SmartServe tennis ball

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Abstract

This project addresses the challenge of improving tennis serve technique by accurately detecting the apex of the ball toss. A critical aspect of the serve is timing the strike, as mistimed serves reduce performance consistency and are difficult for players to correct without precise feedback. To address this, we developed SmartServe, a prototype ball equipped with a Seeed nRF52840 board and custom firmware designed to detect and record the highest point of the toss. The system provides real-time audio cues to guide the player. The tests showed that SmartServe identified the apex with an average accuracy of −30% in repeated trials, demonstrating robust sensing and reliable data retrieval.

Introduction

In tennis, one of the key factors that determines the outcome of a match is the ability to serve [1]. The quality of the serve is strongly influenced by the timing between the ball toss and impact [2]. However, amateur players often struggle to consistently recognize and time their swing [3, 4].

Current methods for improving serve timing rely heavily on subjective or indirect approaches. The most common method is coach feedback, which provides expert guidance but depends on the coach's availability and observational accuracy. More advanced motion tracking systems, such as radar or camera-based sports analytics tools, can provide detailed measurements of ball speed and spin. Still, their high cost and operational complexity make them beyond the reach of most players [5, 6]. These systems have primarily been applied in scientific research contexts, requiring extensive data analysis [3, 4, 7], and are also used in elite tournaments, Hawk-Eye being the most widely adopted system [8]. Recent studies have explored more affordable setups, achieving promising results, but these require post-processing (i.e., AdaBoost algorithms to video track small objects [9]).

These approaches highlight the need for a more direct, in-situ solution capable of measuring toss timing directly on the ball without relying on external equipment. Incorporating sensors into sports equipment provides a practical means to address this challenge, enabling detailed, real-time data collection. Sensor-equipped balls have already been applied across multiple sports disciplines. Examples include the Adidas miCoach Smart Ball [10], 94Fifty Smart Sensor Basketball [11], GEN i1 Smart Golf Ball [12], and pitchLogic Ball [13]. For tennis, similar approaches have primarily focused on the racket rather than the ball, with commercially available products such as the Sony Smart Tennis Sensor and Babolat Play racket [14]. More recently, Foot et al. (2025) demonstrated the integration IMU sensor into an IPF-approved Vermont 90 mm foam tennis ball, with the system designed to measure accurate ball RPM during groundstrokes [15].

The contributions of this paper focus on a smart tennis ball prototype that integrates a Seeed nRF52840 microcontroller with onboard motion sensors to detect the apex of a serve in real time using acceleration and velocity measurements. The embedded system implements algorithms for free-fall detection, velocity reconstruction, and zero-crossing-based apex identification, while providing acoustic feedback and wireless data transmission for immediate and post-session analysis. Experimental evaluation demonstrated apex detection with an average error of approximately −30% relative to video tracking. These results, combined with the compact and robust hardware design, highlight the potential of in-ball sensing to deliver immediate, quantitative feedback, offering a practical and accessible tool for tennis training.

Design

The smart tennis ball prototype was built around the Seeed Studio XIAO nRF52840 Sense board, which integrates a Nordic nRF52840 microcontroller, a six-axis inertial measurement unit (IMU), and Bluetooth Low Energy (BLE) functionality. The microcontroller provides sufficient computational power for onboard signal processing while maintaining low energy consumption. The integrated IMU enables the measurement of both linear acceleration and angular velocity, which are critical for estimating ball speed and detecting the apex of the toss. The integrated BLE module allows wireless data transfer, enabling recorded measurements to be retrieved after play without a physical connection. To facilitate integration of the electronics, a foam-based training tennis ball was used, providing sufficient volume and flexibility to embed the components while preserving the general shape and handling of a tennis ball. This combination of sensing, processing, and communication in a compact form factor enabled the construction of a functional and durable prototype. An overview of the system design and signal flow is presented in Figure 1.

