

# MULTI-MODE TABLE TENNIS TARGET TRAINING SYSTEM

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Project Proposal for ECE 445, Senior Design, Fall 2026

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16 September 2026

Project No. 22

# 1. Introduction

## 1.1 Problem

Shot placement is a fundamental component of table tennis performance. Prior work on table-tennis stroke effectiveness has shown that ball placement is a meaningful performance variable and can help distinguish between players of different performance levels [1]. In practice, however, many accuracy drills rely on tape, cones, paper targets, or verbal instructions from another person. These methods show a player where to aim, but they cannot automatically determine which location was struck, distinguish a correct hit from a wrong-target hit, or maintain quantitative performance statistics over repeated trials.

This limitation is especially relevant for players who want to practice independently. Randomized placement drills typically require a coach, partner, or ball-machine operator to tell the athlete where to aim and then manually judge the result. This dependence on a second person makes repeatable practice less accessible and makes it difficult to collect consistent metrics such as placement accuracy, misses, wrong-target hits, and streaks. Our project addresses this problem with reusable electronic targets that provide an immediate visual cue and automatically record the outcome of each attempt.

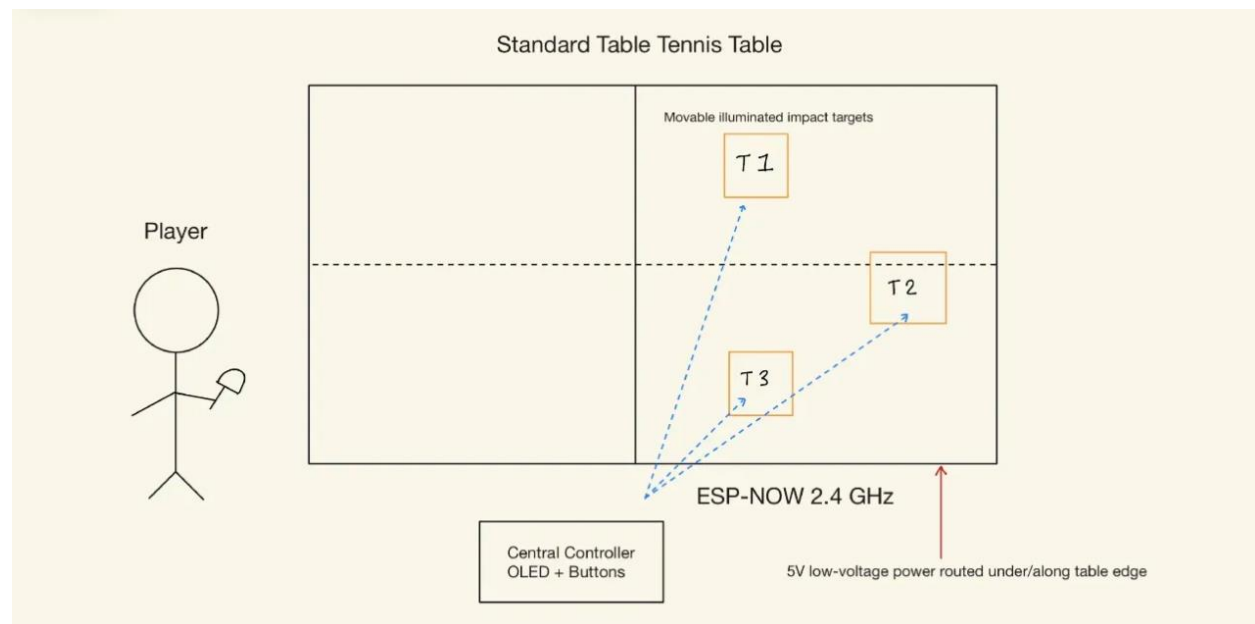
The project also has broader societal, economic, environmental, and safety considerations. A self-contained trainer can make structured practice more accessible in recreational, school, and club environments without requiring a dedicated coach for every repetition. The system is designed around reusable target modules rather than a specialized table, allowing an existing table to be upgraded instead of replaced. The targets use low-voltage external power, protected electronics, secured cabling, and low-profile removable suction cups to stabilize each target without permanent modification of the table.

