REFLX: Reaction Enhancement in Fitness using Light-based Exercises for UPV Athletes

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Abstract

Traditional training methods, such as cone and ladder drills, inadequately simulate the rapid, stimulus-driven demands of real-game scenarios in racket sports like badminton, tennis, and table tennis. While commercial light-based systems like FITLIGHT and BlazePod show promise in enhancing visual-motor coordination, reaction speed, and agility, they are hindered by high costs, connectivity issues, and limited transferability from lab to field performance. This research proposes an integrated hardware–software solution utilizing infrared sensors, RGB LED modules, and audio cues to deliver multimodal stimuli capable of simulating sport-specific decision-making demands. The study outlines the design, construction, and calibration of a wireless IoT-enabled prototype employing ESP-NOW communication for real-time responsiveness and synchronized data capture.

Experimental trials will evaluate the system's effectiveness in improving reaction time and agility compared with traditional methods, while usability assessments will gather insights from athletes and coaches to refine functionality and user experience. By merging principles from computer science, sports science, and human–computer interaction, this study contributes to the development of accessible, evidence-based athletic training technologies and provides a foundation for future enhancements in adaptive, data-driven performance systems.

Keywords: Wireless integrated network sensors, sensor networks, applied computing, human-centered computing, interactive systems and tools

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Chapter 1

Introduction

1.1 Overview of the Current State of Technology

In the realm of sports science, the enhancement of athletes' response time and agility remains a critical focus, as these attributes directly influence performance in dynamic, unpredictable environments such as team sports and combat disciplines (Hassan et al., 2023). Traditional training methods, including cone drills and ladder exercises, have long been employed to improve these skills, yet they often fall short in replicating the rapid, stimulus-driven demands of real-game scenarios. Over the past decade, light-based reaction training systems—devices utilizing visual stimuli like LED lights to prompt immediate motor responses—have emerged as innovative tools to bridge this gap. Systems such as FITLIGHT, BlazePod, and XLiGHT have been critically analyzed for their design features, including sensor connectivity, battery life, and operational reliability, revealing strengths in portability and customization but limitations in diagnostic precision and validity (Ezhov et al., 2021).

Empirical studies have demonstrated that these systems can significantly enhance visual-motor coordination, reaction speed, and cognitive functions. For instance, interventions using FITLIGHT in small-sided games have led to marked improvements in harmonic abilities (e.g., rhythmization and responsiveness) and basic skills like dribbling among young basketball players (Hassan et al., 2023). Similarly, a 10-week FITLIGHT program improved reaction times and dribbling speeds in female basketball athletes, with effect sizes indicating substantial neural adaptations (Hassan, 2025). In motorsport contexts, light-based reactive agility training has boosted selective attention, cognitive flexibility, and cardiorespiratory capacity in car racing drivers (Horváth et al., 2022). A systematic review of visual training interventions, including light board and stroboscopic methods, further corroborates these benefits, reporting 5-27% reductions in reaction time across various sports, with greater efficacy in elite and younger athletes (Jothi et al., 2025). Reliability assessments of systems like BlazePod have also affirmed their validity for measuring simple and complex reactions in mixed martial arts (MMA) athletes, with high intraclass correlations supporting their use in training protocols (Polechoński et al., 2024).

Despite these advancements, significant gaps persist in the literature. While light-based systems show promise in controlled settings, their predictive value for field-based reactive agility remains limited, as evidenced by weak correlations between laboratory reaction speeds and on-field performance in soccer players (Broodryk et al., 2025). This suggests a disconnect between isolated visual stimuli and the multifaceted perceptual-cognitive demands of sports, highlighting the need for more integrated, sport-specific designs. Moreover, comparative analyses underscore inconsistencies in system performance, such as variable Bluetooth stability and sensor delays, which could undermine training reproducibility (Ezhov et al., 2021). These issues are largely tied to the wireless protocols used by commercial systems—typically Bluetooth or Wi-Fi—both of which introduce transmission overhead and variable latency, limiting their suitability for real-time reaction measurement. This technological gap highlights the need to explore emerging low-latency communication protocols.

