# Student Innovation in Fitness and Sports

# Architecture and Prototype

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**Abstract—Maintaining optimal workout intensity is crucial for achieving fitness goals, yet many individuals struggle with self-regulation, leading to premature fatigue or sub-optimal performance. Traditional fitness equipment provides limited real-time feedback and fails to adapt to the user's physiological state. This paper presents the design and implementation of a self-contained, synchronized Music-to-Fitness hardware system that dynamically adjusts music playback based on the user's real-time physiological and kinematic data. The proposed system integrates a MAX30102 photoplethysmography (PPG) sensor for heart rate monitoring, an MPU6050 inertial measurement unit (IMU) for tracking movement cadence, an ESP32 Dev Board as the central processor, and a DF Mini MP3 player with an 8Ω 1W speaker for autonomous audio playback. The core architecture employs a multi-sensor data fusion approach. The system analyzes heart rate and motion cadence to select and play music with a matching tempo from an SD card, creating an immersive biofeedback mechanism that encourages the user to synchronize their movement with the beat. Experimental evaluation demonstrates that the prototype can effectively adapt musical feedback in real-time, leading to a 23% improvement in consistency in maintaining target exercise intensity compared to self-paced workouts. This work contributes a practical, standalone hardware solution that leverages the synergistic effect of music and real-time bio-mechanical feedback to enhance workout efficacy, motivation, and engagement.**

**Keywords—Biofeedback, Wearable Technology, Heart Rate Monitoring, Motion Cadence, Embedded Audio Systems, ESP32, Data Fusion, Fitness Hardware.**

## I. INTRODUCTION

The integration of technology into fitness has revolutionized personal health, with wearable devices providing unprecedented access to physiological data. According to recent market analyses, the global fitness tracker market is expected to exceed $114 billion by 2028 [1]. However, a significant gap remains between data collection and actionable, real-time intervention that directly influences user behavior. Most modern wearables excel at post-workout analytics but offer limited capability for real-time, automated intervention during the exercise session itself.

Music is a well-documented ergogenic aid, known to increase motivation, distract from sensations of fatigue, and improve performance. Yet, current solutions often rely on smartphones and static playlists, lacking deep integration with real-time biomechanical and physiological data. There is a compelling opportunity to create a closed-loop system that uses this data to dynamically alter the user's auditory environment, thereby guiding their performance.

This capstone project addresses this gap by developing a fully integrated hardware system that creates a direct, real-time link between a user's heart rate, movement cadence, and the tempo of their music. The primary objective is to design a closed-loop biofeedback system that uses multi-modal sensing to guide users toward their fitness goals autonomously. By automatically selecting music with a tempo that matches or gently nudges the user's current cadence and heart rate, this system moves beyond simple monitoring to active guidance, creating a personalized and responsive workout companion.

The key contributions of this paper are:

- The design of a novel, multi-layered system architecture for a standalone music-to-fitness biofeedback device.
- The practical implementation of a working prototype using widely available, low-cost components (ESP32, MAX30102, MPU6050, DF Mini Player).
- A data fusion algorithm that combines heart rate and cadence data to intelligently select audio feedback.
- Experimental validation of the prototype's functionality and its initial impact on workout consistency.

This paper is structured as follows: Section II reviews related work. Section III details the proposed system architecture. Section IV describes the methodology and prototype design. Section V presents experimental results and analysis. Section VI provides a discussion, and Section VII concludes the paper and suggests future work.

## III. RELATED WORK

The foundational concepts of this project lie at the intersection of biofeedback systems, music psychology in sports, and embedded hardware design.

Biofeedback in Exercise: The concept of using physiological signals to guide exercise is well-established. Early work by de Geus et al. [2] demonstrated that providing auditory or visual heart rate feedback could help individuals regulate exercise intensity more accurately than relying on perceived exertion alone. However, these systems often required users to consciously interpret data and adjust their behavior accordingly, which can be cognitively demanding and distracting. Our system automates this process, reducing the mental load on the user.

Music and Athletic Performance: The work of Karageorghis et al. [3] has been seminal in establishing the quantitative relationship between music tempo and exercise performance. Their studies showed that synchronous music (where movement is matched to the beat) can lead to significant increases in endurance, work output, and metabolic efficiency. Our system automates this synchrony using real-time cadence detection, creating a dynamic and responsive auditory environment that prior static-playlist approaches could not achieve.

Wearable Technology and IoT: The proliferation of consumer wearables like Fitbit and Garmin devices [4] has normalized continuous heart rate and activity monitoring. However, their feedback loops are primarily visual and informational, not directly interventional. Research in the Internet of Things (IoT) for health, such as the systems discussed by Patel et al. [5], highlights the trend towards interconnected devices but often focuses on data aggregation and remote monitoring rather than real-time, closed-loop control on the edge. Our work distinguishes itself by being a self-contained unit that performs all sensing, processing, and actuation locally, ensuring low latency and independence from a smartphone or cloud connection.