## 1.2 Solution

The proposed system consists of three movable electronic target pads placed on the opponent's side of a standard table-tennis table and one central controller. Each target contains a rigid low-profile impact surface, a piezoelectric impact sensor, a custom analog front end, perimeter LEDs, an ESP32-C3-based control section, wireless communication, and a custom PCB. Four low-profile suction cups on the underside secure each target to the table during a drill while still allowing the target to be removed and repositioned for a different exercise. The three target units use the same hardware design and are distinguished by unique software identifiers. The central controller selects the active target, manages the selected training mode, receives impact messages, classifies each attempt, and displays performance statistics.

The required implementation supports two operating modes. In Rapid-Fire Placement Mode, one target is illuminated at a time. After a correct hit, wrong-target hit, or timeout, the controller records the result and automatically activates another randomized target. In Serve Accuracy Mode, the same targets are repositioned to represent serve locations. One target is illuminated before each serve, and the controller records a correct hit, wrong-target hit, or a user-confirmed miss when no electronic target is struck. Reaction Return Mode, in which target selection is synchronized with an incoming ball feed, will be pursued only as a stretch goal after the two required modes are complete.

## 1.3 Visual Aid



**Figure 1. Use context for the Multi-Mode Table Tennis Target Training System. A player aims at the illuminated electronic target while the central controller communicates wirelessly with the three target units and records the result of each attempt.**

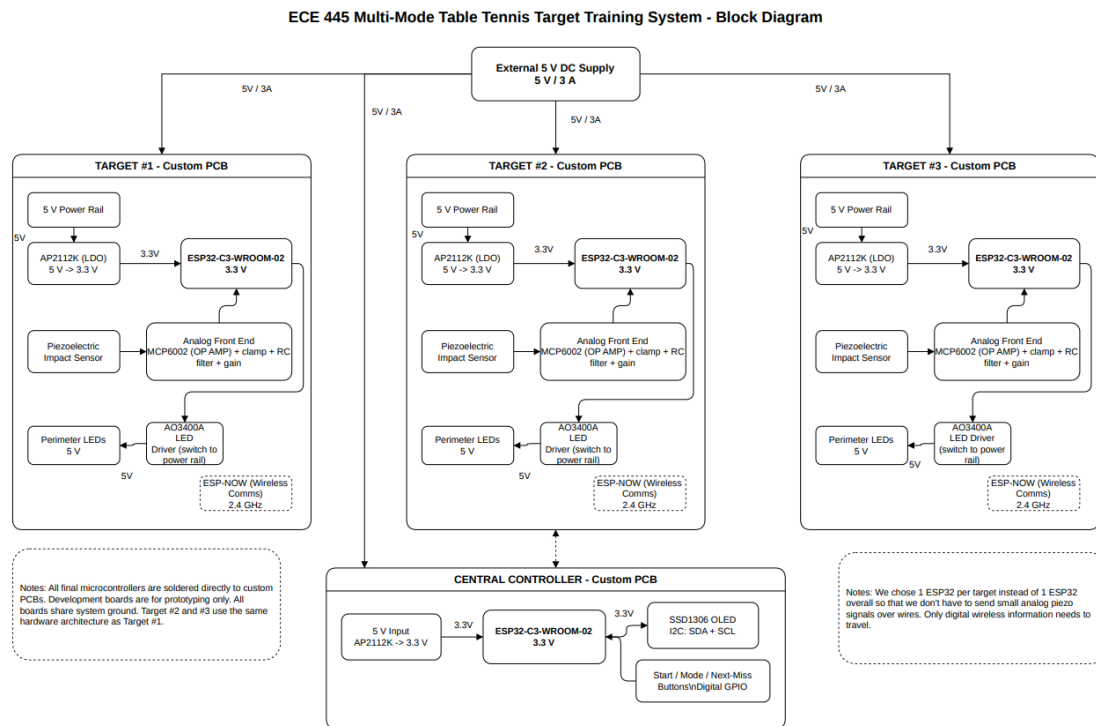
## 1.4 High-Level Requirements

- The system shall correctly detect at least 90% of direct table-tennis-ball impacts on each electronic target during a controlled test of at least 30 impacts per target, with impacts distributed across multiple locations on each target surface.
- When one target is active, the system shall correctly classify at least 90% of at least 30 controlled electronic-target impacts as either a correct-target hit or a wrong-target hit.
- The system shall complete both required training modes by performing at least 20 randomized target activations in Rapid-Fire Placement Mode and at least 10 serves using at least three target locations in Serve Accuracy Mode, while recording the required session statistics and automatically selecting the next target when appropriate.

