

Self-Balancing Robot

Course: ELEC 391 201 2024W2

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1 Introduction

This project focused on the design and development of a self-balancing robot which can be driven via **Bluetooth Low Energy (BLE)**. The robot autonomously maintained its upright position with real-time feedback from an on-board microcontroller **IMU**, with closed-loop controller continuously adjusting the motors to correct for angular tilt.

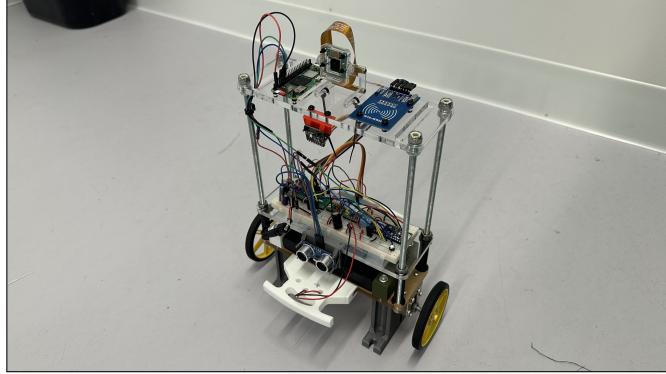


Figure 1: WALL-E: Self-Balancing Robot Prototype

It was also designed to support wireless control from a human user, responding to directional commands from a mobile device. The system integrates both stability and mobility, demonstrating precise control in dynamic environments.

2 Requirements, Specifications and Constraints

2.1 Functional Requirements

Table 1 lists the functional requirements of the self-balancing robot. These are prioritized by category as either a core or additional feature.

ID	Requirement Description	Priority
FR1	The robot must balance on a flat surface by controlling the DC motors.	Core
FR2	The robot must maintain balance while driven externally on a flat surface.	Core
FR3	The robot must maintain balance while turning at a reasonable speed.	Core
FR4	The robot must move forward and backward under external control.	Core
FR5	The robot must be controlled via Bluetooth with four directional commands.	Core
FR6	The robot must be able to recover when disturbed	Core
FR7	The robot is powered solely by a pack of $8 \times 1.2V$ rechargeable batteries.	Core
FR8	The distance sensor must detect obstacles and stop when it gets too close to an object	Additional Feature
FR9	The color sensor must be able to detect at least one color	Additional Feature
FR10	The RFID module must authenticate an RFID tag and prevent unauthorized operation.	Additional Feature
FR11	The Raspberry Pi Zero must process and transmit a camera feed through Pi Connect	Additional Feature
FR12	The AWS Bucket should store all the saved images and videos from the camera	Additional Feature

Table 1: Functional Requirements of the Self-Balancing Robot

The core functionality of the robot relate to its ability to autonomously balance itself and be driven by a human user via **BLE**. The additional features were designed to enhance the robot's capabilities, in detecting environmental factors and providing useful information to the user.

2.2 Performance Requirements

Table 2 outlines the performance requirements for the self-balancing robot, providing specific quantitative targets to assess the system's effectiveness. These closely align with the functional requirements, but with the addition of measurable criteria—such as recovery angle, speed and transmission speed.

ID	Requirement Description	Priority
PR1	The robot must respond to a 15° disturbance and re-balance	Core
PR2	The robot must maintain balance with a positional drift of less than 15 cm over 10s on a flat surface.	Core
PR3	The Bluetooth latency for control commands must be less than 100 ms.	Core
PR4	The robot must be able to maintain a Bluetooth connection within a range of at least 5m.	Core
PR5	The robot must be to move forward, backward, left (45°) and right (45°) within 5 seconds	Core
PR6	The obstacle detection system must stop the robot within 1cm of an obstacle detected between 2 – 30cm.	Additional Feature
PR7	The color sensor must identify red and respond accordingly within 100ms	Additional Feature
PR8	The RFID reader must successfully detect and authenticate tags within 1s.	Additional Feature
PR9	The Raspberry Pi Zero must transmit a camera feed at no less than 1 FPS.	Additional Feature

Table 2: Performance Requirements of the Self-Balancing Robot

By translating functional goals into performance metrics, we ensured that the robot's behavior could be consistently validated against clearly defined benchmarks. This approach helped guide both the design process and iterative improvements throughout development.

2.3 Constraints

2.3.1 Financial

This project operated under a strict financial constraint, with a maximum budget of \$65 allocated specifically for additional features (excluding taxes and shipping). To maximize the number of features within this limit, we opted to purchase components from alternative vendors when they offered more competitive prices than DigiKey. We determined that the most effective use of our budget was to prioritize implementing multiple smaller features, rather than allocating the entire amount toward a single major feature.

For a detailed breakdown of the expenses and financial details, refer to the following Google Sheet. The high-level breakdown is also included in the Appendix (i.e. Figure 28).

2.3.2 Temporal

Although the final project deliverable was due on **2025–04–08**, we set several soft deadlines along the way to track our progress and prevent last-minute workload buildup. Some of the main deadlines are shown below.

2025–02–28: Motor Control PWM for Arduino

2025–03–06: Completed BLE Integration with Python App

2025–03–07: Completed Distance Sensor and Color Sensor STM32 Firmware

2025–03–13: Completed PID k-value Calculations

2025–03–14: Completed RFID STM32 Firmware

2025–03–20: Completed Raspberry Pi App

2025–03–21: Completed Speaker Integration STM32 Firmware

2025–03–28: Completed Robot Balancing

Although most deadlines were met, a few, particularly the robot balancing milestone were not achieved on time. This delay was primarily due to some questionable firmware design decisions that introduced unforeseen challenges. Fortunately, these issues were resolved, and the system was successfully completed in the end.

2.3.3 Materials

For the custom construction of our self-balancing robot, we were limited to using thick plastic for laser cutting and standard 3D printing filament, as these materials were readily available and did not impact our budget. While other materials—such as aluminum, carbon fiber, or specialized fasteners—could have offered enhanced strength or reduced weight, they would have required additional spending from our \$65 budget. To stay within our constraints, we opted not to purchase any external materials and instead focused on optimizing our design using the provided components and available fabrication methods.

2.3.4 Environmental

The performance of a self-balancing robot can be significantly affected by environmental constraints such as battery levels, electromagnetic interference (EMI), temperature, and terrain conditions. Low battery voltage can reduce motor torque and sensor accuracy, leading to instability. EMI from nearby motors or power electronics can disrupt IMU readings and communication systems, making balance control less reliable. Temperature extremes can alter sensor calibration and battery efficiency, while uneven or slippery terrain can interfere with traction and cause the robot to lose balance. These factors must be carefully considered to ensure reliable operation in real-world environments.

3 Conceptual Design

3.1 High-level Functional Diagram

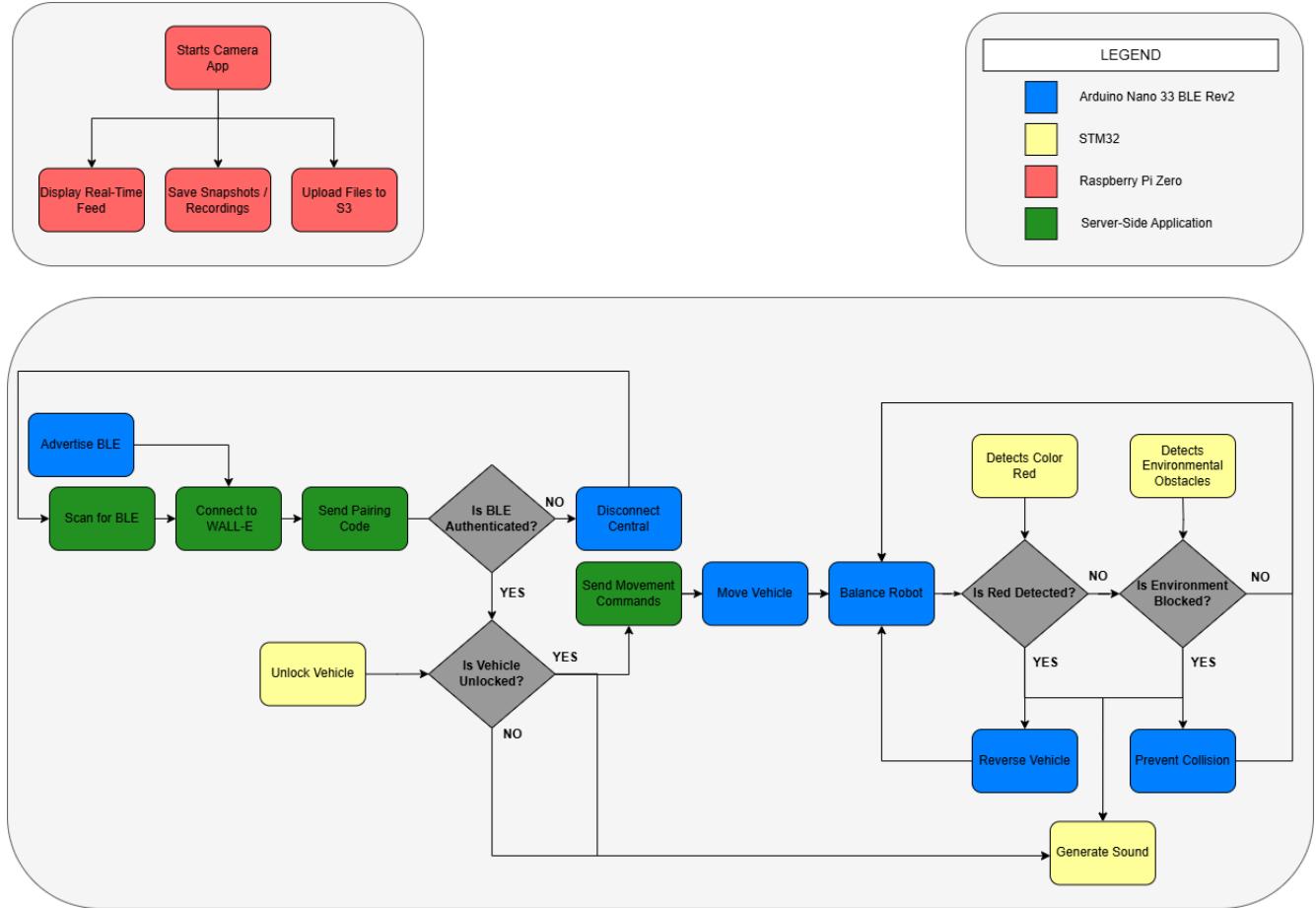


Figure 2: High-level Functional Diagram

The functional diagram in Figure (2) highlights our system-design for enforcing secure access of the robot with **RFID** and **Bluetooth Low Energy (BLE)**. We prevent users from balancing or moving the robot without the required authentication. Once successful, the firmware was programmed to prioritize safe operation of the robot, while accounting for environmental factors such as distance and color detection.

3.2 Architecture Diagram

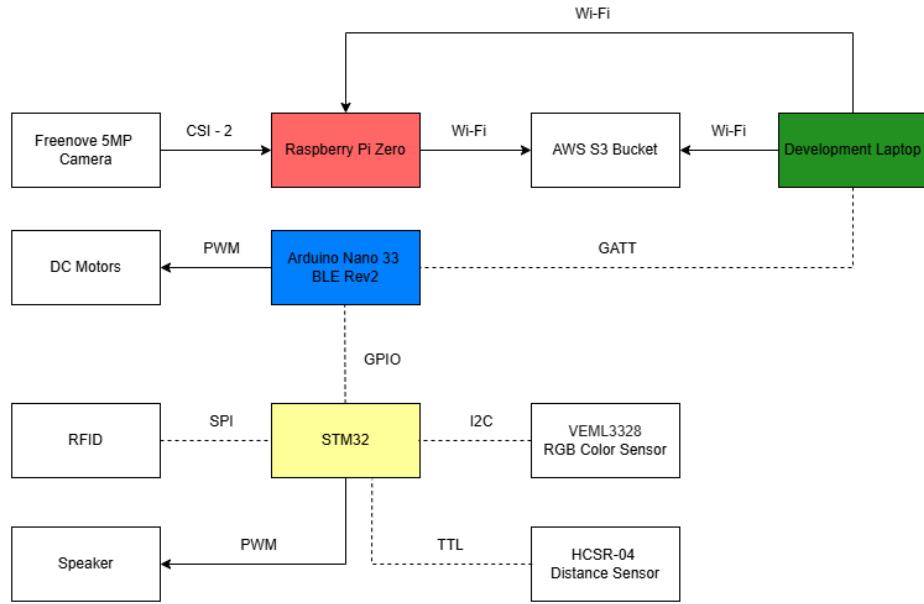


Figure 3: Architecture Diagram

The architecture diagram in Figure (3) describes the interfaces between robot peripherals and the three boards used in the project:

- **Arduino Nano 33 BLE Sense Rev2** was responsible for driving the motors and maintaining balance.
- **STM32L051K8T6** was responsible for environmental detection and physical authentication.
- **Raspberry Pi Zero W** was responsible for displaying and processing camera input for the user.