1.2 Problem Statement

While traditional methods such as cone and ladder drills have been widely used to enhance reaction time and agility, they often fail to simulate the complex, stimulus-driven conditions of real-game scenarios (Hassan et al., 2023). Recent light-based reaction training systems have shown potential in improving visual-motor coordination and cognitive response (Horváth et al., 2022; Jothi et al., 2025). However, these systems remain limited by high costs, connectivity issues, and questionable transferability of laboratory-based improvements to on-field performance (Broodryk et al., 2025; Ezhov et al., 2021).

To address these limitations, this study bridges engineering innovation and applied sports performance research by incorporating ESP-NOW—a low-latency, connectionless wireless communication protocol developed by Espressif—in its development of a low-cost and customizable light-based reaction training system. By leveraging ESP-NOW's novel capabilities, the system aims to eliminate the communication bottlenecks present in existing technologies and provide a more temporally accurate, cost-efficient, and reliable training tool. If such limitations in current systems persist, athletes and coaches will continue to rely on devices that cannot fully simulate realistic gameplay conditions nor guarantee measurement precision. Thus, the integration and evaluation of ESP-NOW become central to developing a responsive and scientifically validated reaction training system.

1.3 Research Objectives

1.3.1 General Objective

The goal of this study is to develop and evaluate a light-based reaction training system that enhances the response time and agility of athletes, specifically in racket sports such as badminton, tennis, and table tennis.

1.3.2 Specific Objectives

Specifically, this study aims to:

1. design and construct a device equipped with infrared sensors, RGB lights, and speakers while integrating ESP-NOW for accurate motion detection and response measurement,
2. develop a software application that manages the device operations, records performance data, and functions both online and offline,
3. calibrate and test the system to ensure precision, responsiveness, and synchronization between hardware and software components.

4. conduct experimental trials assessing the system's effectiveness in improving athletes' response time and agility compared to traditional training methods, and

5. evaluate the system's usability, functionality, and overall user satisfaction based on feedback from athletes and coaches.

1.4 Scope and Limitations of the Research

This study focuses on the design, development, and short-term evaluation of a programmable light-based reaction training system specifically tailored for racket sports, including badminton, tennis, and table tennis. These sports were selected because they demand rapid visual processing, anticipatory decision-making, and fine motor control—abilities strongly linked to reaction time and agility.

Experimental trials will be conducted in controlled indoor training environments, using drills that simulate racket-sport scenarios such as serve returns, directional changes, and split-step reactions. The prototype system will incorporate LED visual cues and integrated speakers to deliver multimodal stimuli, allowing assessment of both single and dual sensory response conditions.

The evaluation will be limited to short-term performance outcomes, measuring pre-post changes in reaction and movement response metrics following exposure to the prototype system. Long-term effects, such as learning retention, in-game transfer, or perceptual-cognitive adaptations, are beyond the scope of this research.

1.5 Significance of the Research

This research integrates engineering, computer science, and sports science by developing a light- and sound-based reaction training system that enhances athletes' response time and agility through multimodal stimuli and data-driven feedback. Through a technical lens, the study contributes to the computer science community by implementing real-time sensor processing, audio-visual cue synchronization, and a user-centered software design. The inclusion of both infrared sensors and speakers allows for dynamic and varied training scenarios that engage multiple sensory pathways, thereby improving cognitive-motor coordination. The use of ESP-NOW as the primary wireless protocol for synchronizing training stations is the central innovation this study. Unlike traditional Bluetooth-based systems, ESP-NOW enables stable, connectionless, and ultra–low-latency communication, thereby ensuring accurate temporal measurements essential for reaction-time research. Its novel application into a light-based athletic training device positions this study at the intersection of sports technology and modern IoT communication design.

From a societal perspective, the system democratizes access to advanced reaction training technologies by providing an affordable and portable tool suitable for athletes, coaches, and educational institutions. It can also serve as a supplementary device for rehabilitation programs that aim to improve motor control and sensory processing. By combining technical innovation with accessibility, this research promotes evidence-based athletic development and supports the broader integration of smart, adaptive technologies in sports and human performance training.

