grasp without precise feedback. Current training methods often rely on professional coaching, which might not be readily accessible or affordable for all golfers. Additionally, the subtle mechanics of a golf swing, including swing path, speed, and force, are not easily quantifiable through mere observation. There's a growing need for a more accessible and scientific approach to golf training that leverages modern technology to provide real-time, detailed feedback directly to the golfer. According to multiple comprehensive reviews such as Bourgain M, (2022/06/09), precise metrics such as joint angles, clubhead speed, and swing trajectory are vital to optimizing performance and preventing injuries. Despite the importance of these metrics, many golfers lack access to the necessary technology to measure them accurately in real-time. Launch sensing and analytic golf devices already exist on the market, but in our research we have found none that track positional data or grip force. These metrics would aid in improving a golfer’s backswing tremendously

1.2 Solution

We propose to develop the Real-Time Golf Swing Tracker equipped with an integrated sensor system and a companion mobile application to analyze and improve golf swings. The core of our solution involves embedding accelerometers, gyroscopes, and force sensors within the grip of a standard golf club. These sensors will capture critical data points such as swing speed, angle, and grip pressure during each stroke. This data is then processed by a microcontroller that filters and interprets the raw sensor outputs. The processed information is wirelessly transmitted to a mobile application that provides the golfer with immediate visual feedback and historical data analysis. We plan to compare the acquired sensor data to existing studies on golfing biomechanics such as Nesbit S, (2005/12/01), in order to determine optimal swings. Additionally, our group’s stretch goal involves utilizing known data sets such as GolfDB to create an accompanying computer vision project to our software component. If our baseline goals are met, we intend on expanding in order to provide more in-depth analysis.

1.3 Visual Aid

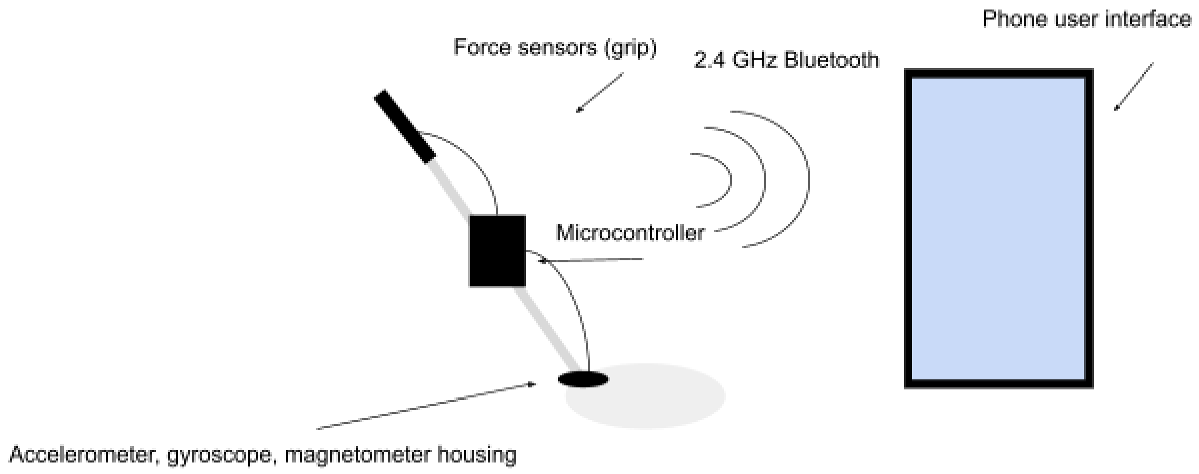


Figure 1: Simple Project Design

The analytics devices currently on the market do not physically attach to the club and instead track data at point of contact with the golf ball. This causes important data to be missed out on. The visual aid describes our example club with the positional sensors being housed on the neck of the shaft and the club head, the microcontroller being positioned towards the top of the club, and the force sensors being underneath the grip.