*Note that we wirelessly accessed the **Raspberry Pi** and **Arduino** from a development machine.*

4 Subsystem Design

4.1 Structural Design

4.1.1 Design Decisions

Since the transfer function of the robot was derived under the assumption that the center of mass of the pendulum is perfectly centered, the structural design follows the principle of evenly distributing mass to ensure that the center of mass is as close as possible to the rotor axis.

Another design decision we made was to mount the third layer as high as possible. This choice addresses the fact that the plant is a nonlinear and inherently unstable system, which can only be effectively controlled within a region where it can be approximated as linear. To evaluate the impact of the third layer's height on system behavior, we simulated the plant's step response at different mounting heights:

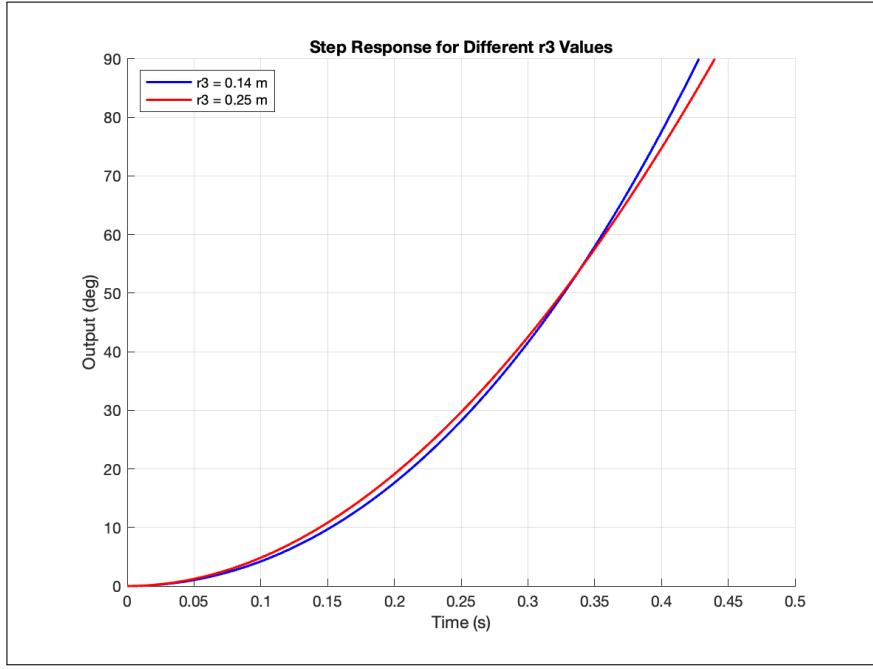


Figure 4: Step Response of the Plant with Different Height of the Third Layer

As shown in the figure, increasing the height of the third layer results in a step response that more closely resembles that of a linear system, making it easier to control.

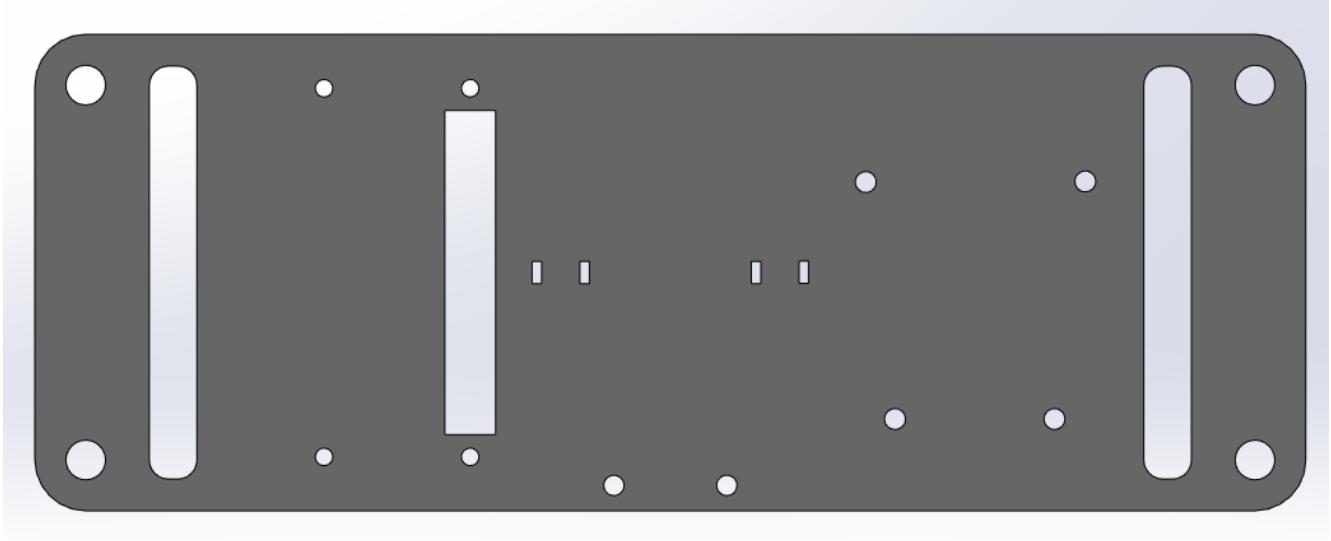


Figure 5: Design of the Third Layer

4.1.2 Third Layer Design

On the third layer, we need to mount the Raspberry Pi, color sensor, RFID reader, and camera. The four mounting holes on the left side are for securing the Raspberry Pi, while the four holes on the right are for the RFID reader. These holes are positioned to ensure that both components are centered relative to the third layer once mounted. At the bottom, two mounting holes are used to attach the L-stand for the color sensor. Since we only have one color sensor, its placement causes a deviation in the center of mass. To compensate for this imbalance, the camera is zip-tied at the center, allowing its position to be adjusted to help realign the center of mass. Although not shown in the figure, two distance sensors are also mounted on the second layer symmetrically.

4.1.3 L-stand Design

The design of the L-stand is shown below:

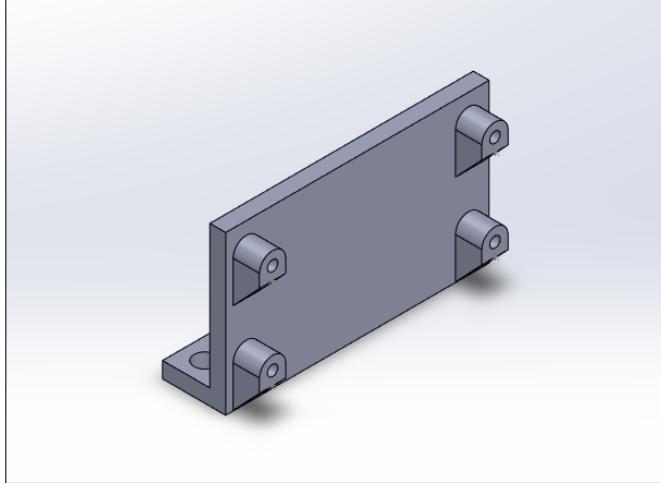


Figure 6: Design of the L-stand for Mounting the Distance Sensor

The L-stand includes four columns to provide clearance for the distance sensor, as there are components located on the back of the PCB. Ribs are added beneath each column to address potential issues during 3D printing. Since overhangs can lead to poor print quality or failed prints, the ribs provide structural support under the columns, eliminating overhangs and making the printing process more reliable and efficient.

The L-stand for the color sensor follows the same design principles with different dimension, thus is not shown here.

4.2 PID Modeling and Simulation

4.2.1 Robot Parameters

With the corrected transfer function, we need to find the values of the parameters in order to get the transfer function.

We start with the motor constants. For K_t , from the datasheet we know that the stall current is 5.5 A and the torque at 12 V is 85 kg·mm, or 0.83N·m, we can then get the value of K_t by dividing the torque by the stall current, which is 0.1516.

For K_e , from the datasheet we know that the free run speed of the rotor without the gearbox is 1047.19 rad/s, we can then get the value of K_e by dividing the load voltage 12 V by the free run speed of the rotor, which is 0.01146.

To obtain the moment of inertia of the pendulum J_p , we need to simplify the plant model. The robot consists of four rods and three layers. Assuming the center of mass is perfectly centered, the four rods can be approximated as a single equivalent rod located at the center of the three layers. Similarly, the three layers can be modeled as three point masses, which are further simplified into a single point mass located at their collective center of mass. The resulting simplified model consists of a single rod rotating about one end and a point mass positioned at the center of mass of the three layers.

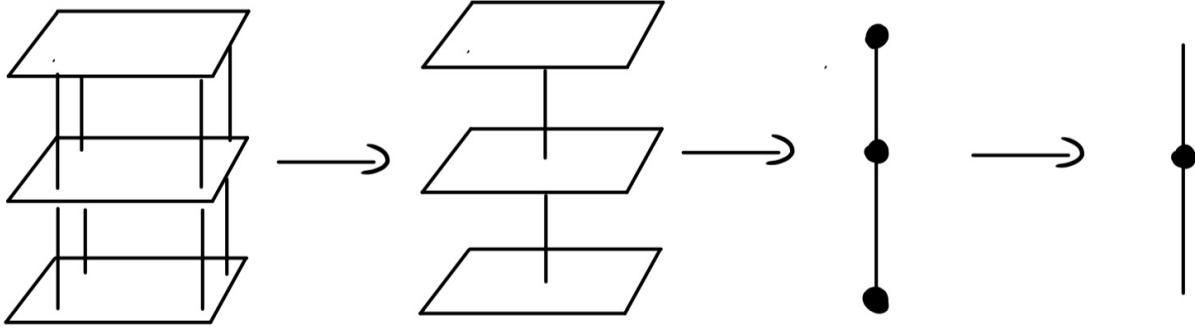


Figure 7: Simplification of the Plant Model

All of the other parameters can either be measured directly, or are negligible and have minimal impact on the overall transfer function.