Chapter 2

Review of Related Literature

2.1 Physiological Basis of Reaction and Agility

Reaction time and agility in athletes are influenced by a complex interplay of neurophysiological factors, including perceptual-cognitive processing, neural pathways, and motor control. Reaction time encompasses the interval from stimulus detection to response initiation, modulated by sensory input (primarily visual), central nervous system processing, and efferent motor commands. Agility, defined as the ability to change direction rapidly while maintaining balance and speed, integrates these with biomechanical elements like strength and coordination (Pojskic et al., 2019). Neurophysiological mechanisms involve the visual cortex for stimulus detection, the prefrontal cortex for decision-making, and the basal ganglia for motor planning, with reaction accuracy linked to efficient attentional orienting and split attention across multiple stimuli (Chow et al., 2022). The prefrontal studies highlight that perceptual factors, such as anticipation and visual search efficiency, contribute significantly, alongside physical attributes like explosive strength and elastic strength (Yildiz et al., 2020). For instance, factor analyses reveal independent components: explosive strength for acceleration, elastic strength for rebound, change-of-direction speed (CODS), and maximal strength. Correlations show that faster reaction times predict superior agility test performances, such as in the Illinois Agility Test or 20-m shuttle sprint, emphasizing the role of neural efficiency (Wang et al., 2024).

Methodologies in these studies often employ systematic reviews and correlational analyses, drawing from diverse athletic populations (e.g., team sports like soccer) (Turna, 2020). Limitations include reliance on lab-based tests that may not fully replicate field conditions, potentially underestimating contextual factors like fatigue or cognitive load (Pojskic et al., 2019). Implications suggest that training targeting neuroplasticity—through repeated stimuli—can enhance synaptic efficiency, reducing reaction latencies and improving agility in sports requiring rapid responses, such as basketball or racing (Chow et al., 2022). Patterns indicate stronger associations in high-level athletes, where cognitive fatigue and sleep quality positively correlate with prolonged reaction times, highlighting the need for holistic training approaches (Yildiz et al., 2020).

2.2 Existing Reaction Training Technologies

Commercial systems like FITLIGHT Trainer and BlazePod represent established light-based technologies for reaction training, with evidence supporting their effectiveness in enhancing athletic performance. FITLIGHT, a wireless LED sensor system, simulates game-like conditions to improve reaction time, reflexes, and cognitive functions (Hassan, 2025). Studies demonstrate its reliability, with a test-retest intraclass correlation coefficient (ICC) of 0.89 and minimal detectable changes in reaction metrics (Myers, 2021). In young basketball players, a 10-week FITLIGHT intervention improved executive functions (e.g., inhibition, working memory) and fitness, though gains were comparable to traditional training, suggesting added cognitive demand without superior outcomes (Hassan, 2025). Another trial integrated FITLIGHT into small-sided games for 18 weeks, yielding significant enhancements in coordinative abilities and basic skills, outperforming controls with large effect sizes (Steff et al., 2024).

BlazePod, a pod-based visual-cognitive system, shows similar promise, with excellent reliability in balance activities (Çekok & Anaforoğlu, 2025). A 6-month program in adolescent soccer players improved simple reaction time and cognitive tasks, but between-group differences were non-significant compared to standard training, indicating contextual benefits rather than inherent superiority (Theofilou et al., 2022). Methodologies typically use randomized controlled trials (RCTs) with pre-post assessments, validated via tools like the Stroop Test for cognition and TUG for effort (Çekok & Anaforoğlu, 2025). Limitations include fairly small samples (n = 20-70) and short durations (6-18 weeks), risking overestimation of effects due to novelty; discrepancies arise in massed vs. distributed scheduling, with longer protocols showing sustained gains. Implications underscore these systems' role in individualized drills, boosting engagement through gamification, though high costs and proprietary designs limit accessibility for broader athletic populations (Hassan, 2025).

2.3 Light- and Sensor-Based Training Research

Research on light-based stimuli consistently shows enhancements in sports performance, particularly cognitive-motor integration and agility. A 6-week RCT using Witty SEM lights for car racing drivers improved cognitive abilities and cardiorespiratory fitness, with significant group-time interactions (Horváth et al., 2022). In basketball, light stimulation exercises enhanced attention focus (visual/auditory) and skilled hand speed, with pre-post improvements attributed to neuroplastic adaptations (Shimi et al., 2025). VR-adapted light tasks revealed attentional mechanisms, with orienting speed predicting performance, emphasizing split attention for larger stimuli arrays (Shimi et al., 2025). Soccer-specific lighting interventions (6 months) manipulated visual processing, reducing reaction times under varied conditions, though transfer to matches was inferred rather than directly measured (Theofilou et al., 2022).