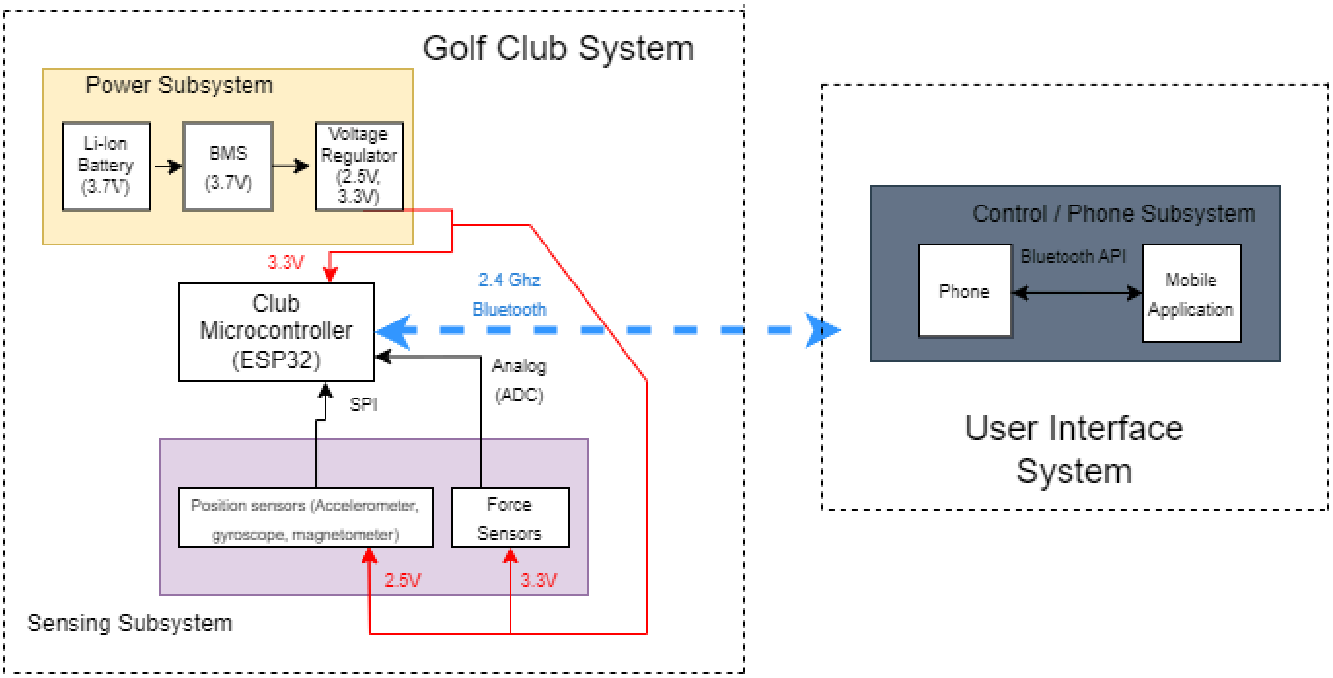
The phone user interface when implemented will not only be able to receive and display data sent by the club microcontroller, but it will have data analytics tools for the user to cross reference their swing and grip with

1.4 High Level Requirements

a. All sensors integrated into the Smart Golf Club, including accelerometers, gyroscopes, and force sensors, must maintain a tolerance of accuracy outlined within the tolerance analysis section (This level of precision is essential to ensure that the data collected is consistently reliable and reflects true performance.
b. The user interface of the Smart Golf Club's accompanying mobile application is designed to display data in real-time, ensuring that all information is updated and presented to the user within 5 seconds following each golf swing. This prompt update allows golfers to immediately see the impact of their swings on parameters such as swing speed, angle, and force, facilitating on-the-spot adjustments and learning.
c. The total weight of the Smart Golf Club, after integrating all hardware systems including sensors, microcontroller, and power supply, should not exceed a 10% increase over the weight of a standard golf club. This stringent weight threshold is essential to ensure that the club retains a natural feel and balance, allowing golfers to swing with their usual technique without adaptation to added bulk.