## 2. Design

### 2.1 Block Diagram

Figure 2 shows the final system-level architecture used for this proposal. Each target performs impact sensing locally so that the small analog piezoelectric signal does not have to travel across the table. Only digital wireless information is exchanged between the target units and the central controller. All three target PCBs use the same hardware architecture.



**Figure 2. System block diagram showing the external 5 V supply, local 3.3 V rails, piezoelectric sensing paths, LED-control paths, I2C and GPIO interfaces, and ESP-NOW 2.4 GHz communication between each target and the central controller.**

### 2.2 Mechanical Concept

Each target will be approximately 10 in by 10 in and no more than 0.5 in high. A thin rigid plate will form the impact surface. A piezoelectric sensor will be attached beneath the plate, perimeter LEDs will indicate when the target is active, and a protected enclosure near the rear edge will contain the PCB and connectors. Four low-profile removable suction cups mounted under the target will secure the target to the table during impacts while allowing the unit to be detached and moved between drills. The suction cups will be tested on the exact table surface used for the demonstration. The final impact-plate material will be selected using rebound testing so that the target does not substantially change the bounce of the ball compared with the bare table surface.

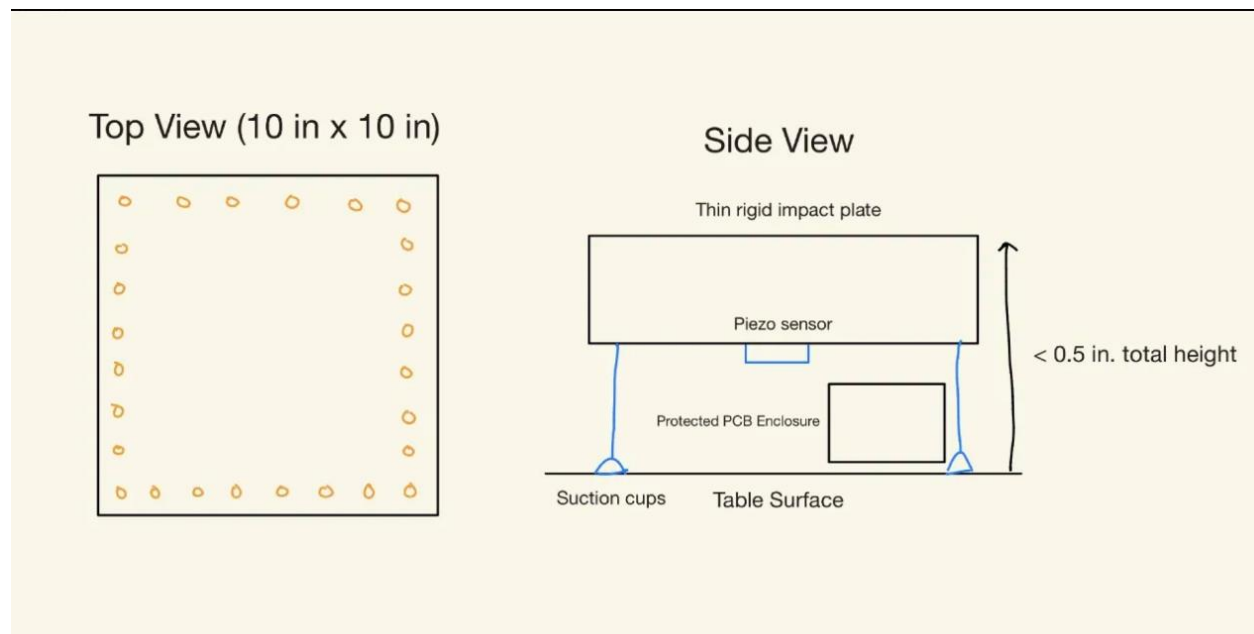


Figure 3. Conceptual target construction showing the rigid impact plate, piezo sensor, perimeter illumination, protected PCB enclosure, and four low-profile suction cups used to secure the target to the table.

