BetaSpray: Climbing Route Visualization System

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1 Introduction

1.1 Problem

Spray walls are a popular fixture in modern climbing gyms, consisting of a dense grid of holds mounted on a single wall surface. Unlike pre-set routes marked with colored tape, spray walls allow climbers to define their own routes by choosing any subset of holds. This flexibility makes spray walls an excellent training tool, but it introduces a significant usability problem: there is no practical way to record, recall, or share a custom route once a climber steps off the wall.

Currently, climbers must memorize which holds belong to a given route or resort to taking photographs and manually annotating them. This process is error-prone, time-consuming, and does not scale. In a training environment, inconsistent route recall leads to unreliable progression tracking. In a community setting, the inability to easily share routes limits the collaborative potential of spray walls. The International Federation of Sport Climbing (IFSC) has noted the growing importance of structured training tools for competitive climbing [1], and existing commercial solutions such as the Kilter Board and MoonBoard address this need only for proprietary, purpose-built walls with integrated LEDs—not for the far more common generic spray walls found in most gyms [2].

1.2 Solution

Beta Spray is a standalone device that scans a spray wall, identifies individual holds, and uses servo-actuated laser pointers to visually highlight route-specific holds for climbers in real time. The system consists of three subsystems: a vision mapping subsystem that captures images of the wall and detects hold positions using a camera and computer vision pipeline, a projection subsystem that directs laser beams onto target holds via 2-axis servo gimbals, and a user interface subsystem that allows climbers to create, store, and replay routes through a web or mobile application hosted on an ESP32-S3 microcontroller.

The device is designed to sit on the floor in front of a spray wall, powered from a standard wall outlet. The camera captures the wall layout, hold positions are extracted and stored, and when a route is selected, the laser gimbals sequentially illuminate the corresponding holds. Routes are stored locally on the ESP32 via SPI flash or SD card, and the lightweight HTTP server allows wireless route management from a phone or laptop. The total footprint of the device is less than 25 cm × 25 cm with a maximum height of 40 cm.

1.3 Visual Aid

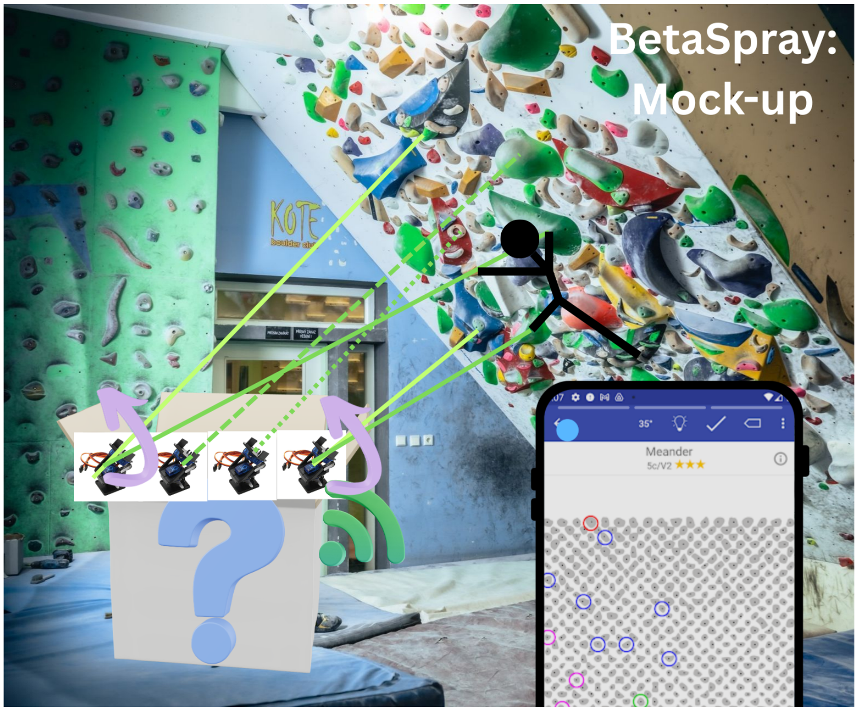

Figure 1: Visual aid of the Beta Spray system in use.