2 Design

2.1 Block Diagram



2.2 Physical Design

The Smart Golf Club project integrates a sophisticated sensor system designed to capture detailed swing analytics without significantly altering the feel or balance of the club. FlexiForce sensors are embedded within the grip to measure grip pressure, ensuring the golfer's natural hold is not disturbed. The PCB, housing the ESP32 microcontroller and the IMU (accelerometer, gyroscope, magnetometer), is enclosed in a compact casing mounted on the shaft just below the grip. This enclosure, with dimensions of approximately 40mm x 30mm x 10mm, is securely attached to the shaft via lightweight brackets. The positioning near the grip allows for precise motion tracking and real-time data transmission while ensuring the golfer’s comfort and maintaining the club’s performance.

The expected total weight of the system, including the sensors , PCB , ESP32 , IMU, enclosure, and mounting hardware, is approximately 100 grams. Given that a typical golf driver weighs around 12 lbs, this additional weight is well below the 10% increase threshold that could potentially impact the club’s balance and performance. Thus, the added weight from the Smart Golf Club's components is minimal, ensuring that it does not negatively affect the golfer's swing dynamics or the overall feel of the club.

2.3 Functional Overview & Block Diagram Requirements

2.3.1 Power Subsystem

The power subsystem will ensure that all electronic components within the golf club are powered during usage. We will use the 3.7V Li-ion batteries to provide consistent power to necessary subsystems for extended periods, ensuring usability through multiple rounds of gold. The 3.7 volts batteries will be regulated through a voltage regulator to get our desired 3.3 volts to be supplied through the entire system.

Power Subsystem Requirements

This power subsystem is required to continuously send power / current to necessary circuits, last for at least 10 holes of golf (equivalent to about 2.5 ~ 3 hours), and have a charging system to fully recharge the batteries within 2 hours.

Requirements	**Verification**
Power Subsystem supplies at least 0.5 A, continuously at 3.3 V ± 0.1V.	● Connect a multimeter to the power source to measure voltage and current flow.
Power subsystem integrates a charging circuit that fully recharges the batteries within 2 hours.	● Connect the battery to the charging circuit and monitor the voltage across battery terminals using an oscilloscope / multimeter during charging ● Record the time taken for the voltage to reach the battery's full charge voltage and that it is within 2 hours
Batteries should last for at least 10 holes of golf on a single charge without performance degradation.	● Verify that the power source continues to supply voltage for at least 2 hours

2.3.2 Sensor Subsystem

The Sensor Subsystem involves accelerometers, gyroscopes, and force sensors integrated in the golf club's grip. These sensors will capture critical real-time data on golf swing parameters such as swing speed, swing angle, and grip pressure. The MPU-9250 sensor includes an accelerometer, gyroscope, and a magnetometer, which will be attached right above the golf head to collect accurate data when swinging the club up and down. Also, we plan to use FlexiForce A201 as our force sensors, which will be utilized to sense the grip force from our hands to the golf grip. We would insert these under the grip such that the pressure resulting from our hands will be transmitted to the microcontroller. The power subsystem will provide sufficient power for the sensors to continuously gather and send data.

Sensor Subsystem Requirements

For this subsystem, we require the MPU-9250 to update readings rapidly to capture dynamic swing data with high accuracy. Also, sensors must be able to withstand harsh environmental conditions, such as rain or wind.

Requirements	Verification
MPU-9250 must update readings at least 1000 times per second to capture dynamic swing data accurately.	● Connect the MPU-9250 to an oscilloscope and send the outputs of the MPU-9250 to a monitor to record the sensor readings ● Ensure that the frequency measured at its highest reporting rate meets 1000 Hz
This subsystem must function effectively under the environmental conditions typically experienced on a golf course (rain, strong wind).	● Confirm that this subsystem can withstand a testing chamber of pouring rain (water) and strong gust wind source (20~30 mph) for 30 minutes

2.3.3 Control Subsystem

The Microcontroller Subsystem is at the core of the Smart Golf Club, responsible for processing sensor data and managing communication with the mobile application. It interfaces with multiple sensors, including the accelerometer, gyroscope, and magnetometer, embedded within the club, sampling data from all sensors at high frequencies to ensure accurate tracking of the golf swing. Additionally, the microcontroller must handle wireless communication via Bluetooth Low Energy (BLE) to transmit real-time data to the mobile application while ensuring minimal latency and high reliability. To manage these operations efficiently, the microcontroller needs sufficient processing power, memory, and support for the necessary communication protocols. The subsystem must be optimized for power consumption to ensure long battery life during extended use. Finally, the microcontroller must execute its tasks within a defined timeframe to meet the real-time processing demands required for a smooth user experience.