## 2.3 Subsystem Overview

### 2.3.1 Target Power Subsystem

The target power subsystem receives the common 5 V DC system supply. The 5 V rail powers the perimeter LEDs and also feeds a local 3.3 V regulator for the ESP32-C3 and analog front-end circuitry. Local bypass and bulk capacitors will reduce supply disturbances caused by wireless transmission and LED switching. Keeping the LED load on the 5 V rail prevents the LEDs from consuming the current margin needed by the 3.3 V sensing and control electronics. This subsystem supports the high-level requirements by providing stable power during simultaneous sensing, wireless communication, and illumination.

### 2.3.2 Impact-Sensing Subsystem

A piezoelectric element mounted beneath the target plate converts the mechanical vibration caused by a ball impact into a transient analog voltage. The custom analog front end protects the microcontroller input, biases the signal around a mid-supply reference, amplifies the useful impact signal, and filters unwanted electrical noise before the signal reaches the ESP32 ADC. Firmware continuously compares the conditioned signal with a calibrated baseline, detects the first valid threshold crossing, and applies a short lockout interval to prevent mechanical ringing from being counted as multiple impacts. This subsystem directly supports the impact-detection and correct/wrong-target classification high-level requirements.

### 2.3.3 Target Illumination Subsystem

The target illumination subsystem uses perimeter LEDs to indicate which target the player should aim for. The LEDs are powered from the 5 V rail and switched by an N-channel MOSFET controlled by an ESP32 GPIO signal. The ESP32 therefore controls the LED state without sourcing the full LED current directly from a GPIO pin. The LEDs are placed around the edge of the target to keep the primary impact region unobstructed. This subsystem enables the player to identify the selected target during both Rapid-Fire and Serve Accuracy modes.

### 2.3.4 Target Embedded Control and Wireless Subsystem

Each target contains an ESP32-C3 control section. The microcontroller samples the impact-sensing ADC signal, executes the impact-detection algorithm, controls target illumination, assigns timestamps and target IDs to hit events, and exchanges wireless packets with the central controller using ESP-NOW over the 2.4 GHz radio. Performing detection locally reduces susceptibility to noise that would be introduced by long analog signal wires. All three target boards use the same hardware and are distinguished by software IDs. This subsystem allows the central controller to determine which physical target was struck.

### 2.3.5 Central Controller and User-Interface Subsystem

The central controller coordinates the training session. Its ESP32-C3 selects the active target, sends activation commands, receives impact messages, determines whether a correct or wrong electronic target was hit, maintains session statistics, reads the Start, Mode, and Next/Miss buttons, and updates an OLED display through I2C. The Next/Miss button is required in Serve Accuracy Mode because a serve that misses all electronic targets does not generate a sensor event. This subsystem implements the training-mode logic required by the third high-level requirement.

### 2.3.6 Mechanical Target Subsystem

The mechanical subsystem consists of the rigid impact plate, sensor attachment, four low-profile suction cups, protected LED perimeter, cable strain relief, and electronics enclosure. It must provide reliable mechanical coupling to the piezo sensor while remaining sufficiently similar to the normal table surface that a successful target hit still produces a usable rebound. The suction cups must keep the target flat and stable under repeated impacts without permanently modifying the table. This subsystem supports reliable sensing and prevents the training aid from becoming an excessive obstruction on the playing surface.

## 2.4 Subsystem Requirements

### 2.4.1 Target Power Subsystem Requirements

**PWR-1:** With a nominal 5.0 V system input, the target power subsystem shall maintain the local 3.3 V rail between 3.135 V and 3.465 V during normal operation, including wireless transmission and LED switching.

**PWR-2:** The local 3.3 V rail shall support a transient load of at least 400 mA without falling below 3.135 V.

**PWR-3:** Switching the target LEDs on and off repeatedly for five minutes while the target is stationary shall not produce more than one false impact detection.

**PWR-4:** The complete four-board system shall draw less than 3.0 A from the external 5 V supply during the defined worst-case operating test.

### 2.4.2 Impact-Sensing Subsystem Requirements

**SNS-1:** The impact-sensing subsystem shall detect at least 27 of 30 direct table-tennis-ball impacts distributed across the center and edge regions of the target surface.

**SNS-2:** A single physical table-tennis-ball impact shall produce no more than one registered hit event.

**SNS-3:** Normal table vibration and nearby ball bounces shall produce no more than one false hit during a five-minute stationary test.

**SNS-4:** The conditioned analog signal presented to the microcontroller ADC shall remain between 0 V and 3.3 V during the controlled impact test.

