

VARIABLE SPEED RUNNING MUSIC DEVICE

By

Nithin Boopalan

Weston Heard

Alan Wan

Project Proposal for ECE 445, Senior Design, Fall 2026

TA: Jianchong Chen

Project No. 40

Abstract

The abstract is short (150 words or less) and provides enough of a summary of the report for the reader to decide whether to read the entire document. State very concisely what your device or system does, and the main findings and results of your project. Save background information (e.g., motivation, competitors) for the introduction and design details for the body of the report. Do not give an advertising pitch. Note that the abstract does not appear in the table of contents. (This achieved by stripping out the heading style.)

Note that **you can ignore the TOC on next page because it is generated automatically**. Work on the body of the report, then hit the Update tab on the TOC and *voilà*.

When you double-clicked “ECE 445 Template.dotx,” you opened a new, untitled document in Microsoft Word, which has the main components of your final report set up for you. Save the new document, replace the red text and bracketed section heads with your own, insert carefully prepared graphics, follow the guidelines document (“Preparing Your Final Report for ECE 445”), proofread and revise, and you’ll likely end up with a successful report.

Contents

1. Introduction.....	3
1.1 Problem.....	3
1.2 Solution.....	4
1.3 Visual Aid.....	4
1.4 High-Level Requirements List.....	5
2 Design.....	6
2.1 Block Diagram.....	6
2.2 Subsystem Overview and Requirements.....	6
2.2.1 Motion Sensing.....	6
2.2.2 Music Storage and Playback.....	6
2.2.3 Audio Output.....	6
2.2.4 Power.....	7
2.2.5 Display and Controls.....	7
4. Parts.....	8
4.1 Orders.....	8
5. Conclusion.....	9
5.1 Accomplishments.....	9
5.2 Uncertainties.....	9
5.3 Ethical considerations.....	9
5.4 Future work.....	9
References.....	10
Appendix A Requirement and Verification Table.....	11

1. Introduction

Runners who want to maintain a consistent cadence have no convenient way to do it, and the music many runners already run to isn't doing the job because a fixed playlist cannot follow a changing pace. This proposal describes a self-contained wearable device that measures the runner's cadence from hip motion and continuously adjusts the tempo of stored music to match it.

1.1 Problem

Most people bring their phone on a run to listen to music. It is big and bulky, and unless you have a perfect playlist, no music syncs with your running. If you do happen to have music that is the same as your pace, there is nothing to enforce that you are running at that speed.

This matters because the runner's cadence is one of the few parameters that a runner can change, also just happening to be one of the most consequential. A study done by Anderson et al. found that increasing step rate reduces loads at many of the runner's joints, including the ankle, knee, and hip, while decreasing step rate increases them [1]. Running is among the most common forms of exercise while also being very high in injury rate. So helping recreational runners hold a higher and steadier cadence can improve their personal health and safety.

We plan to use something most runners are already familiar with: music. However, most runners aren't using it to its maximum effect. Van Dyck et al. found that runners held the most consistent cadence when the beat was matched to their own cadence [2]. Matching music to cadence works, but only when this match is maintained. Static playlists cannot do that, as a runner's pace can speed up or slow down over a run, while a track's tempo does not. Once the runner's cadence and musical tempo drift apart, the music starts to compete with the runner's stride instead of supporting it. The alternatives all carry costs: formal cadence retraining needs an exercise lab or a coach, phone applications require carrying a phone, which is never comfortable, and running watches only report cadence after a run.

1.2 Solution

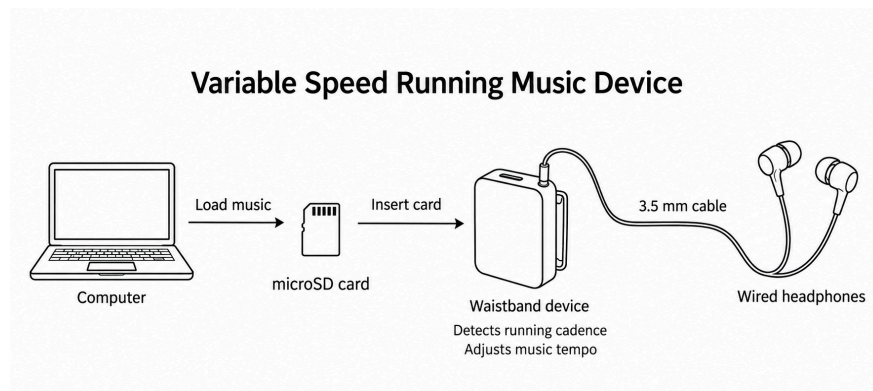
We intend to fix this by creating a device that can react to how fast or slow you are going compared to your intended pace, and a mode where the music will automatically adjust to the speed you are going, in case you don't want to have to worry about keeping on pace.