Requirements	**Verification**
The microcontroller must sample data from all sensors (accelerometer, gyroscope, magnetometer, and force sensors) at a minimum rate of 1 kHz. -1 kHz was concluded through Bourgain M, (2022/06/09) as the study concluded that average golf swings last around 0.9 seconds, with critical paths (such as downswing) lasting as little as 0.3 seconds	● Connect the microcontroller to the accelerometer, gyroscope, and magnetometer sensors. Implement a data acquisition routine that samples data from all sensors concurrently. ● Implement timestamp logging in the microcontroller's firmware. Capture the time of each sensor data sample by using a high-resolution timer available in the microcontroller such as esp_timer_get_time() and then log the given timestamps
The microcontroller must process and store sensor data from each swing without exceeding 80% of its available RAM and flash memory. -Estimation made by 1kHz sampling: One acquisition cycle will grab around 50 bytes from all the sensors. We want around 1000 cycles per second, consequently we will use up approximately 50 kb/second. Considering overhead of maintaining bluetooth connection, we don't want to ever exceed memory constraints	● Measure the memory usage of the microcontroller during typical operation, including sensor data acquisition, processing (e.g., sensor fusion), and data transmission. Log RAM and flash memory usage at key points. ● Simulate high data load conditions by swinging multiple times and monitor the memory usage to ensure that the microcontroller does not exceed 80% of its RAM or flash capacity by using built-in tools like memory profiling.
The microcontroller's power consumption should not exceed 300 mW during active	● Measure the power consumption during typical operation by connecting

operation	the microcontroller to a power analyzer or multimeter. Monitor the current draw and voltage during sensor data collection, data processing, and BLE transmission. ● Multiply the measured current by the operating voltage to calculate the power consumption (in watts). ● Ensure that during active operation, the power consumption stays within a 20% threshold of the expected esp32 BLE (bluetooth) 40 mA - 80 mA range. This can be done by verifying the calculated wattage is within (80 + 0.2*80) mA or roughly 100 mA.

2.3.4 Mobile Application Subsystem

The Mobile Application Subsystem is responsible for receiving data from the golf club's microcontroller via ESP32 Bluetooth Low Energy (BLE) and providing the user with real-time swing analytics and historical trend analysis. The application must be capable of accepting BLE connections from the microcontroller and ensuring a stable connection throughout the golf session. To provide timely feedback, the app is required to update and display relevant data within 45 seconds after each swing, ensuring the golfer has immediate access to key performance metrics such as swing speed, angle, and grip pressure.

High-level, process-intensive code will be executed within the mobile application to run algorithms and potential machine learning models aimed at analyzing swing techniques. The Mobile Application Subsystem must also feature an intuitive user interface that presents data in a clear and actionable manner, allowing users to easily understand their performance trends. Hard requirements include a design that prioritizes usability, ensuring that even amateur golfers can navigate and interpret the results without difficulty. Additionally, the app should provide sensory feedback, such as visual cues or auditory alerts, to notify the user of any detected errors or significant data patterns. These features will collectively ensure the app is not only functional but enhances the overall training experience.

Requirements	**Verification**
The application must be able to accept and maintain stable BLE connections from the ESP32	● Connect to the ESP32 from the mobile app. Confirm that the connection is successfully established within a time frame typical of a BLE handshake (3 seconds). ● Once connected, simulate normal data transmission (e.g., sensor data every second) and maintain the connection for 1 hour. During this period, move the mobile device up to 10 meters away from the ESP32, based on standard BLE specifications, which allow reliable connections within a range of 10 meters to 30 meters under typical conditions ● Finally, force a disconnection by moving the mobile application device out of range. Ensure that the application is no longer updating/processing data. Reconnect to the esp 32 and resume data analysis
The application must update and display relevant data within 45 seconds after each swing.	● Start the mobile application with no data loaded ● Simulate a golf swing event by generating sensor data from the ESP32 ● Measure the time from the moment the ESP32 sends the final data packet until the moment the processed data is displayed on the mobile application. Ensure that this time does not exceed 45 seconds. ● Confirm that the acquired data from the mobile application match the simulated data to ensure relevancy
The application must provide a visual cue such as a pop-up notification when a swing-related error or data anomaly is detected.	● Induce an error condition by sending erroneous data from the ESP32, such as a fatal connection input