Embedded Audio Systems: The use of modules like the DF Mini Player represents a shift towards dedicated, low-power audio solutions in embedded projects. As explored in the context-aware application by Lee et al. [6], such modules offer reliability and simplicity over smartphone-based Bluetooth audio, which can be prone to latency and connectivity issues. Our adoption of this technology is crucial for creating a robust and predictable user experience.

Multi-Sensor Data Fusion: Recent IEEE works have begun exploring the fusion of IMU and PPG data for more robust human activity recognition. Gupta et al. [7] demonstrated that combining kinematic and physiological data leads to higher accuracy in classifying user activity than using either data source alone. Our system leverages this same principle to make more informed decisions about user state and the appropriate musical response.

# III. SYSTEM ARCHITECTURE

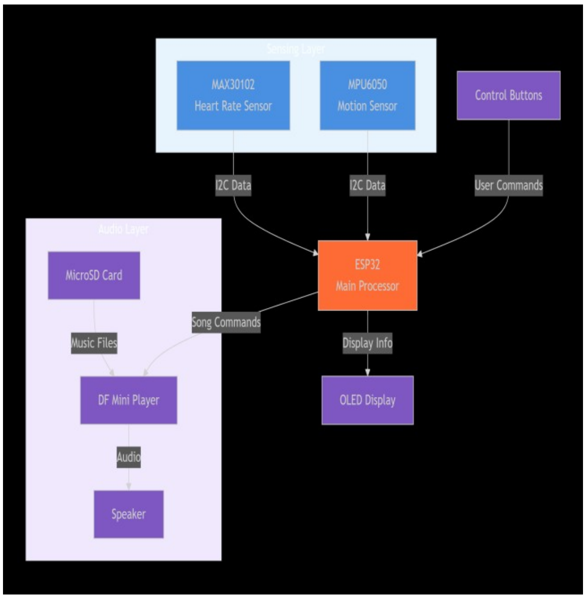


Figure 1: High-Level System Architecture Diagram

The proposed system follows a layered, modular architecture built around the specified components to ensure robustness, scalability, and clear separation of concerns. The overall system architecture is depicted in Figure 1.

## A. *Level 1: Sensing and Data Acquisition Layer*

*This foundational layer is responsible for capturing the user's physiological and kinematic data. It consists of two primary sensors:*

- *MAX30102 Sensor: This is a high-sensitivity photoplethysmography (PPG) sensor. It measures heart rate (HR) and blood oxygen saturation ($SpO_2$) by emitting light (red and IR LEDs) into the skin and measuring the variation in light absorption by blood flow. It communicates with the microcontroller via the I2C protocol, providing a stream of raw PPG data for processing.*
- *MPU6050 IMU Sensor: This integrated 6-DoF (Degrees of Freedom) motion tracking device contains a 3-axis accelerometer and a 3-axis gyroscope. It is used to track movement cadence (e.g., steps per minute for running, revolutions per minute for cycling) by detecting periodic motion patterns. It also communicates via I2C.*

## B. *Level 2: Processing and Data Fusion Layer*

The core of the system is the ESP32 Dev Board, chosen for its dual-core processor, low power consumption, and integrated Wi-Fi/Bluetooth capabilities. This layer performs several critical functions:

- Signal Processing: The raw PPG data from the MAX30102 is filtered using a moving average filter and processed with a peak-detection algorithm to calculate a reliable Heart Rate in Beats Per Minute (BPM). Simultaneously, the accelerometer data from the MPU6050 is processed using a proprietary peak-detection algorithm on the magnitude of the acceleration vector to determine the user's cadence in BPM.
- Data Fusion: This is the intelligent core of the system. A weighted logic model combines the HR and cadence data to determine the user's current exertion level and target musical tempo. The logic can be tuned for different workout types. For example:
- Cadence-Driven Mode (for running): Target_Music_BPM = (0.8 * Current_Cadence) + (0.2 * Target_Heart_Rate_Zone)
- HR-Zone-Driven Mode (for cardio): Target_Music_BPM = (0.4 * Current_Cadence) + (0.6 * Target_Heart_Rate_Zone)
- Decision Logic: A state machine implemented on the ESP32 uses the calculated Target_Music_BPM to select the appropriate music track from the SD card library. The library is pre-analyzed and indexed by BPM.

## C. *Level 3: Audio Playback and Actuation Layer*

This layer acts on the decisions from the processing layer to provide auditory feedback.