Methodologies favor RCTs with tools like the Vienna Test System for cognition and breath-by-breath gas analysis for physiology, ensuring objective evidence (Horváth et al., 2022). Limitations encompass single-blinding, uncontrolled nutrition, and lab-based focus, potentially inflating effects; patterns show greater benefits in open-skill sports, with discrepancies in exercise vs. rest conditions (Zhao et al., 2024). Implications highlight light stimuli's potential for dual physical-cognitive gains, transferable to agility-dependent sports, but call for ecological validity in future studies (Shimi et al., 2025).

2.4 Wireless Communication Protocols in IoT

The rapid evolution of Internet of Things (IoT) and embedded-device systems has introduced novel communication protocols designed for low-latency, low-power, peer-to-peer connectivity. Among these, ESP-NOW stands out as a connectionless, peer-to-peer protocol by Espressif that operates on the Wi-Fi PHY layer while bypassing the full TCP/IP stack, which reduces handshake overhead and enables low-latency broadcast and one-to-many messaging for ESP32 and ESP8266 devices (Becker et al., 2025). Multiple empirical evaluations have assessed ESP-NOW's performance under different environmental and traffic conditions.

An outdoor performance study reported one-way transmission delays as low as approximately 1–2 ms even at extended distances, showing that ESP-NOW maintains stable latency and packet delivery across open-field environments (Becker et al., 2025). A lab analysis further confirmed these results by comparing ESP-NOW directly with Bluetooth Low Energy (BLE), finding that ESP-NOW exhibited measurably faster transmission times, significantly lower jitter, and more stable multi-node communication—attributes essential for synchronized sensor systems (Labib et al., 2021). Similarly, a comparative evaluation showed that ESP-NOW outperformed both classic Bluetooth and standard Wi-Fi in key metrics such as transmission speed, barrier resistance, and latency, including tests through walls and indoor obstacles (Eridani et al., 2021). An indoor performance evaluation of ESP-NOW reported high packet-delivery ratios and consistent millisecond-level timing across typical indoor IoT deployment ranges (Urazayev et al., 2023). These studies show that ESP-NOW reliably achieves one-way transmission times in the range of about 1–5 ms with low jitter—performance characteristics.

2.5 Identified Gaps in Literature

The literature reveals notable gaps, particularly the scarcity of open-source, customizable systems for individualized athlete training. While commercial tools like FITLIGHT dominate, they are proprietary and costly, limiting adaptation for diverse needs (Seçkin et al., 2023). Emerging technologies emphasize open-source platforms for tele-exercise, enabling collaborative customization via AI and IoT, yet only 9% of trials target healthy populations, with inadequate standardization of training parameters (Rebelo et al., 2023). Gaps include high dropout in asynchronous modes, data security concerns, and underexplored adherence factors (Rebelo et al., 2023). Methodologies in gap analyses rely on narrative reviews, highlighting sustainability challenges in open-source projects (Seçkin et al., 2023). This implicates the need for accessible systems to democratize training, addressing disparities in research on healthy athletes.

Another notable gap is the absence of research exploring low-latency wireless communication protocols—particularly ESP-NOW—in the design of reaction-training technologies. Existing systems largely depend on Bluetooth, which suffers from variable transmission delays and connectivity interruptions. No current studies assess whether protocols like ESP-NOW can enhance timing precision or improve synchronization in multi-station athletic training systems, underscoring a significant technological gap this research intends to address.

Chapter 3

Research Methodology

This study follows a step-by-step research process to develop and evaluate a light-based reaction training system for racket sports. The methodology includes gathering background information, consulting experts, and creating the initial system design. It then covers building the hardware prototype, developing the software, and testing the system with UPV athletes to measure reaction time and agility. Each stage is planned to ensure that the device is accurate, usable, and aligned with actual training needs. The process ends with analyzing the results and completing the final technical documentation.