The device clips onto the waistband with the user's music stored on an SD card. An IMU (Inertial Measurement Unit) inside the device measures acceleration at the hip, and firmware running on an STM32 microcontroller calculates the runner's cadence in steps per minute by autocorrelating a four-second window of that signal. The device then selects a track from its library whose tempo is in the range of the measured cadence and applies WSOLA time-scale modification to adjust the playback tempo without altering the pitch of the song. Small drifts in pace can be fixed by adjusting the stretch used; a pace change too large to alter cleanly will cause the device to switch to a different track instead. Audio is converted by an on-board DAC (Digital to Analog Converter), passed through a reconstruction filter and headphone amplifier, then driven out through a standard 3.5 mm jack. Everything runs on the device itself, so the user doesn't need a phone or connection to use it.

The device will have 2 modes. In follow mode, the music continuously tracks the runner so the beat stays locked in without the runner needing to think about it. In target mode, the runner sets an ideal cadence, and the device holds the music at that tempo. If the runner's cadence is too slow or fast, the device will apply a low-pass filter on the music that progressively muffles the audio and again slowly clears up as they return to it. This gives the runner continuous feedback on their pace without requiring any input on the runner's side.

Music is prepared on a computer before a run. A script analyzes each track's tempo and writes the results to a CSV index file stored alongside the audio on the SD card. The device then only performs a lookup at run time rather than having to analyze audio in real time.

1.3 Visual Aid



1.4 High-Level Requirements List

- The device must measure the runner's cadence to within 1 step per minute of the true value across the running range of 140 to 190 steps per minute, so that the tempo selected is an accurate reflection of the runner's stride.
- The device must also hold the playback tempo to within 1 beat per minute of the measured cadence (or exactly half or double), and converge to a new tempo within 10 seconds of a pace change of at least 15 steps per minute
- The device must operate on its own for at least 2 hours of continuous use, without any external device at any point.

Figure 1 Example of placement and caption for a block diagram. With picture selected, go to References ☐ Insert Caption. This creates a neat, consistent caption style that stays connected to the figure. Size the figure so that one-inch margins are preserved. Group the figure and caption to hold them together.