1.4 High-Level Requirements

1. The laser projection subsystem shall direct laser pointers to target holds with a positional accuracy of $\pm 5\,\text{cm}$ at a projection distance of $3\,\text{m}$, sufficient to unambiguously identify individual holds on a standard spray wall.

2. The vision mapping subsystem shall detect and localize at least 90% of holds on a spray wall under standard gym lighting conditions within 30 seconds of initiating a scan.

3. The user interface subsystem shall allow a user to create, save, and replay a route with an end-to-end response latency of less than $200\,\text{ms}$ from command input to laser actuation.

2 Design

2.1 Block Diagram

Please refer to figure 2

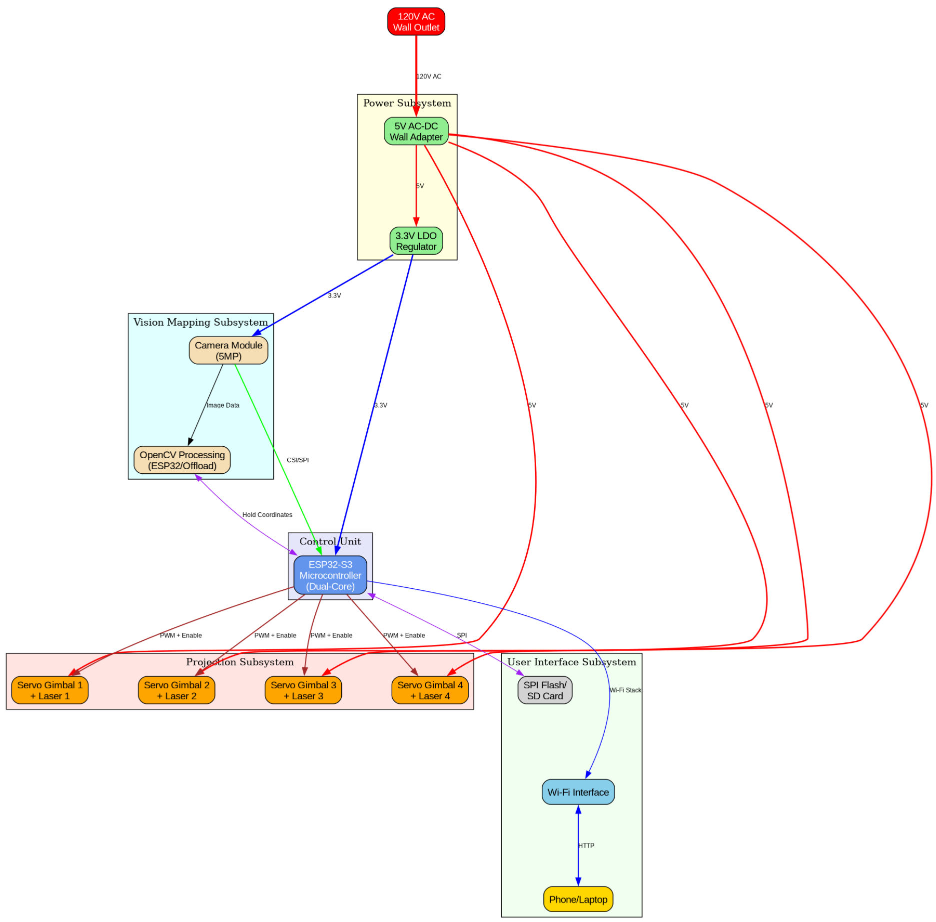

Figure 2: Block Diagram

2.2 Subsystem Overview

2.2.1 Power Subsystem

The power subsystem provides regulated voltage to all other subsystems. A 5V AC-DC wall adapter supplies the main power rail. A 3.3V low-dropout (LDO) linear regulator steps the 5V rail down to 3.3V for the ESP32-S3 microcontroller and camera module. The servo motors operate directly from the 5V rail. This subsystem interacts with every other subsystem by providing their required operating voltages.

2.2.2 Vision Mapping Subsystem

The vision mapping subsystem is responsible for scanning the spray wall and detecting the positions of climbing holds. A camera module (Raspberry Pi Camera Module 3 or Arducam OV5647) captures high-resolution images of the wall. The ESP32-S3 handles image acquisition and runs an on-board OpenCV-based processing pipeline that identifies hold contours and assigns each hold a coordinate relative to the wall geometry.