3.1 Research Activities

Research activities include inquiry, survey, research, brainstorming, canvassing, consultation, review, interview, observe, experiment, design, test, document, etc.

3.1.1 Research and Consultation

The researchers will work closely with the UPV PE department as they will serve as consultants to ensure and validate the feasibility of the proposed system for racket sports. This stage will involve a comprehensive research on reaction time training that utilizes light-based systems, focusing those for racket sports. The consultations will take place in the UPV Covered Court, specifically in the PE faculty rooms. This stage is important to establishing a strong theoretical foundation, identifying gaps, and ensuring the design aligns with athletic performance needs.

3.1.2 Brainstorming and System Design

This phase will involve resource persons from the UPV Computer Science and PE Departments in developing the final design concept of the system, including the integration of infrared (IR) sensors, LED light modules, and speakers. The user interface of the system software will be done in this phase as well. Consultations and brainstorming sessions will be carried out online or face-to-face with the goal being to conceptualize an efficient, portable, and user-friendly hardware–software system tailored to the specific training needs of racket sports.

3.1.3 Latency Benchmarking

To ensure that the proposed reaction training system provides temporally accurate measurements, the wireless communication latency of the ESP-NOW protocol will be empirically benchmarked under controlled indoor conditions. Since reaction-time assessment is highly sensitive to communication delays, quantifying the transmission latency between the master controller and station nodes is essential for validating the system's responsiveness and synchronization reliability.

The benchmarking setup consists of one ESP32 master controller and three ESP32-based station nodes positioned at distances of approximately 1 m, 5 m, and 10 m within an indoor environment similar to the intended deployment setting. Each station node will be configured as an ESP-NOW peer of the master controller. All devices operate on a fixed Wi-Fi channel to minimize external interference.

Latency measurements will be obtained using a timestamp-based approach. Upon initiating a stimulus command, the master controller records a transmission timestamp using the ESP32's internal clock. Upon reception of the command, the station node immediately transmits an acknowledgment packet back to the master controller. The master then records the reception timestamp of this acknowledgment. One-way latency will be estimated from the transmission-to-reception interval at the station, while round-trip latency will be computed as the time difference between command transmission and acknowledgment reception at the master.

Each latency test will be repeated over 3 trials to account for variability. The mean latency, standard deviation, and worst-case delay will be computed for each distance condition. The results of this benchmark will serve as the empirical basis for selecting ESP-NOW as the system's wireless protocol, demonstrating that its low-latency, connectionless design is suitable for synchronized, multi-station reaction training where precise timing is critical.

3.1.4 System Development and Programming

The researchers will be working closely with their adviser to guide the development of the system. It involves assembling the hardware components and developing the accompanying application responsible for system control and data management. If benchmarking results prove to be positive, this phase will also involve integrating ESP-NOW as the wireless communication protocol of the system. The goal of this phase is to produce functional devices capable of reliably recording and analyzing athlete response data, thereby demonstrating the technical feasibility of the proposed system.

3.1.5 Testing and Experimentation

The system calculates the athlete's reaction time using the ESP32's internal clock in conjunction with a timestamp-based measurement approach. Upon receiving a start signal from the main device, the station device immediately records an initial timestamp and activates the indicator light. When the user subsequently interrupts the line of sight of the IR sensor, a second timestamp is recorded. The user's reaction time is then computed as the difference between the two timestamps, expressed as:

$$\text{RT} = \text{timestamp(end) - timestamp(start)}$$

A total of 15 participants, 5 of whom are from each racket sport (badminton, tennis, and table tennis), will be measured for the purpose of the study. The testing and training will take place at the UPV Covered Court. Athletes will undergo training sessions 4 times a week for a duration of 4 weeks, with each session lasting 2 hours.