Table 1 Example of a Table and Its Title

Part	Electricity	Magnetism
Field intensity	E	H
Flux density	D	B

Constitutive factor	ϵ^b	μ^c
---------------------	--------------	---------

2 Design

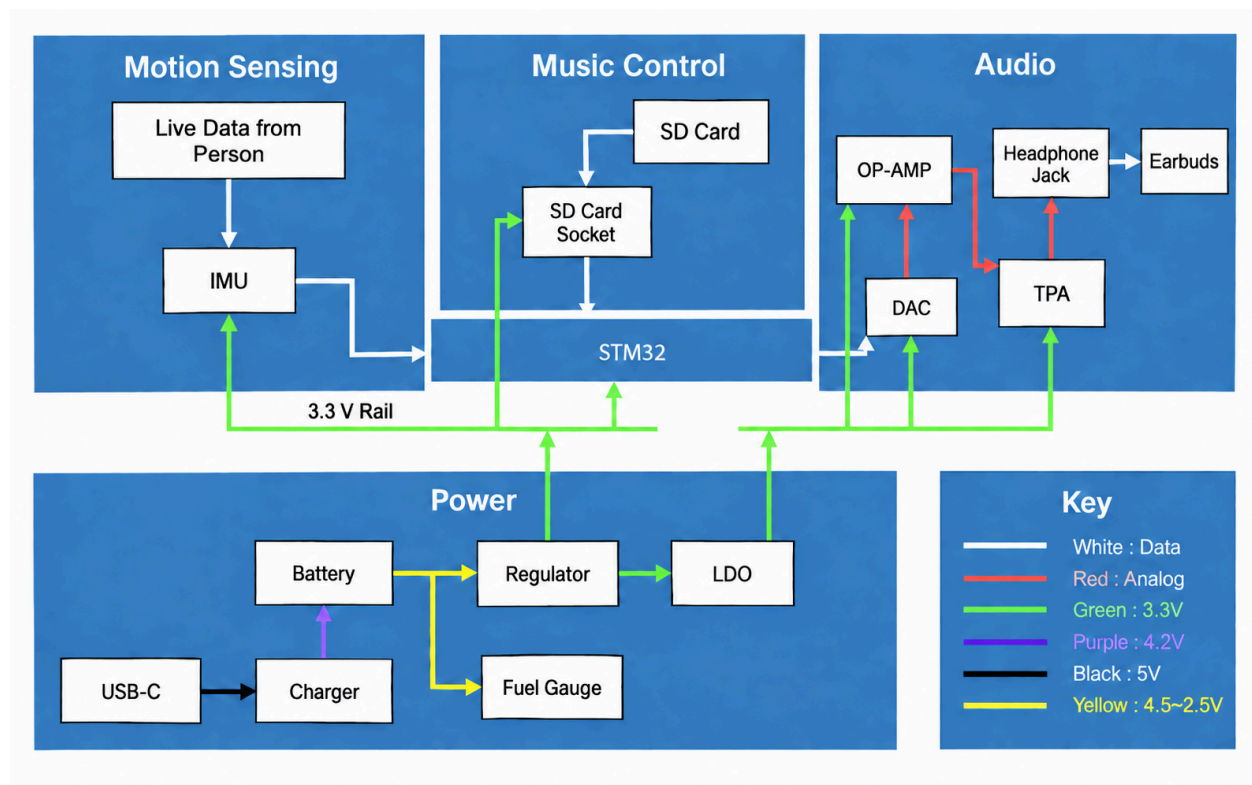
Discuss general design alternatives. Give equations, simulations, general circuits. Describe design in detail, addressing each major component. Include schematics with components, drawings, flowcharts, etc. Some teams may wish to split this chapter in two: 2. Design Procedure, and 3. Design Details. This template will not automatically update numbering systems for chapters, sections, figures, tables, etc., so keep track of them as you develop and revise the text.

Following is a “template” for displayed math. Use the MathType extension of Word to generate your own content, and note the use of the invisible table (no borders) to keep the optional number flush right.

Insert math here using MathType

(number)

2.1 Block Diagram



2.2 Subsystem Overview and Requirements

2.2.1 Motion Sensing

This subsystem determines the runner’s cadence, measured in steps per minute. It will use an IMU mounted on the hip to sample acceleration and pass the measured values to the STM32 microcontroller over SPI (Serial Peripheral Interface). The firmware then filters and autocorrelates the signal to calculate the cadence as well as the runner’s state: running, walking, or stopped. The cadence estimate is the only

input to the rest of the system, with the Music Storage and Playback using it to choose a song and stretch, and Display to show it.

Autocorrelation:

2.2.2 Music Storage and Playback

This subsystem holds the music library and outputs the stream to be played. It reads the raw audio from a microSD card over SDIO (Secure Digital Input/Output from STM32) using DMA (Direct Memory Access) and picks a track within range of the cadence (± 3 BPM) from the Motion Sensing subsystem using each track's precomputed BPM. It then applies either the WSOLA time-scaling to match the runner's steps or a possible low-pass filter for pace feedback depending on the set mode. The output goes to Audio Output over I2S at a fixed 44.1 kHz (fixed rate, not fixed tempo).

2.2.3 Audio Output

This subsystem converts the digital sample stream into an analog signal that can then be used to drive headphones or earbuds, and also contains the analog circuit design for the project. The Audio Output receives samples from the Music Storage and Playback over I2S and converts them using a DAC. It then removes high-frequency image copies in a reconstruction filter, and amplifies the result to be used for 16 to 32 ohm headphones through a 3.5 mm headphone jack.

2.2.4 Power

This subsystem powers the device from a single lithium cell battery and handles charging. The lithium cell will fall from 4.2V to 3.0V as it drains, and in the process will cross a 3.3V logic rail. A buck-boost converter can then be used so the rail remains stable as the discharge finishes, boosting the voltage below 3.3V or bucking the voltage above 3.3V to be exactly 3.3V. This provides our system with a consistent and reliable supply of power. The DAC and headphone amp are also fed through dropout regulators to prevent noise in the audio from the buck-boost converter. There will also be an MCP73831 charge management controller to charge the cell over USB-C and a Maxim MAX17048 fuel gauge to report the charge to the microcontroller.