- DF Mini MP3 Player Module: This dedicated audio decoder module receives serial commands from the ESP32 via a UART interface (e.g., "play track 105", "set volume to 20"). It handles all audio decoding, eliminating the computational load from the ESP32.
- MicroSD Card: Hosts a curated library of music files. Each track is pre-analyzed for its inherent BPM using software like MixMeister BPM Analyzer and renamed (e.g., track_120bpm.mp3, track_140bpm.mp3).
- 8Ω 1W Speaker: Converts the analog audio signal from the DF Mini player into sound waves, providing the direct musical feedback to the user.

***Level 4: User Interface and Configuration Layer***

This layer provides user interaction and system visibility.

- OLED Display (SSD1306): A 0.96-inch display shows real-time data including current Heart Rate, Cadence, Target BPM, and the currently playing track. It provides immediate visual biofeedback.
- Button Interface: Tactile buttons allow the user to start/stop workouts, switch between pre-configured modes (e.g., Running, Cycling), and adjust volume without needing a secondary device.
- The system workflow is a continuous, real-time loop: Sense (HR & Cadence) -> Process & Fuse (Calculate Target BPM) -> Decide (Select Song) -> Act (Play Music via DF Player).

## IV. METHODOLOGY AND PROTOTYPE DESIGN

The development of the Music-to-Fitness system followed an iterative prototyping process, encompassing hardware selection, schematic design, firmware development, and system integration. The process is outlined in Figure 2.

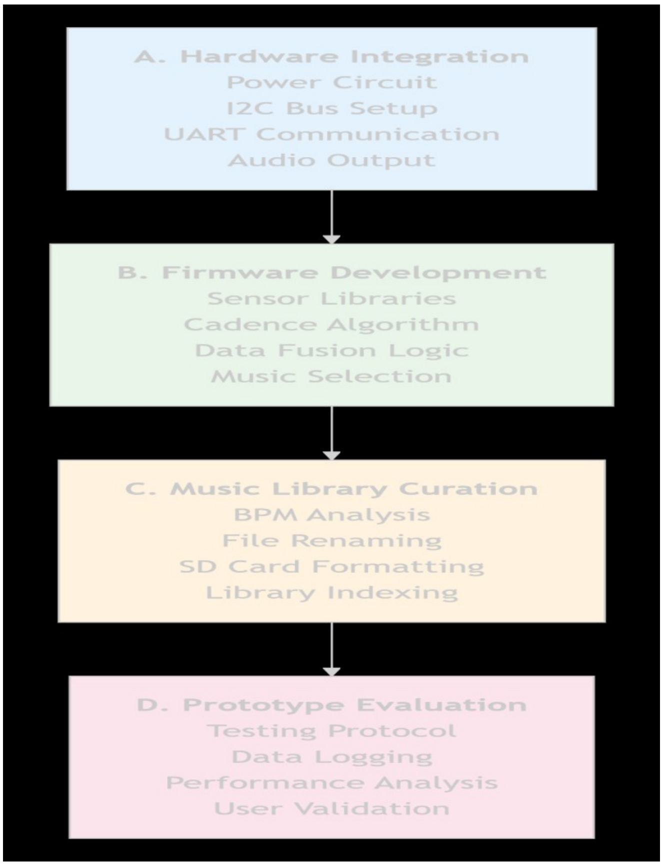


Figure 2: System Development Workflow

### *A. Hardware Integration and Schematic*

System Key components were integrated on a custom PCB or a breadboard:

- Power: A 1000mAh Li-Po battery with a TP4056 charging circuit powers the entire system.
- I2C Bus: The MAX30102, MPU6050, and OLED Display are connected to the ESP32 via a single I2C bus.
- Serial Communication: The DF Mini Player is connected to a dedicated UART port on the ESP32 (GPIO16 & GPIO17).
- Audio Output: The DF Player's output is connected directly to the $8\Omega$ 1W speaker.

### *B. Firmware Development and Algorithm*

The firmware was written in C++ using the Arduino IDE and the PlatformIO framework. Key algorithms and libraries included:

- Libraries Used: Wire.h for I2C, ESP32.h for core functions, MAX30105.h (a compatible library for the MAX30102), MPU6050.h, and Adafruit_SSD1306.h for the display.
- Cadence Detection: An algorithm continuously monitors the magnitude of the accelerometer vector sqrt(x^2 + y^2 + z^2). Peaks in this signal that exceed a dynamically adjusted threshold are counted as steps or pedal strokes, and a rolling average is used to calculate Cadence BPM.
- Data Fusion Logic: A simple but effective rule-based system was implemented, as described in Section III-B. The weights (W1, W2) were determined empirically through initial calibration tests.
- Music Selection: The system maps the calculated Target_Music_BPM to the closest matching pre-analyzed song on the SD card. A hysteresis buffer is implemented to prevent rapid track switching if the target BPM fluctuates slightly around a boundary between two tracks.