We have selected the ESP32-S3 specifically for its dual-core architecture (Xtensa

LX7 cores running up to 240 MHz) and large PSRAM support (up to 8 MB), which should—hopefully—provide sufficient computational resources to run all computer vision processing directly on the microcontroller without offloading to an external device. The CV pipeline will leverage color segmentation and edge detection techniques studied in ECE 310 (Digital Signal Processing) and ECE 418 (Image and Video Processing) to supplement OpenCV functions. Specifically, we will implement Canny edge detection and HSV color thresholding to isolate climbing holds from the wall background, taking advantage of the typically high-contrast colors used for holds in climbing gyms.

In addition to initial hold detection, the vision subsystem continuously tracks laser spot positions during route playback. By comparing the detected laser spot location with the intended target hold coordinates, the subsystem computes a 2D error vector for each servo gimbal. This error feedback is sent to the projection subsystem to enable closed-loop vision-based control, compensating for servo positioning inaccuracies and mechanical drift. If on-device processing proves too compute-intensive during development, the ESP32-S3 can transmit image data via HTTP to a nearby laptop running OpenCV or TensorFlow Lite as a fallback, but the goal is to maintain fully autonomous on-board operation.

2.2.3 Projection Subsystem

The projection subsystem visually indicates route holds using servo-actuated laser pointers. Up to four laser modules are each mounted on a 2-axis servo gimbal, controlled via PWM signals from the ESP32-S3. When a route is selected, the system directs the laser beams to the coordinates of each hold in the route, illuminating them sequentially or simultaneously depending on the mode.

The servo gimbals use standard hobby servos (e.g., SG90 or MG996R) with a resolution of approximately 1° per step. Unlike traditional motor control systems where PID feedback is obtained by measuring current draw, servos do not expose internal position feedback. To address this limitation, we employ a vision-based closed-loop control strategy: the vision subsystem detects the actual laser spot position on the wall and computes the positional error relative to the target hold. This error is decomposed into azimuth and elevation components corresponding to the two gimbal axes. The ESP32-S3 then applies corrective PWM adjustments to iteratively reduce the error below the ± 5 cm tolerance threshold.

This vision-in-the-loop approach effectively creates a software-based feedback mechanism that compensates for servo backlash, mechanical play, and thermal drift. The control loop operates at approximately 5–10 Hz, limited by camera frame rate and image processing latency. The mechanical mount is designed with adjustable pitch to accommodate wall inclines of up to 45°. If laser precision or eye-safety concerns arise, an alternative approach would substitute a compact DLP or LED pico-projector calibrated through the same coordinate mapping pipeline.

2.2.4 User Interface Subsystem

The user interface subsystem allows climbers to interact with Beta Spray through a web-based application. The ESP32-S3 provides Wi-Fi connectivity and runs a lightweight HTTP server using the ESP-IDF SDK. Route data is stored locally on SPI flash or an SD card connected via SPI. The web interface, accessible from any phone or laptop on the same network, provides controls for wall scanning, route creation (selecting holds from the mapped layout), route saving, and route replay.

If Wi-Fi latency or bandwidth limits affect responsiveness, a fallback wired serial or USB interface can be used for configuration. The frontend will be developed using Flask or a simple static HTML/JavaScript page served directly by the ESP32-S3.

2.3 Subsystem Requirements

2.3.1 Power Subsystem

1. Must supply at least 2 A continuously at 5V $\pm$ 0.25V to support simultaneous operation of servos, camera, and microcontroller.

2. The 3.3V LDO regulator must maintain output within $\pm$0.1V under load transients caused by servo actuation.

3. Must include a polarity protection diode and a resettable fuse rated at 3 A to prevent damage from miswiring or overcurrent.

4. Must include decoupling capacitors (100 μF bulk, 0.1 μF ceramic) on the 3.3V rail to filter noise from servo PWM switching.

2.3.2 Vision Mapping Subsystem

1. The camera module must capture images at a minimum resolution of 2592$\times$1944 (5 MP) to resolve individual holds at distances up to 4 m.