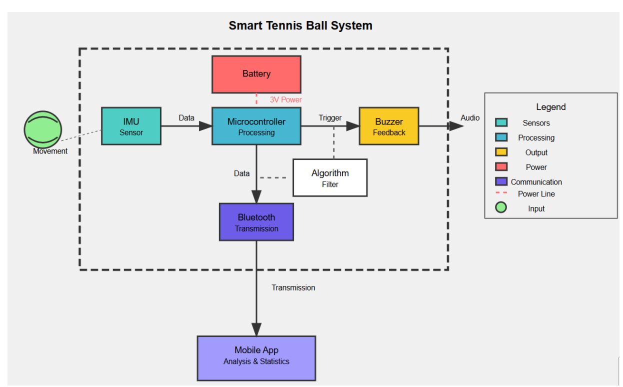

Figure 1: Schematic design diagram

The control unit was assembled according to the schematic design, combining the Seeed Studio XIAO nRF52840 Sense board, power supply, buzzer, and wiring into a compact and functional prototype. The layout was optimised to ensure reliable operation during testing. This prototype enabled practical validation of the sensing algorithms and the acoustic feedback system, serving as a bridge between the conceptual design and a fully integrated smart tennis ball. An image of the assembled unit is shown in Figure 2.

The Seeed platform enabled implementation of the developed algorithms in C++ for real-time apex detection and acoustic feedback using the Arduino IDE. The IMU's inertial data, obtained from the onboard LSM6DS3 sensor, were sampled at

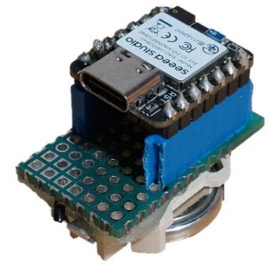

Figure 2: Sensor assembly

$52Hz$. The acceleration norm was computed as

$$\|a\| = \sqrt{a_x^2 + a_y^2 + a_z^2} - g \tag{1}$$

where a_x, a_y, and a_z represent the acceleration components along the three axes, and g denotes gravitational acceleration. The signal was low-pass filtered at 5 Hz to reduce measurement noise, then high-pass filtered at 0.5 Hz to compensate for drift and obtain a stable velocity estimate.

Free-fall initiation was detected when $\|a\|$ dropped below $-7m/s^2$ for a minimum duration of $40ms$, and flight termination when it exceeded $1m/s^2$. During the flight phase, the apex was identified by detecting a zero-crossing in the filtered vertical velocity, marking the transition from upward to downward motion. The initial release velocity was further used to predict the expected time to apex, allowing synchronisation of the acoustic feedback generated by the buzzer. All relevant timing and motion data were transmitted via BLE for post-analysis.

For system validation, video tracking was performed using a custom Python-based tool to record and compare actual apex events against those detected by the IMU-based system. This setup allowed quantitative assessment of detection accuracy and latency, providing a reliable framework for subsequent performance evaluation.

Results

The SmartServe system was fully functional during testing, including the complete electrical circuit, buzzer, and Bluetooth communication with a mobile device. To receive the data, the nRF Connect app was used.

To examine the validity of the system, a series of ball throws ($N = 7$) were recorded, varying in height between approximately $\sim 50cm$ and $\sim 150cm$. During these trials, synchronized video recordings were captured to establish a ground truth. Using video tracking, the time to apex was determined and subsequently compared with both the predicted and detected apex times calculated by the SmartServe system.

The results of this analysis are presented in Figures 3 and 4. The predicted time to the apex showed a mean error of $-0.19s$ (-47.7%) relative to the video-based reference, while the detected time exhibited a mean error of $-0.13s$ (-30.5%). These findings indicate that both the predicted and detected apex times occurred substantially earlier than the ground truth. The observed errors fall outside the acceptable range for reliable application in training scenarios, suggesting that further refinement of the system is necessary. The approximately linear relationship between the observed errors and the time to apex implies that a mathematical correction factor or calibration model could potentially improve the accuracy of both prediction and detection.