**SNS-5:** The firmware shall sample the conditioned impact-sensor signal at no less than 20 ksample/s while the target is monitoring for impacts.

#### 2.4.3 Target Illumination Subsystem Requirements

**LED-1:** The active target shall be visually identifiable from at least 3 m away under normal indoor lighting.

**LED-2:** The illumination subsystem shall transition from a valid target-activation command to visible LED activation within 100 ms.

**LED-3:** The illumination hardware shall not obstruct the primary ball-impact region or prevent the target from satisfying the rebound requirement.

#### 2.4.4 Target Embedded Control and Wireless Subsystem Requirements

**COM-1:** Each target shall maintain a unique target identifier and include that identifier in every transmitted impact event.

**COM-2:** At an indoor separation of 5 m, each target shall successfully complete at least 99 of 100 command-and-response wireless communication trials with the central controller.

**COM-3:** After a valid local impact is detected, the target shall transmit the impact event to the central controller within 50 ms.

**COM-4:** All three targets shall continue monitoring for impacts while only the selected target is illuminated.

#### 2.4.5 Central Controller and User-Interface Subsystem Requirements

**CTL-1:** In Rapid-Fire Placement Mode, the controller shall automatically initiate the next trial after a correct hit, wrong-target hit, or configurable timeout.

**CTL-2:** During a 20-trial Rapid-Fire session, the controller shall correctly maintain the counts for correct hits, wrong-target hits, misses/timeouts, total trials, accuracy percentage, and current hit streak.

**CTL-3:** In Serve Accuracy Mode, the controller shall accept a manual miss input and select the next target without imposing a timing requirement on the player's serve.

**CTL-4:** The OLED shall update the current target and session statistics within 250 ms of a classified trial result.

#### 2.4.6 Mechanical Target Subsystem Requirements

**MEC-1:** The target shall extend no more than 0.5 in above the table surface within the usable target area, including the suction-cup mounting arrangement.

**MEC-2:** With all suction cups fully engaged, the target shall remain flat, no suction cup shall release, and the target shall not move more than 2 cm from its initial location after any individual impact during a 20-impact stability test.

**MEC-3:** The average rebound height from the target surface shall be within 25% of the average rebound height from the bare table surface over at least 10 fixed-height drop trials on each surface.

**MEC-4:** The PCB, connectors, suction-cup hardware, and LED elements shall remain outside or below the primary ball-impact region and shall be protected from direct ball contact during normal use.

## 2.5 Tolerance Analysis

The highest-risk subsystem is impact sensing. A table-tennis ball is lightweight, and a piezoelectric sensor can produce a short waveform containing both a useful impact transient and mechanical ringing. The design must preserve enough signal bandwidth for reliable detection while preventing excessive noise and ADC overvoltage.

The proposed AB2036B piezoelectric element has a nominal capacitance of approximately 25 nF and a resonant frequency of approximately 3.6 kHz [2]. Modeling the piezo electrically as a source with its sensor capacitance, a 1.0 M $\Omega$  bias/return resistance gives the electrical time constant:

$$\tau = RC \rightarrow \tau = (1.0 \times 10^6 \Omega)(25 \times 10^{-9} \text{ F}) \rightarrow \tau = 25 \text{ ms}$$

The corresponding high-pass corner frequency is:

$$f_{hp} = 1 / (2\pi RC) \rightarrow f_{hp} = 6.37 \text{ Hz}$$

This corner frequency is far below the piezo's approximately 3.6 kHz mechanical resonance, so the bias network will not significantly suppress the fast impact transient.

A proposed output low-pass network consisting of a 2.2 k $\Omega$  resistor and a 10 nF capacitor gives:

$$f_{lp} = 1 / (2\pi RC) \rightarrow f_{lp} = 7.23 \text{ kHz}$$

At 3.6 kHz, the magnitude of a first-order low-pass filter is:

$$|H(f)| = 1 / \sqrt{1 + (f / f_{lp})^2} \rightarrow |H(3.6 \text{ kHz})| = 0.895$$

Therefore, approximately 89.5% of the 3.6 kHz signal magnitude remains after the low-pass filter, while higher-frequency electrical noise is increasingly attenuated.

The ADC sampling rate is planned to be at least 20 ksample/s. This gives a 50  $\mu$ s sample interval and a Nyquist frequency of 10 kHz. A 3.6 kHz component is represented by approximately  $20,000/3,600 = 5.56$  samples per cycle. This provides adequate temporal resolution for threshold detection and peak capture of the dominant piezo response.