4.2.2 Transfer Function

Considering the difficulty of deriving the transfer function from first principles, and given the abundance of studies on the same topic, we chose to reference a published paper for guidance [1]. However, upon reviewing the paper, we identified errors in part of the derivation:

Assuming the correctness of

$$K_t \frac{V_s - K_e \dot{\theta}_m}{R_a} = J_m \ddot{\theta}_m + \tau_w + b \dot{\theta}_m \quad (1)$$

$$\tau_w = J_w \ddot{\theta}_w - F_{pH} r_w + m_w \ddot{\theta}_w r_w^2 \quad (2)$$

$$F_{pH} = m_p (r_w \ddot{\theta}_w + l_g \ddot{\theta}_p) \quad (3)$$

$$F_{pH} l_g = J_p \ddot{\theta}_p \quad (4)$$

$$\theta_m = \frac{\theta_w}{G_r} \quad (5)$$

Substitute (3) into (4) gives:

$$\begin{aligned} m_p (r_w \ddot{\theta}_w + l_g \ddot{\theta}_p) l_g &= J_p \ddot{\theta}_p \\ m_p l_g r_w \ddot{\theta}_w + m_p l_g^2 \ddot{\theta}_p &= J_p \ddot{\theta}_p \\ m_p l_g r_w \ddot{\theta}_w &= (J_p - m_p l_g^2) \ddot{\theta}_p \\ \ddot{\theta}_w &= \frac{J_p - m_p l_g^2}{m_p l_g r_w} \ddot{\theta}_p \\ \theta_w &= \frac{J_p - m_p l_g^2}{m_p l_g r_w} \theta_p \end{aligned}$$

So Eq. 4 in the paper is incorrect. The τ_w in denominator should be r_w . The signs are also wrong. Substitute (3) into (2) gives:

$$\begin{aligned} \tau_w &= J_w \ddot{\theta}_w - m_p (r_w \ddot{\theta}_w + l_g \ddot{\theta}_p) r_w + m_w \ddot{\theta}_w r_w^2 \\ &= (J_w + (m_w - m_p) r_w^2) \ddot{\theta}_w - m_p l_g r_w \ddot{\theta}_p \end{aligned}$$

Substitute the above and (5) into (1) and expand the first fraction:

$$\frac{K_t}{R_a} V_s - \frac{K_t}{R_a} \frac{K_e}{G_r} \dot{\theta}_w - \frac{b}{G_r} \dot{\theta}_w - (J_w + (m_w - m_p) r_w^2) \ddot{\theta}_w + m_p l_g r_w \ddot{\theta}_p = \frac{J_m}{G_r} \ddot{\theta}_w$$

Move the angle terms to RHS and flip both sides:

$$\left(\frac{K_t}{R_a} \frac{K_e}{G_r} + \frac{b}{G_r} \right) \dot{\theta}_w + \left[\frac{J_m}{G_r} + J_w + (m_w - m_p)r_w^2 \right] \ddot{\theta}_w - m_p l_g r_w \ddot{\theta}_p = \frac{K_t}{R_a} V_s$$

Substitute the expression of θ_w in terms of θ_p :

$$\begin{aligned} (J_p - m_p l_g^2) \left(\frac{K_t}{R_a} \frac{K_e}{G_r} + \frac{b}{G_r} \right) \dot{\theta}_p + \left[(J_p - m_p l_g^2) \left[\frac{J_m}{G_r} + J_w + (m_w - m_p)r_w^2 \right] + (m_p l_g r_w)^2 \right] \ddot{\theta}_p \\ = \frac{K_t}{R_a} (m_p l_g r_w) V_s \end{aligned}$$

Laplace transform:

$$\begin{aligned} \theta_p(s) \left[(J_p - m_p l_g^2) \left(\frac{K_t}{R_a} \frac{K_e}{G_r} + \frac{b}{G_r} \right) s + \left[(J_p - m_p l_g^2) \left[\frac{J_m}{G_r} + J_w + (m_w - m_p)r_w^2 \right] + (m_p l_g r_w)^2 \right] s^2 \right] \\ = \frac{K_t}{R_a} (m_p l_g r_w) V_s(s) \end{aligned}$$

Hence the final transfer function:

$$\frac{\theta_p}{V_s}(s) = \frac{\frac{K_t}{R_a} (m_p l_g r_w)}{\left[(J_p - m_p l_g^2) \left[\frac{J_m}{G_r} + J_w + (m_w - m_p)r_w^2 \right] + (m_p l_g r_w)^2 \right] s^2 + (J_p - m_p l_g^2) \left(\frac{K_t}{R_a} \frac{K_e}{G_r} + \frac{b}{G_r} \right) s}$$

The definition of the parameters can be found in the paper.

Plug in the parameters we acquired, the resulting open loop transfer function is:

$$\frac{\theta_p}{V_s}(s) = \frac{977.5}{s^2 + 0.3439s}$$

Notice that the moment of inertia of the wheel and the rotor (J_m & J_r) and friction b are approximated to zero, This is because their magnitudes are negligible compared to other parameters in the system, thus they have minimal impact on the overall transfer function.

4.2.3 PID Parameter Calculation

From the previously derived transfer function, we observe that the two open-loop poles are located at 0 and -0.3439 , indicating that the system is unstable. To stabilize the system, a feedback control loop must be introduced to shift the poles of the closed-loop transfer function to stable locations. To determine the PID parameters, we can apply the pole placement method:

Assuming that we want the resulting poles to be placed at P_A and P_B , the denominator of the resulting transfer function is:

$$(s - P_A)(s - P_B)$$

This can be written explicitly as:

$$s^2 - (P_A + P_B)s + P_A P_B$$

With a PD controller, the characteristic equation is:

$$s^2 + (K \cdot K_d - (P_1 + P_2))s + P_1 P_2 + K K_p$$

Where P_1 and P_2 are poles of the open loop transfer function, K is the DC gain of the transfer function, which is 977.5.

We can relate the above two equations and the following equations can be obtained:

$$\begin{aligned} P_A P_B &= P_1 P_2 + K K_p \\ -(P_A + P_B) &= K K_d - (P_1 + P_2) \end{aligned}$$

The resulting PD gains will make the close loop transfer function be critically damped and stable.

To determine the desired pole locations, we first need to select an appropriate time constant N . By measuring the runtime of the main control loop, we found the worst-case execution frequency to be 25 Hz. According to the Nyquist theorem, the sampling rate must be at least twice the highest frequency component to accurately capture the system dynamics. Therefore, the maximum allowable control bandwidth is 12.5 Hz, corresponding to a minimum time constant of approximately 0.08. To ensure stability and responsiveness while staying within this limit, we chose a time constant of 0.25 s, which places the desired pole at -8π and the resulting K_p and K_d are 0.6462 and 0.0511, respectively.

The I term is added after to address the drifting issue we encountered during the testing. The value of K_i was found by trial and error, and the final value of K_i is 11.5.

4.2.4 Simulink Simulation

Simulink is used to validate the design of the PID controller. The model is shown below:

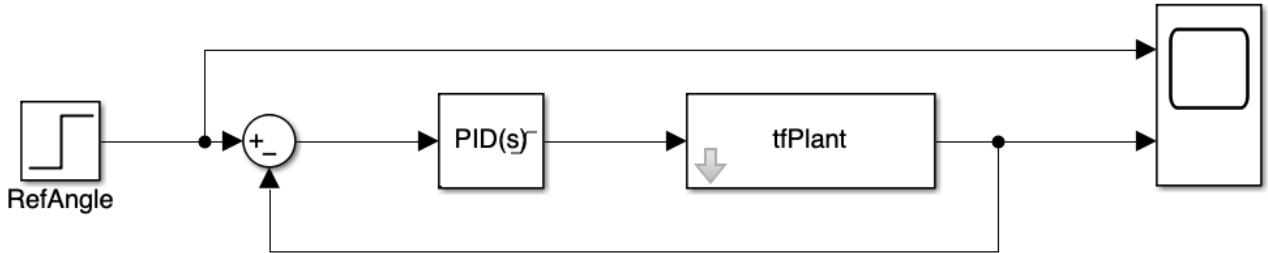


Figure 8: Simulink Model for the Bot

The step responses of the system under filter coefficient $N = 50$ and $N = 25$ were simulated to evaluate the performance of the robot under best- and worst-case scenarios:

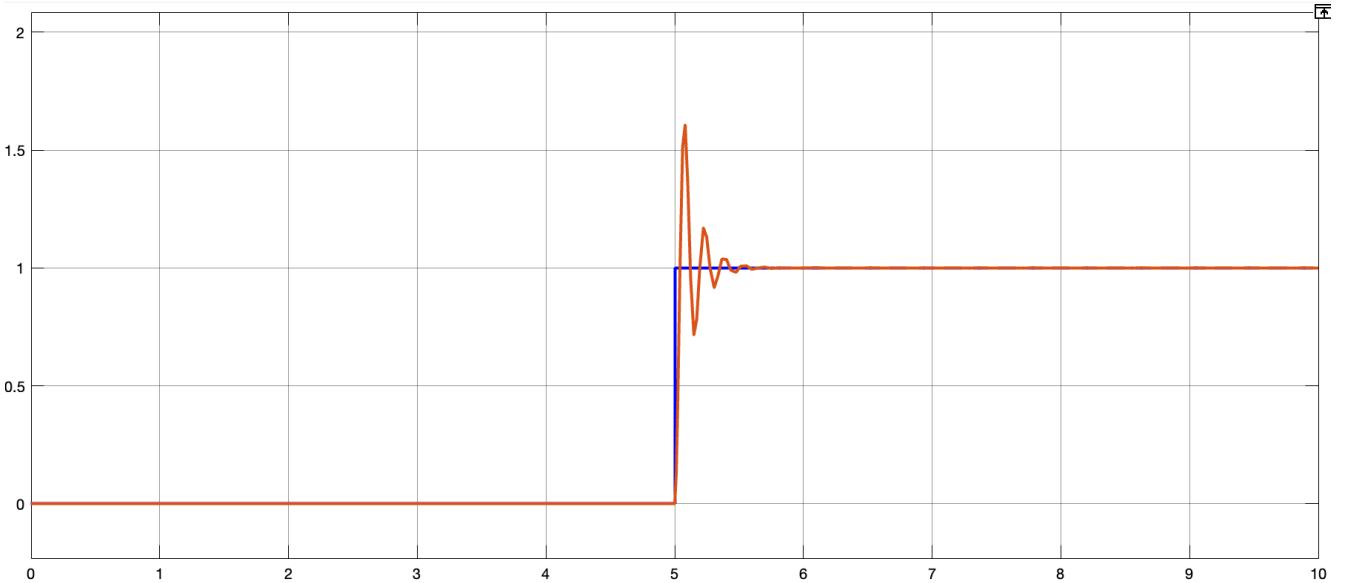


Figure 9: Step Response of the System with $N = 25$

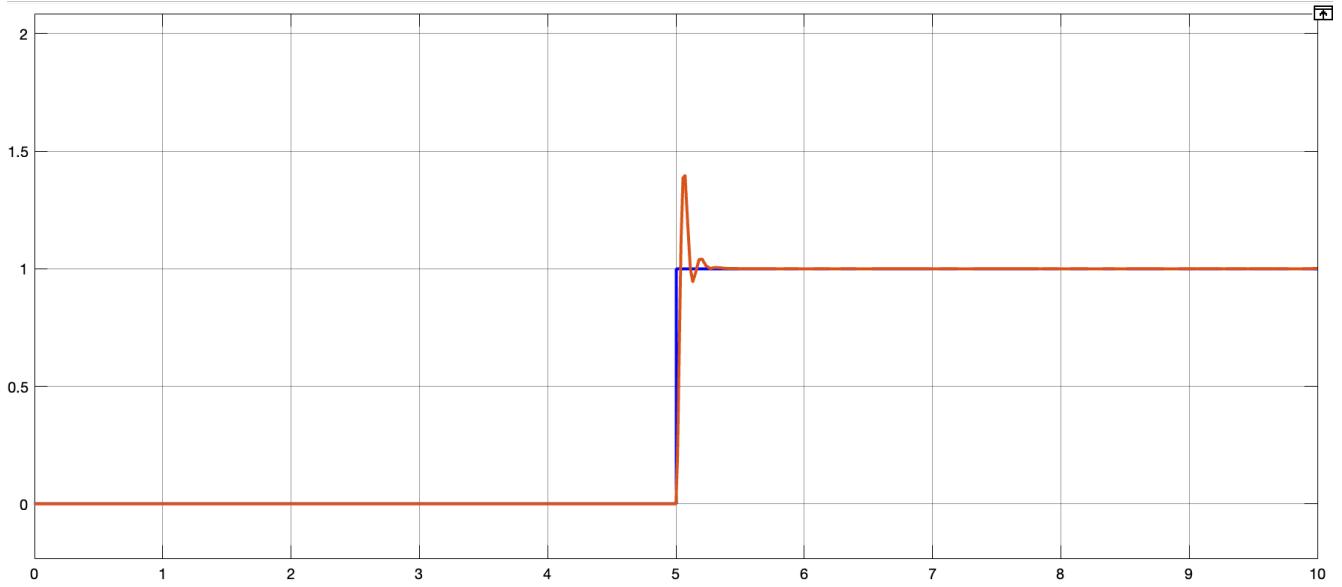


Figure 10: Step Response of the System with $N = 50$

We can see that for both cases the system is stable, with different degree of overshoot. This implies that the design of the PID controller is effective.