The pre- and post-tests involve recording and comparing the reaction time on both hands between the athletes. All athletes underwent 2 tests for each hand. One test was for simple reaction time (SRT), while the second test was for choice reaction time (CRT). In the first test, each athlete was in position and had a light sensor in front of them at 35 cm, which was placed on a table. The athlete's hand rested on the table, and as soon as the light of the sensor turned on, the athlete had to turn it off with a touch. In the second test, the athlete had four light sensors in front of them at 35 cm, having equal distance from the athlete's measuring hand. Each time, all four lights were turned on simultaneously, and the athlete had to touch a specific color. In each test, the athlete was required to touch a specific color, but the corresponding sensor was different and not known to the athlete. Each athlete performed 3 times for each hand and test, thus a total of 12 attempts. The time noted by each athlete is derived from the average of the three attempts performed individually for each test (Table 3.1).

Table 3.1: Reaction time pre- and post-test

	1st attempt	2nd attempt	3rd attempt	Time
Right hand (SRT)	x	x	x	(x+x+x)/3
Left hand (SRT)	x	x	x	(x+x+x)/3
Right hand (CRT)	x	x	x	(x+x+x)/3
Left hand (CRT)	x	x	x	(x+x+x)/3

3.1.6 Evaluation and Calibration

Reaction time benchmarks for athletes were derived from empirical studies comparing trained individuals and non-athletes. Luu et al. (2021) reported that elite athletes exhibit exceptionally fast simple reaction times (SRTs) of approximately 160 ms, while trained young adults typically demonstrate SRTs ranging from 160–180 ms. Most adult athletes perform within the 180–200 ms range, which is generally considered normative for trained populations, whereas reaction times exceeding 200 ms are comparatively slower relative to athletic performance standards. These values provide a reference framework for interpreting changes in reaction time before and after training interventions.

Reaction time thresholds for the general population were informed by studies involving untrained individuals. Woods et al. (2015) documented average simple visual reaction times of approximately 213–231 ms among healthy adults, while Tomczyk et al. (2018) reported baseline SRTs ranging from 200–260 ms in non-athlete adolescents. Based on these findings, reaction times below 180 ms may be classified as exceptional, 180–220 ms as average, 220–260 ms as typical, and values exceeding 260 ms as indicative of slower performance in the general population. These ranges reflect physiological plausibility and the empirical distribution of reaction times observed in untrained cohorts, thereby enabling pre- and post-training performance changes to be evaluated relative to established population norms.

To ensure robust and reliable operation, the device incorporates several key design features focused on hardware integrity, user safety, and error mitigation. Prior to each use, it performs an automated self-diagnostic check to verify that the LEDs and IR sensors are functioning correctly and unobstructed, thereby detecting potential faults early and enhancing overall system reliability. For mitigating accidental triggers, the device automatically ignores reaction times below 50 ms, as such ultra-short latencies are physiologically impossible for human responses, effectively reducing false positives. The internal components are protected by a durable enclosure engineered to withstand common accidents, such as drops or unintentional impacts like kicks, providing structural integrity for everyday handling. Additionally, all components are designed for a precise, snug fit within the enclosure and are securely fixed with appropriate adhesives to prevent displacement from vibrations or minor shocks. In cases of significant physical disturbance during operation, a manual reset may be required to clear any transient glitches caused by mechanical stress and restore the system to a stable state. These measures collectively promote a safe, dependable, and user-friendly device suitable for real-world application.

3.1.7 Documentation and Reporting

This phase will involve the research adviser to ensure that proper documentation and reporting will be done by the researchers. They will compile all research findings, design specifications, performance data, and analyses into a formal technical report and academic paper. This work will be completed at the researchers' personal workstations. The purpose of this phase is to ensure transparency, replicability, and effective academic dissemination of the study's results and methodologies.

3.2 Calendar of Activities

The Table 3.2 presents the chronological schedule of research activities from January to July, outlining the key phases of the study—from research and system design to prototype development, testing, and documentation. Each activity is strategically planned to ensure systematic progress and timely completion of the light-based reaction training system project.