2. The hold detection algorithm must correctly identify at least 90% of holds on a standard spray wall (approximately 100–200 holds) under ambient gym lighting ($\geq$300 lux).

3. The full wall scan and hold detection pipeline must complete within 30 seconds.

4. The subsystem must output a coordinate list with each hold position specified to within $\pm$2 cm accuracy relative to the wall plane.

5. During route playback, the subsystem must detect and track laser spot positions with sufficient accuracy to compute targeting error within $\pm$3 cm, enabling closed-loop feedback to the projection subsystem at a rate of at least 5 Hz.

2.3.3 Projection Subsystem

1. Each servo gimbal must provide at least 180° of rotation on each axis with a positioning accuracy of ±1°.

2. The laser modules must be Class 2 or lower (<1 mW visible) to comply with IEC 60825-1 eye safety standards [3].

3. Each laser must produce a visible spot of at least 1 cm diameter at 4 m distance to ensure the illuminated hold is clearly identifiable.

4. The servo transition time between two target holds must be less than 500 ms to enable responsive route playback.

5. Since we are using a servo as opposed to a motor, we will not be able to use traditional PID control by measuring the current draw of the servo. Instead we will attempt to use the vision subsystem to compute an "error" function for the 2 axes of rotation per gimbal, and use the error to improve the accuracy of the targeting of the gimbals.

2.3.4 User Interface Subsystem

1. The ESP32-S3 HTTP server must respond to client requests within 100 ms under normal operating conditions.

2. The system must support at least 50 stored routes, each containing up to 30 holds, on the local SPI flash or SD card.

3. The web interface must be accessible from any device with a modern web browser (Chrome, Safari, Firefox) without requiring app installation.

4. The Wi-Fi connection must maintain a stable link at distances up to 10 m from the device.

2.4 Tolerance Analysis

The most critical tolerance in the Beta Spray system is the angular accuracy of the servo-actuated laser gimbals, as this directly determines whether the laser spot lands on the intended hold. A pointing error that places the laser on the wrong hold would render the system unusable.

Geometric Model. Consider the laser gimbal mounted at floor level, a horizontal distance d from the wall, pointing at a hold at height h on the wall. The required elevation angle is:

$$\theta = \arctan\left(\frac{h}{d}\right) \tag{1}$$

The positional error on the wall due to a small angular error $\Delta\theta$ in the servo is:

$$\Delta x = \frac{d}{\cos^2(\theta)} \cdot \Delta\theta \tag{2}$$

Worst-Case Analysis. For a typical setup with $d = 3\,\text{m}$ and a target hold at $h = 4\,\text{m}$ (near the top of a standard spray wall), the elevation angle is $\theta = \arctan(4/3) \approx 53.1°$. Standard hobby servos (e.g., SG90, MG996R) have a rated accuracy of approximately $\pm 1°$ ($\pm 0.0175\,\text{rad}$). The resulting positional error is:

$$\Delta x = \frac{3}{\cos^2(53.1°)} \cdot 0.0175 \approx \frac{3}{0.36} \cdot 0.0175 \approx 0.146\,\text{m} = 14.6\,\text{cm} \tag{3}$$

This exceeds our $\pm 5\,\text{cm}$ accuracy requirement. At lower angles ($h = 2\,\text{m}$, $\theta \approx 33.7°$), the error reduces to approximately 6.2 cm, which is closer to but still above the target.

Mitigation. To achieve the required accuracy, we will implement a two-stage approach combining initial calibration with continuous vision-based feedback control. First, after the initial wall scan, the system will project each laser onto known reference points (e.g., corner holds) and compute a correction mapping between commanded servo angles and actual wall positions. By applying this calibration lookup table, we can reduce the nominal angular error to approximately $\pm 0.5°$ or less.

However, calibration alone cannot account for time-varying errors such as thermal drift, mechanical settling, or external vibrations. To address this, we implement a closed-loop vision-based control system as described in the Projection Subsystem. During route playback, the camera continuously observes the laser spot position and computes the positional error. The ESP32-S3 applies corrective servo commands to iteratively null out this error. Assuming the vision subsystem can measure laser positions to within $\pm 3\,\text{cm}$ (as specified in the requirements), and that the servo response is monotonic, this feedback loop can drive the steady-state error below the $\pm 5\,\text{cm}$ tolerance within 2–3 correction iterations.