4.3 Arduino Nano 33 BLE Sense Rev2

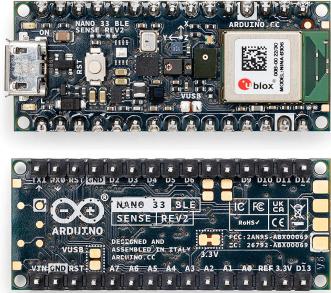


Figure 11: Arduino Nano 33 BLE Sense Rev2

The **Arduino Nano 33 BLE Sense Rev2** is a compact and powerful microcontroller board designed for low-power applications. It features the Nordic **nRF52840** chipset, which supports **BLE** communication, includes a range of built-in sensors, including a 9-axis IMU (accelerometer, gyroscope, and magnetometer). These integrated features make it well-suited for IoT, sensor-based applications, and portable devices.

This made it the ideal choice for our self-balancing robot project and was responsible for many of the core features. It integrated key core components in this project, particularly the **IMU** and the **BLE** module.

4.3.1 Arduino IDE

The **Arduino IDE** was integral in quickly testing new firmware changes to the board with built-in compilation and flashing tools. The extensive library support significantly streamlined the development process, reducing the need for bare metal programming and allowing us to focus on the functionality.

4.3.2 IMU Angle Measurement

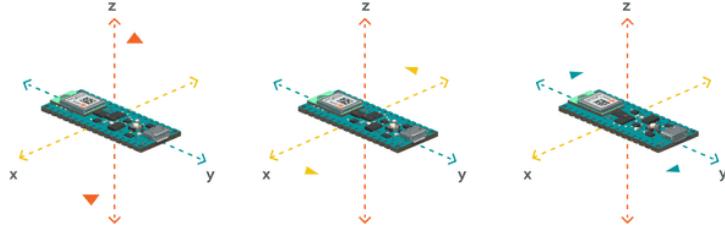


Figure 12: IMU

The **Inertial Measurement Unit (IMU)** was a critical microcontroller component for measuring velocity, orientation, and gravitational forces. This enabled the tracking of motion and orientation of the **Arduino** in three-dimensional space.

We used the accelerometer to measure linear acceleration and the gyroscope to monitor rotational movement. Both of these sensors had advantages and disadvantages, as shown in Table 8.2. By combining them, we ensured reliable and accurate angle measurements for optimized balancing in the control feedback loop.

4.3.3 Complementary Filter

The solution to combine the strengths of both sensors was to use a complementary filter, which combines the accelerometer and gyroscope readings with their respective normalized weights.

Since the gyroscope provided a rough estimate of the angle change, this was essential for detecting quick movements.

The formula used for the complementary angle is:

$$\theta_n = k(\theta_{n-1} + \theta_{g,n}) + (1 - k)\theta_{a,n},$$

where:

- θ_n is the current complementary angle,
- θ_{n-1} is the previous complementary angle,
- $\theta_{g,n}$ is the current gyroscope angle,
- $\theta_{a,n}$ is the current accelerometer angle,
- k is the normalized weight.

\therefore From extensive testing, a value of $k = 0.95$ was selected.

Lower values of k caused the noise from the accelerometer to become significant, leading to large oscillations and loss of balance. Similarly, increasing k was avoided. The gyroscope bias would accumulate quickly (i.e., without a reference point) and cause the robot to lose balance.

The code snippet for this exact implementation is demonstrated in Listing 1.

4.4 Balancing

The most challenging part of this project was to implement the **PID** controller to balance the robot. Since we had closed-loop control, with the measured angle acting as feedback, it was critical that we were able to act upon new measurements when determining the control signal.

Initially, we attempted to implement these **Interrupt Service Routine (ISR)** to meet a designed control frequency of 20 Hz. However, this proved to accumulate complications in firmware logic and was not able to provide the expected results.

We ultimately designed a control loop, run in the main program. This followed the sequence shown in Figure 13.

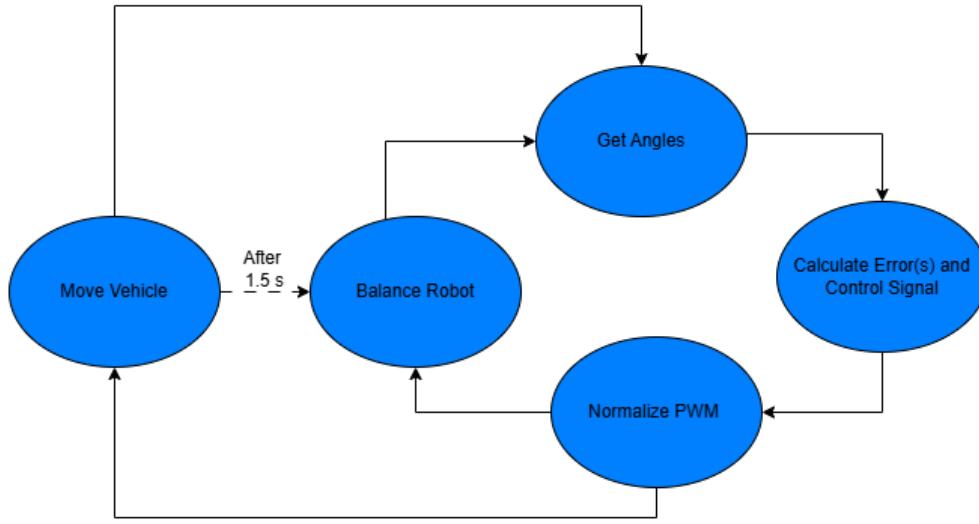


Figure 13: Control Loop Diagram

This ensured that we were able to inject **PWM** signals to both motors, without the constraints typical of an **ISR**. At the same time, this ensured that the robot was acting upon the most recent measurements.

The sign of the control signal determined whether to move the robot forward / backward to maintain balance.

The source code for this implementation is shown in Listing 2, in the Appendix.

4.4.1 Motor Control

To operate the robot wheels, we used the **DRV8833** motor driver to operate the robot with slow decay **PWM**. This entailed one of the motor terminals being driven to logic high, while the other was supplied the PWM signal.

xIN1	xIN2	FUNCTION
PWM	0	Forward PWM, fast decay
1	PWM	Forward PWM, slow decay
0	PWM	Reverse PWM, fast decay
PWM	1	Reverse PWM, slow decay

Figure 14: DRV8833 PWM Control

Supplying slow decay **PWM** enables the robot to gradually diminish its response to error angles, rather than abruptly stopping the motors. This was integral in ensuring the overall system behavior was stable and able to keep the robot balancing.

The source code for this implementation is shown in Listing 3, in the Appendix.

4.5 Movement

The robot was designed to move in four directions: **FORWARD**, **BACKWARD**, **LEFT**, **RIGHT**. As shown in Figure 13, this was designed to be integrated into the control loop.

Balancing was the highest priority of the system at (almost) any given moment. To move the robot, we injected noise into the system for a short duration (i.e. 1.5 s). After this, we returned to idle balancing to prevent the system from reaching a point of instability.

For the complete code snippet of this implementation, it can be found in Listing 4, in the Appendix.

4.5.1 Forward/Backward Movement

The logic for moving the robot forward and backward was very simple. It was a matter of adjusting the setpoint angle on either side of the "zero point". This induced movement in the intended direction (without sacrificing balance).

4.5.2 Left/Right Movement

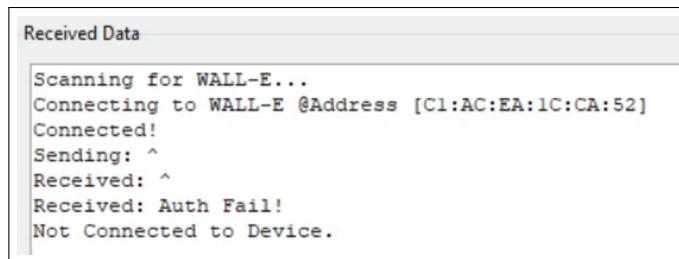
The logic for moving the robot left and right was slightly more complicated and involved software logic to interchangeable turn and balance the robot. This can be summarized as follows:

- After (every) 3 iterations of control loop : balance robot
- If error angle > allowable threshold (i.e. 0.8°): balance robot
- Otherwise:
 - To turn left: move left motor *CW* and right motor *CCW*, with **PWM** adjusted by scale factor 0.6
 - To turn right: move left motor *CCW* and right motor *CW*, with **PWM** adjusted by scale factor 0.5

4.6 Bluetooth Control

The robot was controlled via the **Arduino's Bluetooth Low Energy (BLE)** capabilities. The firmware was developed such that new connections need to be authorized by successfully transmitting the correct pairing code. This follows the workflow shown in Figure 2.

In order to send movement commands, the connection and authentication process must be successfully complete to ensure secure access. A key part of this process was to provide the expected pairing code to the microcontroller.



The screenshot shows a terminal window titled "Received Data" with the following text output:

```
Scanning for WALL-E...
Connecting to WALL-E @Address [C1:AC:EA:1C:CA:52]
Connected!
Sending: ^
Received: ^
Received: Auth Fail!
Not Connected to Device.
```

Figure 15: Unauthorized Bluetooth Connection

If unsuccessful, the robot would immediately disconnect and await an authorized user as shown in Figure 15.

The firmware is also designed such that movement commands are placed on a lower priority. Since **BLE** can be computationally expensive, we polled for new commands every 100 ms in the main loop. This was done to ensure that the control functionality is placed at highest priority, and we can account for the infrequent nature of user driven commands.

4.6.1 Robot Driver App

We developed a **Flask** application, which used GET/POST request **HTTP** methods to asynchronously request device information from the **HTML DOM** elements and send commands to the **Arduino** microcontroller.

This application was run from our computer and temporarily hosted to the Internet using the **ngrok** tool. This enabled us to access the robot via public URL from other devices (including smartphones).

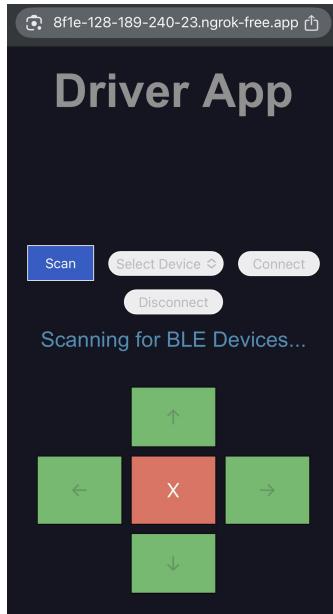


Figure 16: Robot Driver App on iPhone 14

The **Flask** application had the expected pairing code programmed in the source code such that users can easily connect to and control the robot. We programmed the **DRIVE**, **LEFT**, **RIGHT**, **BACK** commands to correspond to specific bytes to be transmitted via **BLE**.

This is shown in the code snippet in Listing 11 in the Appendix.

4.7 STM32L051K8T6 Microcontroller

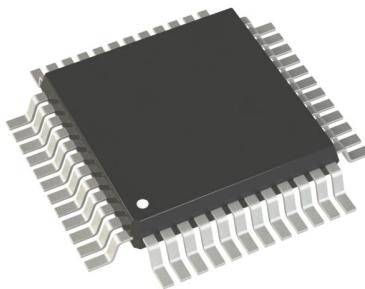


Figure 17: STM32L051K8T6 Microcontroller

The STM32L051K8T6 is a low-power microcontroller from STMicroelectronics, part of the STM32L0 series. It features an ARM Cortex-M0+ core running at up to 32 MHz, with 64 KB of flash memory and 8 KB of SRAM. For

our project, this microcontroller was used to interface with the HC-SR04 (section 4.7.1), TCS34725 (section 4.7.2), RC522 (section 4.7.3) and the CEM-1202 (section 4.7.4) modules. The pinout diagram is shown in Figure 18 (note that USART it was never used in the implementation).