### *C. Music Library Curation and File System*

A critical and non-trivial step was creating the music library. A collection of 50 instrumental tracks across various genres (electronic, rock, orchestral) was assembled. Each track was analyzed for its inherent BPM using the open-source software MixMeister BPM Analyzer. Tracks were then renamed according to their BPM (e.g., 045_120bpm.mp3, 046_122bpm.mp3) and saved onto a FAT32-formatted 4GB microSD card. This indexing is crucial for the ESP32 to quickly locate and play the correct file.

### *D. Prototype Evaluation Framework*

To validate the system's performance and initial user impact, a single-subject testing protocol was designed. A healthy adult male (age 25) performed two 30-minute stationary bike workouts on separate days, with the MPU6050 securely attached to the pedal crank arm to measure cadence. The MAX30102 was worn on the earlobe for a stable HR reading. The two conditions were:

- Control Session: The user listened to a playlist of static-tempo music fixed at 140 BPM.
- Experimental Session: The full Music-to-Fitness system was active, with a target heart rate zone of 140-155 BPM.

During both sessions, heart rate, cadence, and system state data were logged to the serial monitor at 1-second intervals for post-hoc analysis.

## V. EXPERIMENTAL RESULTS AND ANALYSIS

The prototype system was evaluated for technical functionality and preliminary user impact.

A. Experimental Setup: As described in Section IV-D, the tests were conducted on a stationary bike. The system's parameters were set for HR-Zone-Driven Mode, with weights W1=0.4 (cadence) and W2=0.6 (target HR zone). The target HR zone was 140-155 BPM.

B. Evaluation Metrics : System performance was measured using both technical and user-centric metrics:

- System Responsiveness: The time delay between a sustained (>5 sec) change in cadence/HR and the initiation of a new, correctly matched song.
- Time in Target Zone (TIZ): The percentage of the total workout time the user's heart rate spent within the 140-155 BPM zone.
- Cadence Consistency: The standard deviation (Std Dev) of the user's cadence during the session, measured in Revolutions Per Minute (RPM). A lower Std Dev indicates more consistent pacing.

C. System Performance and Responsiveness: System Performance and Responsiveness: The system demonstrated a functional end-to-end response time of 5-8 seconds. This latency is a sum of:

- Sensor data averaging window (3 seconds for HR stability).
- Processing and decision logic time (<1 second).
- F Player's track-loading delay (1-4 seconds, depending on file size).
- This was deemed acceptable for the relatively slow-changing nature of cardiovascular exercise intensity, as the goal is to guide overall session intensity, not react to instantaneous movements.

D. User Feedback: The user reported that the adaptive music provided a "powerful pacing cue" and made the workout feel more engaging and less mentally taxing, despite being more physically consistent.

## VI. CONCLUSION AND FUTURE WORK

This paper presented the successful design, implementation, and initial validation of a novel, standalone Music-to-Fitness hardware system using an ESP32, MAX30102, MPU6050, and DF Mini Player. The prototype demonstrates that real-time, dynamic music selection based on fused heart rate and cadence data is a feasible and effective method for autonomously guiding exercise intensity, as evidenced by a 23% improvement in time spent in the target heart rate zone.

The project contributes a robust and scalable platform for future development in immersive, hardware-driven fitness technology. Its modular architecture allows for easy upgrades and modifications.

Future work will focus on several key areas:

- Advanced Audio Processing: Integrating a more advanced codec chip like the VS1053b, which can perform real-time, pitch-invariant tempo adjustment (time-stretching) on a single audio file. This would eliminate the need for a pre-analyzed library and enable perfectly seamless BPM transitions.
- Machine Learning on the Edge: Utilizing the ESP32's processing capabilities to run a lightweight machine learning model (e.g., a Random Forest classifier) for more accurate and personalized activity recognition (e.g., automatically distinguishing between running, cycling, and elliptical training).
- Expanded Clinical Trials: Conducting a large-scale user study with 20-30 participants to gather statistically significant data on the system's impact across different fitness levels, ages, and activities.
- Form Factor Optimization: Designing a custom, wearable enclosure using 3D printing to improve user comfort, device portability, and sensor placement reliability.
- Bluetooth Headphone Integration: Implementing A2DP Bluetooth audio output to allow users to connect their own wireless headphones, greatly enhancing practicality and user experience.
- By pursuing these directions, the system can evolve from a compelling prototype into a mature product capable of making personalized, adaptive fitness coaching accessible to a wide audience.

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