For example, if the initial open-loop error is 10 cm, a proportional correction can reduce it to $\sim$3 cm on the first iteration, and to $<$2 cm on the second iteration. At $\theta = 53.1°$ and assuming a final corrected error of $\Delta\theta = 0.003\,\text{rad}$:

$$\Delta x = \frac{3}{0.36} \cdot 0.003 \approx 0.025\,\text{m} = 2.5\,\text{cm} \tag{4}$$

This vision-in-the-loop approach ensures robust performance even in the presence of disturbances and component variability. The calibration procedure adds approximately 30 seconds to setup time, while the real-time feedback loop operates at 5–10 Hz with minimal perceptible latency during route playback.

2.4.1 Error Correction Philosophy

Our error correction philosophy is that we will integrate seamlessly with existing climbing gym operations, and rely on human staff to have more viable operation and error recovery strategy for complex cases. The hardware will be able to automatically resolve minor deviations using the camera corner localization, either with pivot adjustments or deliberate biasing/correction to the physical projection subsystem, using the vision localization. In contrast, critical failures—such as irrecoverably obstructed projections, or persistent laser misalignment under correction attempts—should trigger alerts (via HTTP server interface, e-mail, or some combination of highly-visible human-facing interfaces) so that the staff can manually intervene and correct the issue.

3 Tentative Part List

- ESP32-S3 and ESP32-S3-DevkitC-1 (prototyping)
- 3.3V LDO regulator
- Camera Module (Raspberry Pi Camera v3 or Arducam OV5647)
- Class 2 Laser Diodes (KY-008)
- Servo Motors (SG90 microserver OR MG996R)
- Gimbal kit
- Misc components (caps, resistors, diodes)

4 Ethics and Safety

As engineers, we have ethical and professional responsibilities in making design decisions for Beta Spray. We will adhere to the IEEE Code of Ethics [4] throughout the development of this project.

In accordance with IEEE Code 1.1, we are committed to holding paramount the safety and well-being of the public. The primary safety concern in our project is the use of laser pointers, which pose an eye injury risk if directed at a person. To mitigate this, we will use only Class 2 lasers (<1 mW), which comply with IEC 60825-1 [3] and FDA 21 CFR 1040.10 regulations for laser products. Class 2 lasers are considered safe for accidental exposure because the human blink reflex (approximately 0.25 seconds) provides sufficient protection. Additionally, we will implement a software interlock that disables all lasers when the system detects that no valid wall target is loaded, preventing uncontrolled laser emission.

All external references, open-source libraries (such as OpenCV), and third-party hardware designs used in the project will be documented and credited accordingly.

Regarding safety standards, the system will be powered from a standard 5V AC-DC adapter, and all exposed electrical connections will be insulated to prevent shock hazards. The device housing will be designed with no sharp edges and will include rubber feet to prevent slipping on gym floors. Since the device is intended for use in a gym environment where people are physically active, the enclosure must be robust enough to withstand incidental contact without exposing internal electronics.

We will comply with all ECEB lab safety standards during all development and testing [5]. All soldering, PCB assembly, and high-current testing will be conducted in designated laboratory areas with appropriate personal protective equipment.

Beta Spray has the potential to make climbing training more accessible and systematic. By enabling easy route sharing, the system encourages community engagement and lowers the barrier for beginner climbers who may otherwise struggle to identify appropriate routes. The environmental impact of the device is minimal, as it uses low-power components and does not produce waste during normal operation.

References

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[2] Moon Climbing, "MoonBoard," moonboard.com. Accessed: Feb. 12, 2026.

[3] International Electrotechnical Commission, "IEC 60825-1: Safety of laser products," 2014.

[4] IEEE, "IEEE Code of Ethics," ieee.org, `https://www.ieee.org/about/corporate/governance/p7-8.html`. Accessed: Feb. 12, 2026.

[5] ECE 445 Safety Guidelines, "Safety :: ECE 445 - Senior Design Laboratory," `https://courses.grainger.illinois.edu/ece445/guidelines/safety.asp`. Accessed: Feb. 12, 2026.