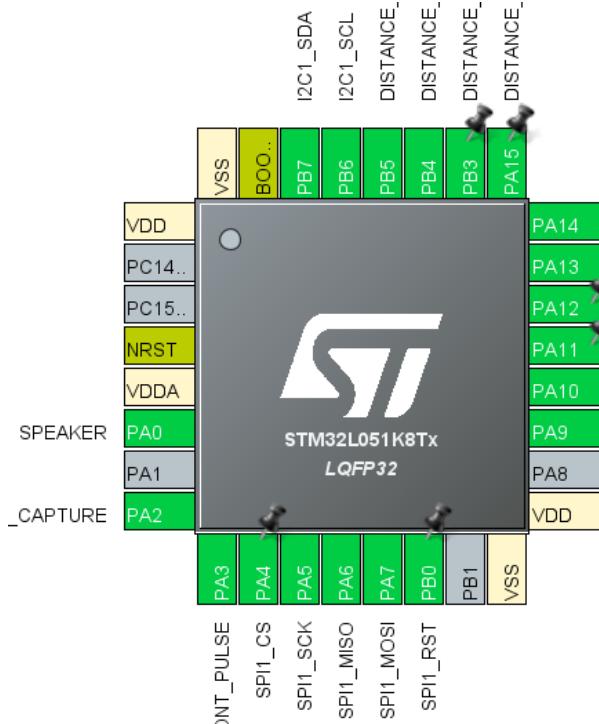


Figure 18: Zoomed In Pinout

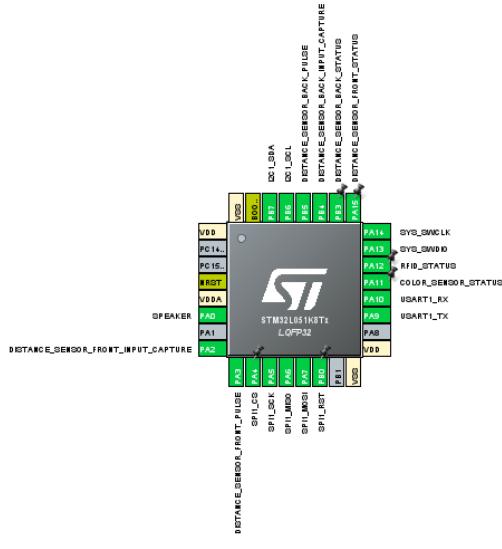


Figure 19: Zoomed Out Pinout

To streamline the firmware development process for the STM32, we utilized the STM32Cube IDE, provided by STMicroelectronics. This development environment facilitated faster progress by offering built-in tools and libraries, allowing us to focus on application logic rather than dealing with bare-metal programming.

4.7.1 Distance Sensing



Figure 20: HC-SR04 Ultrasonic Ranging Module

As an extra feature, we decided to use two **HC-SR04** sensors for sensing proximity to objects. It operates by emitting an ultrasonic pulse from its transmitter and measuring the time it takes for the pulse to reflect off a nearby surface and return to the receiver. The module communicates via a simple TTL interface, requiring a 'trigger' signal to start the measurement and an 'echo' signal to indicate when the reflected pulse is received. By calculating the time interval between the trigger and echo signals, the distance to the object can be determined.

We decided to use timers and interrupt service routines to measure the time of this pulse. Specifically, we used the input capture mode, which would trigger on both rising and falling edges of the Echo signal, enabling precise

capture of timer values at each transition. By handling these events in interrupt service routines, the CPU remained free to execute other tasks concurrently with the distance measurement process.

A code sample for the firmware implementation of input capture interrupt are shown in Listing 7 in the Appendix. More information about input capture mode and its implementation can be found on this site, here. If the module sensed a distance smaller than 30cm, a basic GPIO pin would be set low to communicate to the Arduino of this status.

4.7.2 Color Sensing

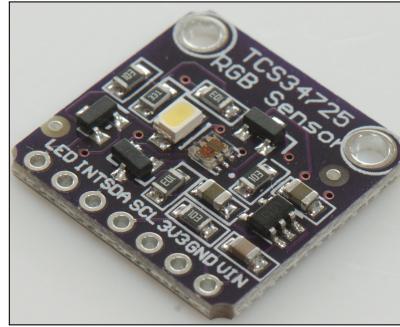


Figure 21: TCS34725 Light-to-Digital Sensor

We decided to integrate the **TCS34725** Color Sensor Module, responsible for detecting the color composition of a surface by measuring the intensity of red, green, blue, and clear light. It communicates via an I²C interface, and was implemented on the *STM32L051* microcontroller. The STM32 HAL libraries simplify I²C communication, as demonstrated in Listing 8.

The `ColorSensor_Handle` function is called within the main control loop. It reads the values from each color channel register (16 bits) and determines the most dominant color. If the red channel is the most prominent, the speaker is triggered to notify the user of the sensor's detection. When this would occur, a basic GPIO pin would be set low to communicate to the Arduino of this status.

4.7.3 RFID Security System



Figure 22: RC522 Contactless Reader IC

The **RC522** RFID Module was responsible for detecting and reading passive RFID tags using radio frequency communication at 13.56MHz. It operates over an SPI interface, allowing for fast and efficient data exchange with the *STM32L051* microcontroller. When a tag enters the RF field generated by the module's antenna, the RC522 initiates a handshake protocol and reads the tag's unique identifier (UID) stored in its internal memory.

In the case where the correct RFID tag would be scanned, a basic GPIO pin would be set low and the speaker would be triggered to communicate to the Arduino of this status. The remaining logic specific to our application is shown in Listing 9 in the Appendix.

4.7.4 CEM-1302 Speaker/Buzzer



Figure 23: CEM-1302 Speaker/Buzzer

We used the CEM-1302 buzzer to indicate the following key events:

- RFID: Indicating successful and unsuccessful RFID card scans
- Ultrasonic Sensor: Alerting when the distance between the robot and an object is too small
- Color Sensor: Signaling when the color sensor detects a predominantly red color

When any of these events occurred, the speaker would either beep, or stay on, depending on the scenario. Code for the setup can be seen in Listing 10. The speaker was also developed on the *STM32L051*, using a square wave PWM running at 2.048kHz. GPIO pins for these events were used to communicate with the Arduino Nano for simplicity and speed.

4.8 Raspberry Pi Zero 2 W

The **Raspberry Pi Zero 2 W** is an affordable single-board computer designed for embedded systems and IoT applications. We leveraged its camera connector (CSI-2 interface) to interface with a **Freenove 5MP Camera**, as well as its Wi-Fi capabilities to wirelessly access it via the **Raspberry Pi Connect** software.



Figure 24: Raspberry Pi Zero 2 W

4.8.1 Camera App

We developed a **Python** application to display the live camera feed in a **Tkinter GUI** window, allowing the user to observe and record the operation of the robot. The user interface provided the ability to also take snapshots and store these in the **SD Card** storage.

The live feed was largely a result of scheduling an update function with **Tkinter's after(...)** method, which allowed us to sample camera frames at a rate of 20 FPS.

Since the **Raspberry Pi Zero 2 W** had power and performance constraints (i.e. 512 MB of SDRAM), we ensured that the application was optimized for performance and iterated software versioning to minimize resource consumption. The camera was configured to capture frames at a resolution of 480 pixels to account for this.

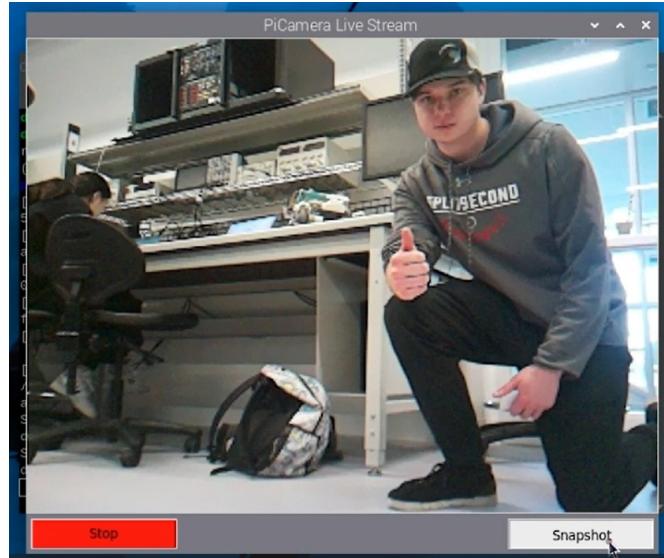


Figure 25: PiCamera Application

The class and methods for the camera display are shown in Listing 12 in the Appendix.

Early on in development, we switched from the **Kivy** framework. This provided smoother animations, but rendering was hardware accelerated. We were unconfident with the **Raspberry Pi Zero 2 W**'s ability to provide adequate performance with this, and ported the application to the current implementation.

4.8.2 AWS Bucket

Another constraint we considered during implementation was the inability to connect to the **Raspberry Pi** without powering on the robot. Having to access recording and snapshots would be quite cumbersome for the user.

The screenshot shows the AWS S3 console interface. At the top, there's a navigation bar with 'Amazon S3 > Buckets > self-balancing-robot'. Below it is a header with tabs: 'Objects' (which is selected), 'Properties', 'Permissions', 'Metrics', 'Management', and 'Access Points'. Under the 'Objects' tab, there's a sub-header 'Objects (9)'. A note below says 'Objects are the fundamental entities stored in Amazon S3. You can use [Amazon S3 inventory](#) to get a list of all objects in your bucket. For others to access your objects, you'll need to explicitly grant them permissions. [Learn more](#)'. There's a search bar with 'Find objects by prefix' and a dropdown menu. To the right, there are buttons for 'Actions', 'Create folder', and 'Upload'. Below these are buttons for 'Copy S3 URI', 'Copy URL', 'Download', 'Open', 'Delete', and 'Actions'. The main area displays a table of 9 objects:

	Name	Type	Last modified	Size	Storage class
<input type="checkbox"/>	Recording_20250405_145944.h264	h264	April 7, 2025, 13:32:01 (UTC-07:00)	11.4 MB	Standard
<input type="checkbox"/>	Recording_20250407_151159.h264	h264	April 7, 2025, 15:37:14 (UTC-07:00)	20.1 MB	Standard
<input type="checkbox"/>	Recording_20250407_151509.h264	h264	April 7, 2025, 15:37:14 (UTC-07:00)	284.0 KB	Standard
<input type="checkbox"/>	Recording_20250407_151902.h264	h264	April 7, 2025, 15:37:08 (UTC-07:00)	11.5 MB	Standard
<input type="checkbox"/>	Snapshot_20250407_151917.jpg	jpg	April 7, 2025, 15:37:08 (UTC-07:00)	0 B	Standard
<input type="checkbox"/>	Snapshot_20250407_151919.jpg	jpg	April 7, 2025, 15:37:08 (UTC-07:00)	0 B	Standard
<input type="checkbox"/>	Snapshot_20250407_151930.jpg	jpg	April 7, 2025, 15:37:08 (UTC-07:00)	0 B	Standard

Figure 26: AWS S3 Bucket

We created an **AWS S3 Bucket** and uploaded the camera recordings and snapshots during operation. The **Boto** package enabled us to implement this in our **Python** application by leveraging the **AWS SDK**. We were able to download these files from the **AWS S3 Bucket** to our local machine for offline access.

5 Meeting Requirements

5.1 Verification

To evaluate the core functionality of the robot, we leveraged the **Serial** and **BLE** capability of the **Arduino** microcontroller to both observe and modify **PID** I/O signals.

This was done to compare performance as we tweaked parameters.

5.1.1 Angle Accuracy

Early on in development, we realized that accurate angle measurements were critical to the robot's ability to successfully balance itself.

We developed a **Python** user interface to visualize the angle measurements from the **Arduino** in real-time, included in Listing 13 in the Appendix.