The MCP6002 has a 1 MHz gain-bandwidth product [3], which is much larger than the required several-kilohertz sensing bandwidth even at the planned adjustable closed-loop gain. The amplifier will be biased around 1.65 V so positive and negative piezo motion can be represented using a single 3.3 V supply. Input-protection clamps will prevent large piezo transients from reaching unsafe ADC voltages.

This analysis demonstrates that the proposed analog bandwidth and ADC sampling rate are feasible for detecting the piezo sensor's primary mechanical response. The exact amplifier gain, impact threshold, and ringing-lockout duration will be finalized experimentally using oscilloscope measurements from direct impacts, edge impacts, nearby table bounces, and LED-switching tests. Mechanical stability of the suction-cup attachment will be verified independently using MEC-2 on the exact demonstration table.

## 3. Ethics, Safety, Societal Impact, and Standards

### 3.1 Ethical Responsibilities

The IEEE Code of Ethics emphasizes holding public safety, health, and welfare as a primary responsibility. Honestly communicating the capabilities and limitations of technology and acknowledging and correcting technical errors [6]. The team will apply these principles by reporting measured performance rather than overstating detection accuracy, documenting failure modes such as missed impacts or cross-target vibration, and retaining test results in the team's permanently bound or GitHub-based laboratory notebook.

The project will also use accurate terminology. If the optional timing feature is implemented, the measurement will be described as target-response time rather than pure human reaction time because the measured interval includes perception, stroke execution, and ball flight. Serve Accuracy Mode will not reward a faster service motion because doing so could encourage a player to alter normal technique solely to improve the recorded metric.

The required system does not use cameras, voice recordings, cloud accounts, or personal biometric data. Training statistics can remain local to the central controller. If later versions add external data logging, the team will limit collected information to training metrics and will not transmit personal information without clear user awareness and consent.

### 3.2 Safety

The system uses an external 5 V DC source and local 3.3 V rails, so no exposed mains voltage is present on the table or custom PCBs. The external AC-to-DC adapter will remain an enclosed commercial supply. The most relevant user-facing hazards are loose cables, damaged wiring, sharp mechanical edges, target movement, exposed electronics, and loss of suction during play.

Power cables will be routed along or underneath the table and secured so they do not create a trip or snag hazard. Connectors will include strain relief, and damaged power cables will be removed from service. OSHA guidance identifies damaged flexible cords and inadequate strain relief as electrical hazards [9]. Before each drill, the table surface and suction cups will be inspected and cleaned as needed so that each target can be fully seated. The suction cups and release features will remain under the target footprint so they do not create a protruding obstacle. The target must satisfy the MEC-2 stability test before use in the final demonstration.

During development, the team will follow ECE 445 laboratory safety rules. All team members have completed the required laboratory safety training and submitted the required certificate. The team will not work alone in the senior design laboratory. Soldering, bench-power-supply use, and mechanical fabrication will be performed using the appropriate laboratory or machine-shop procedures and required personal protective equipment [7].

### 3.3 Applicable Standards and Regulatory Considerations

IEEE 802.11b/g/n: The ESP32-C3-WROOM-02 includes a 2.4 GHz radio that supports IEEE 802.11b/g/n operation [5]. ESP-NOW uses the ESP32 radio hardware for peer-to-peer communication between the targets and the central controller.

47 CFR Part 15: The project uses a 2.4 GHz radio in a band governed by FCC Part 15 requirements for radio-frequency devices. Section 15.247 covers digitally modulated devices operating in the 2400-2483.5

MHz band [8]. The team plans to use an ESP32-C3 radio module and follow the manufacturer's antenna placement and PCB-layout guidance rather than creating a custom discrete RF transmitter.

ECE 445 Laboratory Safety Requirements: Course rules require laboratory safety training and prohibit students from working alone in the senior design laboratory [7]. These requirements will be followed throughout prototyping, soldering, testing, and integration.

IEEE Code of Ethics: Engineering decisions, performance claims, documentation, and testing will prioritize public welfare, truthful reporting, and correction of discovered errors [6].