Table 3.2: Timetable of Activities

Activities (2026)	Jan	Feb	Mar	Apr	May	Jun	Jul
Research and Consultation	●●						
Brainstorming and System Design	●●	●					
Prototype Development and Programming		●●●					
Testing and Experimentation		●	●●●●				
Evaluation and Refinement				●●●●	●●●●		
Documentation and Reporting	●●	●●●●	●●●●	●●●●	●●●●	●●●●	●●

Chapter 4

System Prototype

4.1 System Design and Architecture

This study will employ components to gather accurate measurements of reaction time. The device will be composed of one master controller and multiple stations. The study will use the ESP-NOW protocol to achieve wireless connection between the main controller and the stations. ESP-NOW is a wireless communication protocol defined by Espressif which enables multiple ESP based microcontrollers to communicate wirelessly. It is a quick and low-power way to handle connection that is based on the data link layer to achieve faster transmission. The system will be controlled by a web application initially, as well as storing the data gathered by the system. In later development stages, the system will shift to using a mobile application instead.

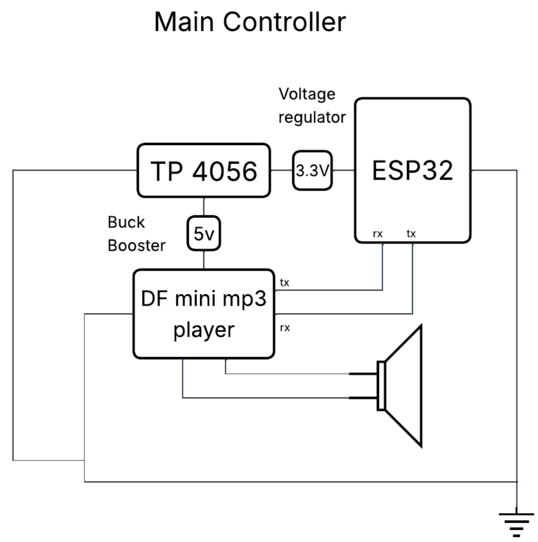

Figure 4.1: Schematic Circuit Diagram of the Master Controller

4.1.1 IOT Components

Figure 4.1 illustrates the schematic circuit diagram of the main (master) controller. At the core of the design is a standard ESP32 microcontroller, which manages two primary tasks: sending commands to the station modules and collecting the reaction-time data they generate. The gathered data will be transmitted using a Python application, displayed through a web application, and then uploaded to a Firebase database for online storage. The main controller also includes a DF Mini MP3 player module that provides audio cues for training modes requiring sound-based stimuli. This module reads audio files stored on an SD card and outputs them through a connected 3W speaker for clear and amplified playback. The entire system is powered by a 3.7V 18650 battery. A TP4056 charging module with built-in protection ensures safe charging and prevents overcharging. A 3.3V voltage regulator provides a stable supply for the ESP32, while a separate step-up converter generates the required 5V output for the DF Mini MP3 module and the speaker.

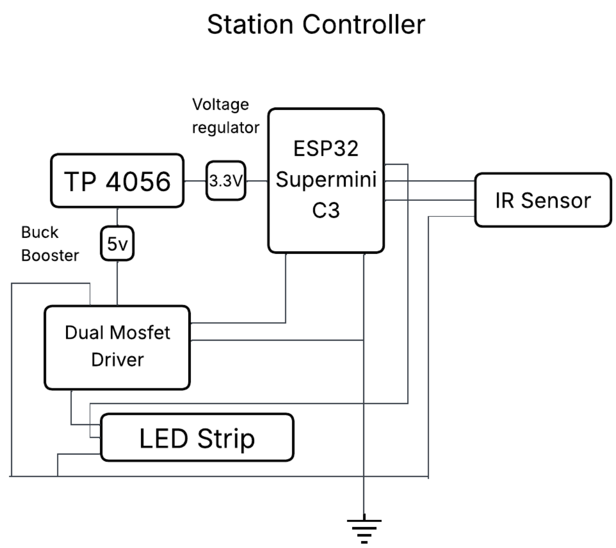

Figure 4.2: Schematic Circuit Diagram of the Station Controller

For the station nodes, Figure 4.2 presents their circuit schematic diagram. Each station uses an ESP32 Super Mini C3 microcontroller, chosen for its compact size and sufficient number of GPIO pins to support the required sensors. The station node receives commands from the main controller and executes them accordingly. It controls a programmable LED strip, which lights up based on the received command and turns off when the connected infrared sensor detects a response. The station then records the performer's reaction time and sends this data back to the main controller. Like the main controller, each station node is powered by a 3.7V 18650 battery paired with a TP4056 charging module with built-in protection. A voltage regulator provides a stable 3.3V supply for the microcontroller, while a step-up converter generates the 5V needed for the LED strip. The LED strip is connected through a dual MOSFET driver, which serves as a switch to safely control the 5V load from the station controller.