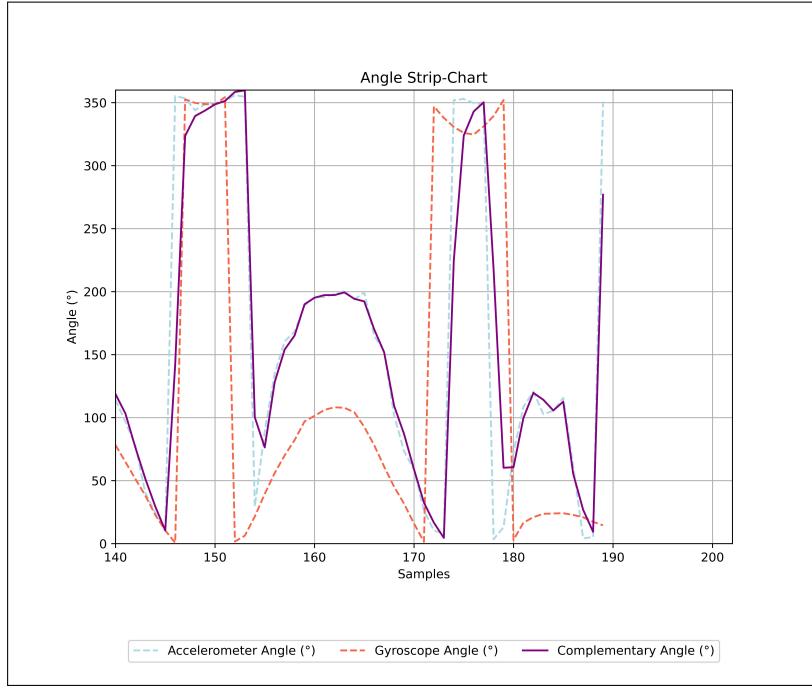


Figure 27: Angle Measurements ($k = 0.6$)

As shown in the example in Figure 27, we rotated the **Arduino** microcontroller within a predefined angle range and observed the complementary filter's performance with a given k value.

From saving and comparing these logs, we observed trends in the angle measurements from the accelerometer and gyroscope. This enabled us to optimize the benefits of both sensors and was critical in ensuring that we were able to balance the robot successfully.

5.1.2 Model Parameters

Similarly, we developed a debugging tool in the **Arduino** firmware to tune **PID** parameters during operation (**FR1**, **FR6**). The source code for this is shown in Listing 6 in the Appendix.

When we were confident in the actual system level logic, we used the **BLE** capabilities to tune the following parameters.

- PID Gains (K_p , K_i , K_d)
- Complementary Filter Weight (k)
- Setpoint Angle (θ_{set})

During operation, we observed the effect of increasing / decreasing each of these on meeting the balancing requirements from Table 1.

Parameter	Behavior When Increased	Behavior When Decreased
K_p	Undershoot	Overshoot, Tipping over When K_p Too High .
K_i	Drifting, Undershoot	Degraded Stability, Oscillates Near Reference Angle.
K_d	Drifting, Overshoot	Oscillates Near Reference Angle
k	Faster, Smooth Response. Accumulates Drift.	Increases Noise Influence, Experiences Jitter. No Drift.
θ_{set}	Drifting in Forward Direction.	Drifting in Backward Direction.

Table 3: PID Parameters and System Behavior

5.1.3 Movement Implementation

To verify that the movement met the requirements outlined in **PR5**, we tested the robot's ability to respond accurately to directional commands sent via the **BLE** interface. Using a mobile device, we issued **FORWARD**, **BACKWARD**, **LEFT**, **RIGHT** commands while observing the robot's response in real time. The robot successfully executed each command within the 5 s time interval, while maintaining balance, demonstrating reliable communication and precise motor control. This confirmed that the **BLE** movement functionality met the performance expectations specified in the requirement.

5.1.4 Remaining Requirements

To verify the remaining requirements not covered above, we relied on a combination of simple tools and observation. For distance and size-related measurements, we used rulers to confirm dimensions and movement ranges. Timing-sensitive behaviors was evaluated with internal timers and debug outputs via **USART**. We used these to ensure response times and delays were adequate. In cases where quantitative measurement was unnecessary or impractical, we used visual observation to confirm correct operation. These methods provided sufficient confidence that the robot met the functional and performance criteria across all remaining requirements.

5.2 Validation

5.2.1 User Acceptance Testing (UAT)

Similar to the software development cycle, we tested the integration of both core and extra features with critical examination from team stakeholders.

We delegated this for there to be an owner responsible for implementation, but another team member who set the requirements for success in Table 1 and Table 2.

Looking at the ability to balance and move the robot, the Modeling Lead was the UAT lead in providing feedback for firmware implementation, whereas the Firmware & Extra Features Leads provided feedback on current parameters.

5.2.2 Balancing Criteria

To observe the borders of stability (i.e. analogous to edge-case testing), we placed the robot on the lab floor and observed its ability to balance (without external assistance) for 1 minute (**FR1**).

A ruler was placed on the ground to measure drift accumulation (**PR2**). Once the robot was able to maintain balance $>$ 5 minutes and remained relatively stationary (i.e. drifting $<$ 5 cm), we unanimously agreed that results indicated that we met the balancing requirement.

5.2.3 Angle Management

To test angle management (i.e. resilience to external force), we introduced noise to the system. We applied a force to the top of the pendulum to tilt the robot ~ 15 deg and observed whether it could recover without tipping over (**PR1**).

The robot successfully recovered from angular tilts ≤ 20 deg without oscillation. However, when the tilt angle > 20 deg, we observed that it was unable to recover from the disturbance. Observing this border of stability gave us understanding of the system behavior while making us confident that we met the set requirement of angle management within the expected operating range.

5.2.4 STM32 Sensors

We approached the integration of environmental response as an enhancement of existing core functionality. We should be able to meet all existing requirements, while enhancing the user experience. When testing the utility of the **HC-SR04** distance sensor and **TCS34725** color sensor, we prioritized the following main criteria:

- Balancing should be unaffected by the addition of sensors (i.e. **PR1**, **PR2**)
- Driver should be able to navigate the robot from A to B within a reasonable time (i.e. **PR3**, **PR5**).
- The robot should not hit any obstacles while moving (i.e. **PR6**).

These are inherently included in the requirements from Table 1 and Table 2. However, we wanted to ensure that we could compare the ability to meet each of these both before / after feature integration, and ensure that we either avoid or reduce performance degradation.

Once we observed that this (qualitatively) made it easier to navigate the robot and meet the relevant performance requirements, we labeled the feature as a success.

5.2.5 Secure Authentication

Similarly, the addition of the **RC522** RFID module and **BLE** authentication were designed to enhance the security of the robot. These actually were designed to make it more difficult for user onboarding in a sense. However, we wanted to ensure that access was as simple for the intended user, while being as difficult as possible for an unauthorized user.

The **Robot Driver App** was appropriately designed such that other team members could easily onboard themselves to the robot, without knowing that the intended application handled the authentication process in the background. The Firmware Lead was responsible for this, and observed team member onboarding difficulty as a success metric.

To ensure security was prioritized, we performed edge-case testing in which either the **BLE** connection was interrupted or the **RC522** RFID module was disconnected. We observed that the robot prevented access under these conditions, but could unconditionally recover if they were reconnected.

5.2.6 Camera File Storage

We struggled the most with the **Raspberry Pi Zero 2 W** camera feed. It was straightforward to meet the success criteria of being able to record at 1 FPS and display the live feed. We were also able to successfully store images/videos to the **SD Card** storage. However, (an implied) success criteria entailed the user being able to successfully complete the end-to-end process of accessing the camera feed and downloading the images/videos from the **AWS S3 Bucket**.

We had to perform this test under the condition that the robot was powered off in the downloading stage. Once this was met, the feature was (tentatively) labeled as a success.

6 Conclusion

The implementation of the PID controller was effective and enabled the robot to balance with reasonable resistance to external disturbances. However, one improvement would be to utilize an encoder and implement an additional, cascaded PID controller. This could help reduce oscillations and improve the robot's ability to remain stationary. It may also enhance the angle management. Since the current system requires a relatively high K_i term to maintain balance, it has degraded stability under significant external disturbances. By introducing a cascaded PID controller, the K_i term in the main controller could be reduced, leading to improved stability and better angle management.

In terms of structural design, we raised the third layer to increase the linearity of the system's step response within its controllable region. While this improves linearity, it also narrows the linear region and makes the robot more prone to external disturbances. One possible improvement is to replace the current motors with ones that have less mechanical slack, which would provide a more responsive system. This would allow us to lower the third layer, enhancing angle management while maintaining linear behavior.

6.1 Future Improvements

For future revisions, especially related to control systems, we have a few key takeaways.

- **Keep the PID control code as simple and straightforward as possible.**
 - Adding excessive logic, layers of filtering, and unnecessary conditions introduced both complexity and instability in our system, which made tuning more difficult.
- **Avoid tuning the PID controller until key modules for background calculations are integrated.**
 - Adding / removing modules can shift timing and alter the effective control behavior, which would lead to a vicious cycle of re-tuning.
 - Introducing deliberate delays can help simulate sensor acquisition timing during early development.
- **Finalize the robot's physical design before tuning the controller (i.e. mass distribution, wheel-base, and component placement).**
 - Significant changes to the hardware likely affect system dynamics and invalidate earlier tuning efforts (i.e. leading to cyclical controller tuning).
- **Use real-time plotting / data logging to observe variables such as sensor readings, control output, and error values.**
 - This helps in diagnosing control issues and speeding up the tuning process.
 - We originally planned on addressing this with the **Raspberry Pi** serial interface, but due to time constraints, were unable to meet the necessary acceptance criteria to use this and enhance our system.
- **Avoid over-relying on simulation unless the model is very accurate.**
 - Physical systems often behave unpredictably due to noise, friction, and delays, which are difficult to capture in simulation.
- **Make safety a priority when testing control systems.**
 - Starting with lower gains and gradually increasing them, especially on inherently unstable systems like the self-balancing robot, helps improve performance without the risk of instability.
- **Seamlessly integrate the security experience in the software tools.**
 - We started enhancing the security of the robot very late during development.
 - Implementing a **BLE** pairing code was an idea we toyed with throughout this 12-week project. However, we were inspired to implement the firmware layer when we realized our robot was vulnerable to unauthorized access.
 - Another addition we'd have added given ~ 1 week of development would be to implement a password in the **Robot Driver App** to add another layer of security (i.e. via software).

7 References

- [1] T. N. Soe and A. S. Khaing, “Mathematical model for two wheeled balancing robot using pid control algorithm,” *International Journal of Latest Technology in Engineering, Management & Applied Science (IJLTEMAS)*, vol. VIII, no. VIII, pp. 1–5, Aug. 2019, Technological University (Mawlamyine), ISSN: 2278-2540. [Online]. Available: <https://www.ijltemas.in>.