	- Confirm that the mobile application stops golf swing analysis and displays error notification

2.4 Stretch Goal

As a stretch goal for the Smart Golf Club project, we plan to integrate a computer vision component using the third-party GolfDB dataset to analyze golf swings through video. This system will be entirely separate from the sensor-based hardware, leveraging the golfer's phone camera to capture video footage of their swing. We aim to train a neural network model using the GolfDB dataset to identify and classify key swing phases, such as the backswing, downswing, and follow-through. This model will be developed and trained on our laptops using deep learning frameworks like TensorFlow or PyTorch, and hosted on local machines for initial testing. Eventually, we plan to either deploy the model to the cloud using services like AWS or Google Cloud, or host it locally on the phone, enabling real-time video analysis. To manage swing data and video inputs, we may utilize cloud databases like Firebase or Amazon S3 to store and retrieve video files for analysis.

The system can then overlay annotations or guidance directly onto the video, highlighting important moments like the transition from backswing to downswing. This helps golfers visually understand where their technique might be breaking down or where they can improve. With GolfDB, we can build a system that not only detects and analyzes the current swing but also compares it with a library of professional swings. By comparing a golfer's swing to ideal swings, the system could provide personalized feedback, showing the differences and offering suggestions for improvement.

Finally, we can continue expanding this component by integrating the real-time sensor data with the computer vision model. This could potentially link the information gathered from the sensors to help explain inconsistencies found by the model. (EX: the sensors might indicate that a golfer's grip pressure was inconsistent during a swing, the computer vision component could show how this inconsistency manifested in their misalignment during the backswing or impact)

3 Cost and Schedule

3.1 Cost Analysis

Description	**Manufacturer**	**Quantity**	**Extended Price**	**Link**
FlexiForce A201 Sensor	TekScan	4	$80.88	https://www.mouser.com/c/?marcom=162104794
MPU9250 +Gyro+Accelerator+Magnetometer Sensor Module	HiLetGo	1	$14.99	https://www.amazon.com/HiLetgo-Gyroscope-Acceleration-Accelerator-Magnetometer/dp/B01I1J0Z7Y
ESP32-S3-WROOM-2-N32R8V	DigiKey	4	$26.72	https://www.digikey.com/en/products/detail/espressif-systems/ESP32-S3-WROOM-2-N32R8V/15970964
Li-Ion Battery	GlobTek	2	$14.67	https://www.digikey.com/en/products/detail/globtek-inc/BL0750F5030481S1PCTC/16515787
12 Pin Headers		8	$8.50	https://www.sparkfun.com/products/14322
Enclosure	PolyCase	1	$5.01	https://www.polycase.com/lp-55f

If we take the average yearly salary of an ECE graduate at around $100,000 dollars per year, $80 an hour and 100 hours for each person involved, we end up with about $32,156.10.

3.2 Schedule

Week	Task	Person
9/30	Design Document	Everyone
10/7	Write first iteration of PCB schematic	Ryan/Ben
	Order Parts for Prototyping	Everyone
	Begin Work on User Interface	Tamir
10/14	Finalize PCB Design and Order	Everyone
	Establish Bluetooth Reception on Protoboard	Tamir
	Begin Writing microcontroller routine for data acquisition	Tamir/Ryan
10/21	Receive PCB / parts and start soldering sensors	Ryan/Ben
	Build First Functioning Iteration of Webapp	Tamir
	First Iteration of Enclosures	Ryan
10/28	Possible PCB Order	Everyone
	Build Successful PCB with Transmission on Club	Ryan/Ben
	Successfully Receive and Process Club Data on Webapp	Tamir
11/4	Enclosures and Stable Golf Club Build	Ryan
	Display Data and UI on Webapp	Tamir