4.1.2 Software Application

The programming of the IOT components will be implemented in C++ using the Arduino-ESP32 core. The master controller manages ESP-NOW peer-to-peer communication with all stations, broadcasts synchronized commands, aggregates reaction-time data, and forwards it to the application via Wi-Fi. Station controllers execute commands, control WS2812B LEDs, measure reaction times with microsecond precision using hardware timers, and return data via ESP-NOW. ESP-NOW was chosen for its less than 2 ms latency and connectionless design, ensuring the temporal accuracy required for valid reaction-time measurement.

The system will initially utilize a web application built with React, Typescript, and Tailwind CSS. Eventually, a mobile application will be developed using Flutter to serve as the primary control method and data management of the system, offering superior performance, smoother animations, native push notifications, better battery management, and both applications connect to the same online database, ensuring identical functionality and seamless data continuity during the transition period.

The mobile application will interface with the hardware device via Bluetooth, enabling both device control and the collection of training data. The application will provide role-based access through two distinct user dashboards: one for coaches and one for athletes.

The coach dashboard will present aggregated and individual performance metrics obtained from athletes during training sessions, allowing coaches to monitor, evaluate, and manage athlete performance. In contrast, the athlete dashboard will display personalized training statistics, enabling athletes to review and track their own performance data. While both user roles will have the capability to control the device through the mobile application, coaches will have the additional responsibility of assigning or selecting the athlete currently using the device.

The system will support offline operation when gathering data. When an internet connection is unavailable, training data will be stored locally on the mobile device and will be automatically synchronized with Google Firebase Firestore once connectivity is restored.

4.2 Training Protocols

To assess the effectiveness of the proposed light-based reaction training system, three customizable training drills were developed to target key perceptual-motor skills essential in racket sports, including reaction time, decision-making, movement initiation, and agility. Each drill employs visual and/or auditory stimuli delivered via the system's LED modules and speakers, while infrared sensors are used to capture response timing and movement execution. Although the drills are designed to be applicable across badminton, tennis, and table tennis, their parameters can be systematically adjusted to accommodate the distinct biomechanical and perceptual demands of each sport.

4.2.1 Randomized Single-Target Movement Drill

In this drill, the athlete starts from a fixed central position while multiple training stations are placed around the athlete at predefined locations. At the beginning of each trial, a single station activates its LED at random. Upon activation, the athlete immediately moves toward the illuminated station and triggers the infrared sensor using the hand or racket. Once the response is detected, the system deactivates the station and initiates the next trial after a short configurable delay. Station placement and distance are adjusted based on the sport: wider spacing is used for badminton and tennis to require forward, backward, and lateral footwork, while closer spacing is used for table tennis to emphasize short, rapid movements.

4.2.2 Multi-Directional Choice Movement Drill

This drill requires the athlete to respond to a sequence of visual stimuli that demand movement in different directions. The athlete begins at a central starting point, and one station activates at a time following a randomized sequence. For each activation, the athlete moves to the corresponding station, triggers the infrared sensor, and returns to the starting position before the next stimulus occurs. Movement patterns include lateral shuffles, diagonal steps, and forward–backward transitions. The number of active stations, sequence length, and response time window are configurable to match the movement demands of badminton, tennis, and table tennis.

4.2.3 Sequential Multimodal Movement Drill

In this drill, movement execution is guided by combined audio and visual cues. An audio signal marks the start of each trial, followed by one or more stations activating in sequence. The athlete responds by moving to each activated station in the order presented and triggering the infrared sensor at each location. After completing the sequence, the system resets and prepares for the next trial. The number of stations in a sequence, activation speed, and movement distance can be adjusted. For badminton and tennis, longer movement paths and rapid direction changes are emphasized, while for table tennis, the drill prioritizes fast alternating movements over shorter distances.

Appendix A

Appendix

Appendix B

Resource Persons

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