### **3.4 Societal, Economic, Environmental, and Global Impact**

Societally, the project is intended to make structured table-tennis practice easier to perform without requiring a dedicated coach for every repetition. The system provides immediate visual cues and quantitative placement feedback while preserving the player's normal racket and table, so it complements rather than replaces human coaching.

Economically, the system reuses a standard table and uses three copies of the same target PCB. A common target-board design reduces PCB-development effort, spare-part variety, and replacement cost. External low-voltage power also avoids the cost, aging, charging, and transport concerns associated with installing a rechargeable battery in every target.

Environmentally, removable targets add functionality without modifying or replacing the table. Reusable suction cups avoid disposable adhesives or permanent fasteners, and the design avoids multiple rechargeable battery packs. Modular electronics allow a failed sensor or board to be repaired independently instead of discarding the entire system. Components with RoHS and REACH documentation will be preferred where practical.

Globally and culturally, table tennis is played in settings with widely varying access to coaching resources. The system's main training cue is visual illumination rather than language-heavy instruction, and the controller can display simple numeric statistics. Therefore, the same core hardware can be used by players in different settings without significant localization changes.

## 4. Verification Summary

Table 1 summarizes the primary end-to-end tests that connect the subsystem requirements to the three high-level requirements.

| Test                         | Procedure                                                                                               | Pass Criterion                                                                                                  | Supports            |
|------------------------------|---------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------|---------------------|
| Impact Detection             | Apply 30 controlled direct impacts to each target, distributed across center and edge regions.          | At least 27 of 30 impacts detected on every target, with no more than one registered event per physical impact. | HLR-1; SNS-1; SNS-2 |
| Correct/Wrong Classification | Select one active target and perform at least 30 controlled impacts across active and inactive targets. | At least 90% of impacts correctly classified as correct-target or wrong-target hits.                            | HLR-2; COM-4        |
| Rapid-Fire Mode              | Run a session of at least 20 randomized target activations.                                             | Next target is selected automatically after each completed trial and required statistics are maintained.        | HLR-3; CTL-1; CTL-2 |
| Serve Accuracy Mode          | Run at least 10 serves using at least three target locations.                                           | Each attempt is recorded as correct, wrong-target, or user-confirmed miss; overall accuracy is displayed.       | HLR-3; CTL-3        |
| False-Trigger Test           | Run five minutes of LED switching plus representative nearby table bounces/vibration.                   | No more than one false impact is registered.                                                                    | PWR-3; SNS-3        |
| Wireless Reliability         | Perform 100 command-and-response trials between each target and controller at 5 m indoors.              | At least 99 of 100 trials succeed for each target.                                                              | COM-2               |
| Mechanical Stability         | Fully engage all suction cups and apply 20 representative impacts.                                      | No suction cup releases; target remains flat and moves no more than 2 cm after any impact.                      | MEC-2               |
| Rebound Test                 | Perform at least 10 fixed-height ball drops on the bare table and 10 on the target surface.             | Target mean rebound height is within 25% of bare-table mean.                                                    | MEC-3               |

Table 1. System verification summary.

## References

- [1] T. Belli, M. S. Misuta, P. P. R. de Moura, T. D. S. Tavares, R. A. Ribeiro, Y. Y. S. dos Santos, K. J. Sarro, and L. R. Galatti, “Reproducibility and Validity of a Stroke Effectiveness Test in Table Tennis Based on the Temporal Game Structure,” *Frontiers in Psychology*, vol. 10, art. 427, Feb. 2019, doi: 10.3389/fpsyg.2019.00427.
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- [3] Microchip Technology Inc., “MCP6002: 1 MHz, Low-Power Operational Amplifier,” product documentation, accessed Sep. 15, 2026.
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- [5] Espressif Systems, “ESP32-C3-WROOM-02 & ESP32-C3-WROOM-02U Datasheet,” ver. 1.7, Mar. 2026.
- [6] IEEE, “IEEE Code of Ethics,” IEEE, accessed Sep. 15, 2026.
- [7] University of Illinois Urbana-Champaign, ECE 445 Senior Design Laboratory, “Safety,” accessed Sep. 15, 2026.
- [8] 47 C.F.R. Sec. 15.247, “Operation within the bands 902-928 MHz, 2400-2483.5 MHz, and 5725-5850 MHz,” 2026.
- [9] Occupational Safety and Health Administration, “Electrical - Flexible Cords,” U.S. Department of Labor, accessed Sep. 15, 2026.