11/11	Possible PCB Order	Everyone
	Data Analysis Techniques on Webapp	Tamir
	Achieve Demo-able Project and Work on Supplementary Tasks	Everyone
11/18	Mock Demo	Everyone
11/25	Fall Break	Everyone
12/2	Polish final presentation and prepare for final demo	Everyone
12/9	Final Presentation	Everyone

3.3 Tolerance Analysis

There are two main systems that require analysis in our project, the wireless communication latency with the amount of data we are processing, and ensuring we sample our sensors at an adequate rate to reach the information processing desired while also not putting too large of a strain on the ESP32's small digital memory.

The MPU9250 has 3 axes on each of its sensors; accelerometer, gyroscope, and magnetometer. We are given that BLE4.2 has a throughput of 700 kb/s, the 9 sensors on our IMU operate at 32 kHz, and the ESP32 GPIO pins can reach a theoretical 240 MHz rate which is plenty to reach the desired data rate. The force sensors are resistive so it is through the ADC pin, which is 6 µs on the ESP32. Given that we can find the frequency using

$$fmax_{ADC} = \frac{1}{6*10^{-6}} = 166.67kHz$$

Which is also well above the desire range of frequency we want to send to the web-app. With all this in mind and given the fact that each data point will be 4 bytes as a float, the hardware involved is viable to collect data fast enough to reach our specifications.

4 Ethics and Safety

In our Smart Golf Club project, the integration of a battery to power the microcontroller subsystem raises important safety and environmental concerns, particularly related to battery disposal. According to IEEE standards and best practices for electronic device development, it is essential to handle battery disposal with care to prevent environmental harm and ensure user safety. The battery used in our system, likely a rechargeable lithium-ion or lithium-polymer battery, contains chemicals that can be hazardous if improperly disposed of. These batteries can pose risks such as leaking toxic chemicals, igniting, or causing explosions if they are damaged or not disposed of correctly.

To mitigate these risks, we will implement the following safety procedures:

- **Proper Disposal**: Batteries should not be disposed of in regular household waste due to their toxic components. Instead, they must be recycled at designated electronic waste recycling centers. Following **IEEE Standard 1625**, which provides guidelines for safe use, testing, and disposal of rechargeable batteries in portable computing environments, we will instruct users to dispose of used or damaged batteries through certified recycling programs. These programs ensure that batteries are handled, dismantled, and recycled properly, minimizing environmental impact and health hazards.
- **Lab Safety Procedures**: During development and testing, we will ensure that all batteries are handled in accordance with **IEEE Standard 1725**, which covers the design and qualification of rechargeable battery systems. In the lab, batteries will be stored in protective casings to prevent short circuits, and they will be monitored for overheating during testing. In the event of damage or malfunction, the battery will be safely removed from the system and isolated to prevent fires or chemical leaks.
- **User Instructions**: We will provide clear user instructions detailing the proper care, handling, and disposal of the battery. This will include warnings about the risks of exposure to extreme heat, physical damage, or improper charging, which could result in hazardous situations. Users will be encouraged to use only authorized recycling facilities to dispose of depleted or damaged batteries, in compliance with local regulations and IEEE guidelines.

By adhering to these procedures, we aim to ensure that the battery in our Smart Golf Club system is managed safely throughout its lifecycle, protecting both users and the environment from potential hazards.

5 Citations

- Bourgain, M., Rouch, P., Rouillon, O., Thoreux, P., & Sauret, C. (2022, June 9). *Golf Swing Biomechanics: A systematic review and methodological recommendations for Kinematics*. Sports (Basel, Switzerland). https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9227529/
- Nesbit, S. M., & Serrano, M. (2005, December 1). *Work and power analysis of the golf swing*. Journal of sports science & medicine. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3899668/
- McNally, W., & Vats, K. (n.d.). *GolfDB: A video database for golf swing sequencing*. GolfDB: A Video Database for Golf Swing Sequencing. https://openaccess.thecvf.com/content_CVPRW_2019/papers/CVSports/McNally_GolfDB_A_Video_Database_for_Golf_Swing_Sequencing_CVPRW_2019_paper.pdf