8 Appendices

8.1 Appendix: Budget

Part	Manufacturer PN	Digikey PN	Link	Datasheet	Description	Quantity	Cost/Unit	Total Cost
Distance Sensor	SNS-HCSR04	1188-SNS-HCSR04-ND	Link	Datasheet	SENSOR OPTICAL 20-100CM TTL	2	2.81	5.62
Raspberry Pi Zero 2	SC1176	2648-SC1176-ND	Link	Datasheet	SBC 1.0GHZ 4 CORE 512MB RAM	1	22.75	22.75
RFID Reader Module	CN0090	4411-CN0090-ND	Link	Datasheet	RCS22 RFID MODULE	1	8.49	8.49
High Current Voltage Regulator 5V	LD1085V50	497-3436-5-ND	Link	Datasheet	IC REG LINEAR 5V 3A TO220	1	2.55	2.55
Color Sensor I2C	TCS34725	N/A	Link	Datasheet	TCS34725 Color Sensor Recognition Modul	1	3.85	3.85
Raspberry Pi Camera	N/A	N/A	Link	None	Freenove 5MP Camera for Raspberry Pi 5 4	1	16.95	16.95
								60.21

Figure 28: Extra Features Financial Summary

8.2 Appendix: Technical Calculations and Simulations

Sensor	Pros	Cons
Accelerometer	<ul style="list-style-type: none"> • accurate gravitational readings • zero-mean noise 	<ul style="list-style-type: none"> • high noise variance (especially with motor vibrations)
Gyroscope	<ul style="list-style-type: none"> • lower noise over short time periods 	<ul style="list-style-type: none"> • accumulates bias over time

Table 4: IMU Sensors: Pros and Cons

8.3 Appendix: Datasheets / Product Specifications

Supporting Datasheets and Technical Documentation for Core Features (does not include battery related components, mechanical components, or generic electrical components):

1. Arduino Nano 33 IoT (ABX00069) Datasheet
2. Pololu 37D Metal Gearmotor Specifications
3. Texas Instruments DRV8833 Dual H-Bridge Motor Driver Datasheet

Supporting Datasheets and Technical Documentation for Additional Features:

1. HC-SR04 Ultrasonic Distance Sensor
2. TCS34725 Color Sensor
3. Raspberry Pi Zero 2 W
4. CN0090 Accelerometer Board
5. L293D Motor Driver IC
6. Freenove 5MP Camera (FNK0056)
7. CEM-1302 Speaker/Buzzer

8.4 Appendix: Source Code

```

1 ANGLES Angles = {0, 0, 0}; // Accelerometer, Gyroscope, Complementary
2 void getAngles(ANGLES &Angles) {
3     float currAccel, currGyro, currComplementary;
4     float sampleTime;
5
6     if (!IMU.gyroscopeAvailable()) return;
7     IMU.readGyroscope(gx, gy, gz);
8
9     if (!IMU.accelerationAvailable()) return;
10    IMU.readAcceleration(ax, ay, az);
11
12    currAccel = atan2(az, ay) * (180 / PI);
13    currAccel = (currAccel - 90) + ACCELEROMETER_OFFSET;
14
15    sampleTime = 1.0 / IMU.gyroscopeSampleRate();
16
17    currGyro = prevGyro + gx * sampleTime;
18
19    prevAngle = prevComplementary;
20    currComplementary = k * (prevComplementary + gx * sampleTime) + (1 - k) * currAccel;
21
22    /* Update Time Variables */
23    t_n = millis(); // Current Time in Milliseconds
24    dt = (t_n - t_n1) / 1000.0; // Time Difference in Seconds
25    t_n1 = t_n; // Assign Current Time to Previous Time
26
27    /* Update Angles */
28    Angles.Accelerometer = currAccel;
29    Angles.Gyroscope = currGyro;
30    Angles.Complementary = currComplementary;
31
32    /* Assign Previous Angles */
33    prevGyro = currGyro;
34    prevComplementary = currComplementary;
35}

```

Listing 1: Source Code : Arduino IMU Complementary Filter

```

1 void balanceRobot(int bleDirection) {
2     // Get Measured Angle
3     measuredAngle = Angles.Complementary; // Complementary Filter
4     errorAngle = setpointAngle - measuredAngle; // e_t = r_t - y_t
5     errorDifference = (errorAngle - prevErrorAngle) / dt; // e_t - e_(t-1) / dt
6     errorAccumulation += (errorAngle * dt);
7
8     // Reset Accumulated Error Value  $\sum e_t$ 
9     if (digitalRead(DISABLE_INTEGRAL_BUTTON) == LOW) errorAccumulation = 0;
10
11    // Calculate Control Signal : u_t = Kp * e_t + Ki *  $\sum e_t$  + Kd * (e_t - e_(t-1) / dt)
12    u_t = (Kp * errorAngle) + (Ki * errorAccumulation) + (Kd * errorDifference);
13    drive(u_t, errorAngle);
14
15    prevErrorAngle = errorAngle; // Update Previous Error Value
16    return;
17}

```

Listing 2: Source Code : Arduino PID Controller

```

1 /*
2  * Fast Decay: Hold Primary Input at PWM Duty Cycle, Secondary Input Low.
3  */
4 void moveFastDecay(XIN &motor, DirPWM dir, float dutyCycle) {
5     if (dir == CW) {
6         motor.Pin1->write(dutyCycle);
7         motor.Pin2->write(0);
8     } else if (dir == CCW) {
9         motor.Pin1->write(0);
10        motor.Pin2->write(dutyCycle);
11    }

```

```

11     }
12 }
13 /*
14 * Slow Decay: Hold Primary Input High, Secondary Input at PWM Duty Cycle.
15 */
16 void moveSlowDecay(XIN &motor, DirPWM dir, float dutyCycle) {
17     if (dir == CW) {
18         motor.Pin1->write(1);
19         motor.Pin2->write(1-dutyCycle);
20     } else if (dir == CCW) {
21         motor.Pin1->write(1-dutyCycle);
22         motor.Pin2->write(1);
23     }
24 }
25 }
```

Listing 3: Source Code : Arduino Motor Driver

```

1 void drive(float u_t, float errorAngle) {
2     currDutyCycle = normalizePWM(u_t, 0);
3
4     if (millis() - startTime >= 1500) {
5         startTime = currTime; // Reset Start Time
6         setpointAngle = SETPOINT_0;
7         bleDirection = IDLE; // Stop Robot
8     }
9
10    if (redAlert) {
11        startTime = currTime; // Reset Start Time
12        setpointAngle = SETPOINT_0 + 1.5 * ANGLE_TILT;
13        bleDirection = REVERSE;
14    }
15
16    switch (bleDirection) {
17        case FORWARD:
18            if (forwardAlert) setpointAngle = SETPOINT_0 + 0.5 * ANGLE_TILT;
19
20            if (u_t > 0) moveForward(currDutyCycle);
21            else moveReverse(currDutyCycle);
22        break;
23        case REVERSE:
24            if (reverseAlert) setpointAngle = SETPOINT_0 - ANGLE_TILT;
25
26            if (u_t > 0) moveForward(currDutyCycle);
27            else moveReverse(currDutyCycle);
28        break;
29        case LEFT:
30            if ((directionCount++ % 3 == 0) || (abs(errorAngle) > MAX_ERR_ANGLE)) {
31                if (u_t > 0) moveForward(currDutyCycle);
32                else moveReverse(currDutyCycle);
33            } else {
34                turnLeft(currDutyCycle, 0.6);
35            }
36        break;
37        case RIGHT:
38            if ((directionCount++ % 3 == 0) || (abs(errorAngle) > MAX_ERR_ANGLE)) {
39                if (u_t > 0) moveForward(currDutyCycle);
40                else moveReverse(currDutyCycle);
41            } else {
42                turnRight(currDutyCycle, 0.5);
43            }
44        break;
45        default:
46            if (u_t > 0) moveForward(currDutyCycle);
47            else moveReverse(currDutyCycle);
48        break;
49    }
50
51 }
```

Listing 4: Source Code : Arduino Movement Statemachine

```

1 void setupBLE() {
2     pinMode(LED_BUILTIN, OUTPUT); // Init Built-in LED to Indicate Connection Status
3
4     if (!BLE.begin()) {
5         Serial.println("Starting BLE Failed!");
6         while (1);
7     }
8
9     // Set Local Name and Device Name
10    BLE.setLocalName("WALL-E");
11    BLE.setDeviceName("WALL-E");
12
13    BLE.setAdvertisedService(customService);
14    customService.addCharacteristic(customCharacteristic); // Add the Characteristic to the
15        Service
16    BLE.addService(customService); // Add the Service to the BLE Device
17
18    // Callback Event Handlers
19    BLE.setEventHandler(BLEConnected, connectBLE);
20    BLE.setEventHandler(BLEDISconnected, disconnectBLE);
21    customCharacteristic.setEventHandler(BLEWritten, rxBLE);
22
23    BLE.advertise(); // Advertising the BLE Device
24
25    while (!BLE.connected()) BLE.poll(); // Wait for Connection
26    customCharacteristic.writeValue("Enter Code:");
27 }
28
29 void connectBLE(BLEDevice central) {
30     digitalWrite(LED_BUILTIN, HIGH);
31     pairPrompted = false; // Reset Pairing Prompt Flag
32 }
33
34 void disconnectBLE(BLEDevice central) {
35     digitalWrite(LED_BUILTIN, LOW);
36     isAuthenticated = false; // Reset Authentication Status
37 }
38
39 void authenticateBLE() {
40     if (strcmp(buffBLE, CODE) == 0) {
41         isAuthenticated = true;
42         customCharacteristic.writeValue("Auth Success!");
43         isAuthenticated = true; // Set Authentication Status
44     } else {
45         customCharacteristic.writeValue("Auth Fail!");
46         BLE.disconnect(); // Disconnect if Authentication Fails
47     }
48 }
49
50 void rxBLE(BLEDevice central, BLECharacteristic characteristic) {
51     int length = characteristic.valueLength();
52     const unsigned char* receivedData = characteristic.value();
53
54     memcpy(buffBLE, receivedData, length);
55     buffBLE[length] = '\0'; // Null-Terminated
56
57     if (isAuthenticated) {
58         // updateParamBLE(buffBLE); // Update PID Parameters Based On BLE Input
59         changeDirection(buffBLE); // Change Direction Based On BLE Input
60     } else {
61         authenticateBLE(); // Authenticate Device
62     }
63     return;
64 }
```

Listing 5: Source Code : Arduino BLE Functionality

```

1 void updateParamBLE(const char* bleBuff) {
2     char paramType[STD_BUFFSIZE] = {0};
```

```

3   char valueStr[STD_BUFFSIZE] = {0};
4   float newValue = 0.0f;
5
6   char returnStr[STD_BUFFSIZE] = {0};
7
8   char cmd[STD_BUFFSIZE] = {0};
9   strcpy(cmd, bleBuff); // Copy Command to Local Buffer
10
11  int start = 0;
12  while ((cmd[start] == ' ') || (cmd[start] == '\t')) start++; // Skip Leading Whitespace
13
14  if (
15      strncmp(&cmd[start], "k=", 2) == 0 ||
16      strncmp(&cmd[start], "set=", 4) == 0 ||
17      strncmp(&cmd[start], "Kp=", 3) == 0 ||
18      strncmp(&cmd[start], "Ki=", 3) == 0 ||
19      strncmp(&cmd[start], "Kd=", 3) == 0
20  ) {
21      char* equalsPos = strchr(&cmd[start], '='); // Find '=' Position
22      if (!equalsPos) return;
23
24      int paramLength = equalsPos - &cmd[start]; // Length of Parameter Name
25      strncpy(paramType, &cmd[start], paramLength); // Copy Parameter Name
26      paramType[paramLength] = '\0'; // Null-Termination
27
28      strcpy(valueStr, equalsPos + 1); // Copy Value String
29      newValue = atof(valueStr); // Convert Value String to Float
30
31      if (strcmp(paramType, "k") == 0) k = newValue;
32      else if (strcmp(paramType, "set") == 0) SETPOINT_0 = newValue;
33      else if (strcmp(paramType, "Kp") == 0) Kp = newValue;
34      else if (strcmp(paramType, "Ki") == 0) Ki = newValue;
35      else if (strcmp(paramType, "Kd") == 0) Kd = newValue;
36      else return; // Invalid Command
37
38      sprintf(returnStr, "NewVal: %s=%s", paramType, valueStr);
39      customCharacteristic.writeValue(returnStr);
40  }
41  return; // Exit Function
42}

```

Listing 6: Source Code : Arduino BLE Parameter Updates

```

1 void DistanceSensor_InputCaptureInterrupt(distancesensor* sensor)
2 {
3     if (HAL_GPIO_ReadPin(sensor->icGPIOPort, sensor->icGPIOPin)) {
4         sensor->IC_Value1 = HAL_TIM_ReadCapturedValue(sensor->timer, TIM_CHANNEL_1); // First
5             rising edge
6         HAL_TIM_PWM_Stop(sensor->timer, TIM_CHANNEL_2);
7     }
8     else {
9         sensor->IC_Value2 = HAL_TIM_ReadCapturedValue(sensor->timer, TIM_CHANNEL_1); // Second
10            rising edge
11         if (sensor->IC_Value2 > sensor->IC_Value1) {
12             sensor->timeDifference = sensor->IC_Value2 - sensor->IC_Value1;
13         }
14         else {
15             sensor->timeDifference = (TIM_PERIOD + 1 - sensor->IC_Value1) + sensor->IC_Value2;
16                 // Handle overflow
17         }
18
19         HAL_TIM_PWM_Start(sensor->timer, TIM_CHANNEL_2);
20         __HAL_TIM_SetCounter(sensor->timer, 65535);
21
22         DistanceSensor_Handle(sensor);
23     }
24
25 // On main.c:
void HAL_TIM_IC_CaptureCallback(TIM_HandleTypeDef *htim) {