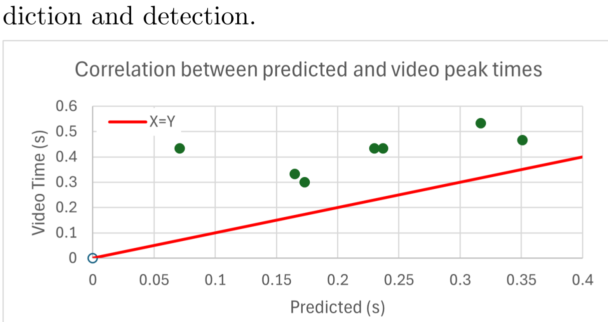

Figure 3: Results of video tracking analysis (Video vs predicted)

During testing, it was observed that excessive ball rotation caused failures in the free-fall detection, likely leading to the inaccurate apex estimation. This issue highlights a key limitation of the current design, as the algorithm assumes a relatively vertical throw for the calculated acceleration to accurately represent the overall motion. When the throw deviates from this vertical trajectory, the correlation between measured and actual acceleration decreases, resulting in reduced reliability. To address this, a rotation-correction algorithm would be required to properly extract the vertical velocity component and improve the robustness of apex detection under realistic serve conditions.

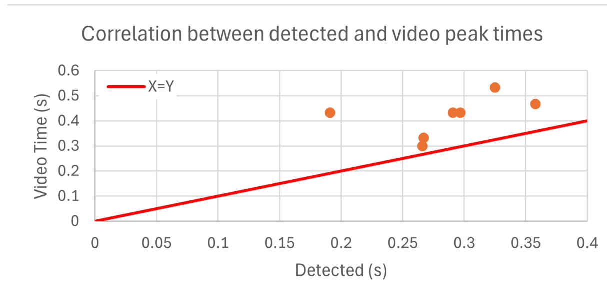

Figure 4: Results of video tracking analysis (Video vs detected)

Two key insights were derived from the analysis. First, the reliability of the SmartServe system appeared to improve with higher ball throws, corresponding to longer times to apex. This trend suggests that the system performs more consistently under conditions resembling actual tennis serves, which is promising for its intended application. Second, a similar improvement was observed when comparing the predicted apex to the detected apex, indicating that the prediction algorithm is also more reliable in serve-like trajectories. These findings collectively suggest that while the current implementation requires further refinement, the system shows potential for accurate real-time feedback in realistic tennis-serving conditions.

Conclusion

The evaluation of the SmartServe prototype demonstrates the feasibility of detecting the apex of a tennis ball toss using onboard sensing and real-time processing. The system successfully integrates motion sensing, wireless communication, and acoustic feedback into a compact platform, and initial tests confirm that apex detection is achievable with reasonable temporal precision. Although the current implementation exhibits timing errors that exceed the acceptable range for training applications, the results indicate that performance improves under conditions resembling real tennis serves, suggesting strong potential for further development.

Future work will focus on improving the accuracy and reliability of apex detection through enhanced algorithms and calibration procedures. The next design iteration will aim to integrate the electronics into a regulation tennis ball rather than a foam training ball, which will require the inclusion of a rechargeable battery, a redesigned printed circuit board (PCB) optimized for mass production, and robust mechanical embedding to ensure that the components remain centered without significantly altering the ball's physical properties. Prototype CAD files for this integration are already available and will serve as the basis for the next hardware version. Additionally, the development of a companion mobile application is planned to enable progress tracking and to provide adjustable acoustic feedback, allowing users to personalize the tone timing based on predictive calculations rather than solely on detection events.

Appendix

All related resources — including the embedded code, electrical schematics, validation videos, 3D CAD files, and documentation — are available in the SmartServe Ball GitHub repository: `https://github.com/NoahVastmans/SmartServeBall`

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