2.2.5 Display and Controls

Controls:

Button: hold = on/off tap = switch mode

Right/Left button = target spm up/down

Up/Down button = Volume Output Up/Down

Display: Current Playback Mode, Current BPM

2.2 Tolerance Analysis

Autocorrelation: While running, there will be a repeating bump in the acceleration every time the runner takes a step. Autocorrelation will compare that signal to a delayed copy of itself to see how well it lines up. By matching the signal to its delayed version, we can figure out what the current rate of Steps per Minute of the runner is by dividing sixty seconds by the time of delay, or the time in between steps. The equation for the Autocorrelation at a delay = average of (acceleration * acceleration one delay later)

Slope Interpolation: While autocorrelation may work for finding the rate at each step, humans and sensors are not always 100% consistent. Some people favor one side while running, they may trip or stumble around, sprint or slow down for a car, or other outside factors that may skew our numbers. While we want our music to match the beats, we don't want it overcompensating and changing the music drastically based off of a slightly slower/faster than expected step. Slope interpolation will help us take the average over the last few points to determine the average speed of the runner over their past few steps. This may also help us decide if the runner has sped up/slowed down enough to determine if the device will react to their change in speed if it reaches a certain threshold. We can also drop any outliers that may confound our data. We will test different models in how we analyze our slope, as if we do a linear interpolation over the past few steps, the estimated SPM will frequently undercompensate for the actual SPM, as we not only need to analyse the steps per minute, but the change in the rate of steps per minute to know if we are speeding up or slowing down to know how to adjust our playback accordingly. One of the equations we may use to find the SPM is: Steps per minute = current steps per minute + (rate of change * delay of measurement)

3. Parts

Parts Costs			
Part	ID	Retail Cost (\$)	Actual Cost (\$)
6-axis IMU, SPI interface	TDK InvenSense ICM-42688-P		
Microcontroller	STM32F4		
microSD card socket	Hirose DM3AT-SF-PEJM5		
microSD card	32 GB SanDisk High Endurance		
Stereo Audio DAC	Texas Instruments PCM5102A		
Low-noise audio op-amp for reconstruction filter	Texas Instruments OPA1662		
Headphone amplifier, no capacitor output	Texas Instruments TPA6132A2		
3.5mm TRS headphone jack	CUI SJ-3524-SMT-TR		
Single-cell lithium-polymer battery			
1000 mAh Low-dropout regulator	Texas Instruments TPS63020		
Buck-boost regulator			
Battery Charger	MCP73831		
Battery fuel gauge	Maxim MAX17048		
Total			

4. Ethics, Safety and Societal Impact

The IEEE Code of Ethics places the safety and health of the public above all other obligations, which we used to shape our audio output and battery safety [3]. Our device delivers audio into a user's ears, and prolonged, high-level exposure can lead to hearing damage. To prevent issues on this front, we have limited the output to a maximum output of 85 dBA, making it so that regardless of what the user chooses, they will never be at risk of any hearing damage. This limitation is done by implementing a fixed amplifier gain in hardware, limiting the output to 150 mV RMS into a 32 ohm load, being the loudest headphones supported.

The other significant hazard in our design is the lithium-polymer cell, as lithium cells can vent or ignite if overcharged, damaged, or shorted. We will use a cell with an integrated protection circuit and have a dedicated charge management controller, so that charging is disabled while the device is running. The cells will also be stored in the designated ECCE 445 laboratory area as per the lab policy. With the device operating below 5V, there is no shock hazard present.

References

- [1] R. W. Anderson, C. Bonanno, H. Menz, S. Bade, and M. Lawrenson, "What is the effect of changing running step rate on injury, performance and biomechanics? A systematic review and meta-analysis," *Sports Medicine - Open*, vol. 8, no. 1, 2022.
- [2] E. Van Dyck, B. Moens, J. Buhmann, M. Demey, E. Coorevits, S. Dalla Bella, and M. Leman, "The power of auditory-motor synchronization in sports: Enhancing running performance by coupling cadence with the right beats," *PLOS ONE*, vol. 8, no. 8, 2013.
- [3] IEEE, "IEEE Code of Ethics," IEEE Policies, Section 7.8, 2020. [Online]. Available: <https://www.ieee.org/about/corporate/governance/p7-8.html>