```

```

26     if (htim->Instance == TIM21) {
27         DistanceSensor_InputCaptureInterrupt(&Front);
28     }
29     else if (htim->Instance == TIM22) {
30         DistanceSensor_InputCaptureInterrupt(&Back);
31     }
32 }
33 }
```

Listing 7: Source Code : STM32 HC-SR04 Firmware

```

1 #include "colorsensor.h"
2
3 #define TCS3472_SLAVE_ADDRESS 0x29 << 1
4 #define TCS3472_EXPECTED_ID 0x44
5
6 #define TCS3472_ID_REG 0x12
7
8 #define TCS3472_WTIME_REG 0x03
9 #define TCS3472_ATIME_REG 0xF6
10 #define TCS3472_ENABLE_REG 0x00
11
12 #define TCS3472_CDATAL_REG 0x14
13 #define TCS3472_RDATAL_REG 0x16
14 #define TCS3472_GDATAL_REG 0x18
15 #define TCS3472_BDATAL_REG 0x1A
16
17 extern speaker Speaker;
18
19 void ColorSensor_Init(colorsensor* sensor, I2C_HandleTypeDef* i2c_handle) {
20     sensor->i2c = i2c_handle;
21     sensor->slave_address = TCS3472_SLAVE_ADDRESS;
22
23     memset(sensor->rgb_data, 0, sizeof(sensor->rgb_data)); // Clear RGB data
24     sensor->enabled = true;
25     sensor->count = 0;
26
27     // Define initialization sequence
28     uint8_t init_data[][2] = {
29         { TCS3472_WTIME_REG | 0x80, 0xFF }, // Wait time
30         { TCS3472_ATIME_REG | 0x80, 0xFF }, // Integration time
31         { TCS3472_ENABLE_REG | 0x80, 0x0B } // Power ON & enable RGBC
32     };
33
34     // Loop through initialization commands and send them
35     for (size_t i = 0; i < sizeof(init_data) / sizeof(init_data[0]); i++) {
36         if (HAL_I2C_Master_Transmit(sensor->i2c, sensor->slave_address, init_data[i], 2,
37             HAL_MAX_DELAY) != HAL_OK)
38             while(1);
39     }
40
41     HAL_GPIO_WritePin(COLOR_SENSOR_STATUS_GPIO_Port, COLOR_SENSOR_STATUS_Pin, GPIO_PIN_SET);
42 }
43
44 void ColorSensor_EnableStatus(colorsensor* sensor, bool enable)
45 {
46     sensor->enabled = enable;
47 }
48
49
50 uint16_t ColorSensor_Read16(colorsensor* sensor, uint8_t reg) {
51     uint8_t buffer[2];
52     uint8_t command = reg | 0xA0; // Add auto-increment bit
53
54     // Send register address
55     if (HAL_I2C_Master_Transmit(sensor->i2c, sensor->slave_address, &command, 1, HAL_MAX_DELAY)
56         != HAL_OK) {
57         return 0; // Handle error
58     }
59 }
```

```

59     // Read 2 bytes from the sensor
60     if (HAL_I2C_Master_Receive(sensor->i2c, sensor->slave_address, buffer, 2, HAL_MAX_DELAY) !=
61         HAL_OK) {
62         return 0; // Handle error
63     }
64
65     // Combine two bytes into a 16-bit value (LSB first)
66     return (uint16_t)(buffer[0] | (buffer[1] << 8));
67 }
68
69 void ColorSensor_ReadAll(colorsensor* sensor) {
70     sensor->rgb_data[0] = ColorSensor_Read16(sensor, TCS3472_CDATAL_REG); // TCS3472_CDATAL
71     sensor->rgb_data[1] = ColorSensor_Read16(sensor, TCS3472_RDATAL_REG); // TCS3472_RDATAL
72     sensor->rgb_data[2] = ColorSensor_Read16(sensor, TCS3472_GDATAL_REG); // TCS3472_GDATAL
73     sensor->rgb_data[3] = ColorSensor_Read16(sensor, TCS3472_BDATAL_REG); // TCS3472_BDATAL
74 }
75
76 color ColorSensor_CalculateColor(colorsensor* sensor)
77 {
78     uint16_t max_val = sensor->rgb_data[1];
79     color detected_color = RED;
80
81     if (sensor->rgb_data[2] > max_val) detected_color = GREEN;
82     if (sensor->rgb_data[3] > max_val) detected_color = BLUE;
83
84     return detected_color;
85 }
86
87 void ColorSensor_Handle(colorsensor* sensor)
88 {
89     ColorSensor_ReadAll(sensor);
90     color detected_color = ColorSensor_CalculateColor(sensor);
91
92     if (detected_color == RED)
93     {
94         HAL_GPIO_WritePin(COLOR_SENSOR_STATUS_GPIO_Port, COLOR_SENSOR_STATUS_Pin,
95                           GPIO_PIN_RESET);
96         if (!Speaker.hasFault)
97             Speaker_Start(&Speaker, COLOR_SENSOR_ID);
98     }
99     else
100    {
101        HAL_GPIO_WritePin(COLOR_SENSOR_STATUS_GPIO_Port, COLOR_SENSOR_STATUS_Pin, GPIO_PIN_SET);
102        if (Speaker.hasFault)
103            Speaker_Stop(&Speaker, COLOR_SENSOR_ID);
104    }
105 }
106 }
```

Listing 8: Source Code : STM32 TCS34725 Firmware

```

1 #include "rfid.h"
2
3 #include "speaker.h"
4
5 #define SERIALNUM_1_IDLE 32
6
7 #define SERIALNUM_0_CORRECT_CARD 170
8 #define SERIALNUM_1_CORRECT_CARD 205
9 #define SERIALNUM_2_CORRECT_CARD 47
10 #define SERIALNUM_3_CORRECT_CARD 3
11 #define SERIALNUM_4_CORRECT_CARD 75
12
13 extern speaker Speaker;
14 extern UART_HandleTypeDef huart1;
15 extern char Data;
16
17 void RFID_Init(rfid* sensor) {
18     MFRC522_Init();
```

```

19     memset(sensor->prevSerialNum, 0, 5);
20     sensor->status = CARD_IDLE;
21
22     sensor->botEnabled = false;
23     sensor->initialSuccessfulCardTap = true;
24     sensor->initialFailedCardTap = true;
25
26     HAL_GPIO_WritePin(RFID_STATUS_GPIO_Port, RFID_STATUS_Pin, GPIO_PIN_SET);
27 }
28
29 rfid_card_status RFID_ValidateCard(rfid* sensor)
30 {
31     uint8_t serialNum[5];
32     MFRC522_Request(PICC_REQIDL, serialNum);
33     MFRC522_Anticoll(serialNum);
34
35     sensor->status = CARD_IDLE;
36
37     if ((serialNum[0] == 170 && serialNum[1] == 205 && serialNum[2] == 47 && serialNum[3] == 3
38         && serialNum[4] == 75) ||
39         (sensor->prevSerialNum[0] == 170 && sensor->prevSerialNum[1] == 205 &&
40          sensor->prevSerialNum[2] == 47 && sensor->prevSerialNum[3] == 3 &&
41          sensor->prevSerialNum[4] == 75))
42     {
43         sensor->status = CARD_SUCCESS;
44     }
45     else if (!(serialNum[0] | !(serialNum[1] == 32 || serialNum[1] == 0)) | serialNum[2] |
46               serialNum[3] | serialNum[4]))
47     {
48         if (!(sensor->prevSerialNum[0] | sensor->prevSerialNum[1] | sensor->prevSerialNum[2] |
49               sensor->prevSerialNum[3] | sensor->prevSerialNum[4]))
50             sensor->status = CARD_IDLE;
51         else
52         {
53             sensor->status = CARD_FAIL;
54         }
55     }
56     else
57     {
58         sensor->status = CARD_FAIL;
59     }
60
61     for (uint8_t i = 0; i < 5; i++)
62     {
63         sensor->prevSerialNum[i] = serialNum[i];
64     }
65
66     return sensor->status;
67 }
68
69 void RFID_SecurityLogic(rfid* sensor)
70 {
71     rfid_card_status cardStatus = RFID_ValidateCard(sensor);
72
73     switch (cardStatus) {
74         case CARD_SUCCESS:
75             if (sensor->initialSuccessfulCardTap)
76             {
77                 Speaker_SetAutoReload(&Speaker, 488);
78                 Speaker_Beep(&Speaker, 150, 0, 1);
79                 sensor->initialSuccessfulCardTap = false;
80                 sensor->initialFailedCardTap = true;
81                 sensor->botEnabled = !sensor->botEnabled;
82                 HAL_GPIO_WritePin(RFID_STATUS_GPIO_Port, RFID_STATUS_Pin, (GPIO_PinState)
83                               !sensor->botEnabled);
84             }
85             break;

```

```

84
85     case CARD_FAIL:
86         if (sensor->initialFailedCardTap)
87     {
88             HAL_Delay(200);
89             if (RFID_ValidateCard(sensor) != CARD_FAIL)
90                 break;
91             Speaker_SetAutoReload(&Speaker, 488 * 4);
92             Speaker_Beep(&Speaker, 150, 50, 4);
93             sensor->initialSuccessfulCardTap = true;
94             sensor->initialFailedCardTap = false;
95
96         }
97         break;
98
99
100    case CARD_IDLE:
101        sensor->initialSuccessfulCardTap = true;
102        sensor->initialFailedCardTap = true;
103        break;
104
105    // Optional: Default case if no case matches
106    default:
107        // Code to execute if none of the above cases match
108        break;
109    }
110
111 }
```

Listing 9: Source Code : STM32 RC522 Firmware

```

1 #include "speaker.h"
2
3
4 #define CLK_SPEED 32000000
5 #define DEFAULT_AUTORELOAD 488
6
7 void Speaker_Init(speaker* speaker, rfid* rfid_struct, TIM_HandleTypeDef* timer)
8 {
9     speaker->rfid_sensor = rfid_struct;
10    speaker->timer = timer;
11
12    speaker->hasFault = false;
13    speaker->beepLengthOn = 0;
14    speaker->beepLengthPeriod = 0;
15    speaker->wantedNumBeeps = 0;
16    speaker->currentNumBeeps = 0;
17    speaker->timerCounter = 0;
18
19    for (uint8_t i = 0; i < sizeof(speaker->featureFault) / sizeof(speaker->featureFault[0]);
20         i++)
21    {
22        speaker->featureFault[i] = false;
23    }
24
25 }
26
27 void Speaker_Start(speaker* speaker, uint8_t ID)
28 {
29
30     speaker->featureFault[ID] = true;
31     if ((speaker->featureFault[0] || speaker->featureFault[1] || speaker->featureFault[2]) &&
32         speaker->rfid_sensor->botEnabled)
33     {
34         speaker->hasFault = true;
35         Speaker_SetAutoReload(speaker, DEFAULT_AUTORELOAD);
36         HAL_TIM_PWM_Start(speaker->timer, TIM_CHANNEL_1);
37     }
38 }
```

```

39 void Speaker_Stop(speaker* speaker, uint8_t ID)
40 {
41     speaker->featureFault[ID] = false;
42     if (!(speaker->featureFault[0] || speaker->featureFault[1] || speaker->featureFault[2]))
43     {
44         speaker->hasFault = false;
45         HAL_TIM_PWM_Stop(speaker->timer, TIM_CHANNEL_1);
46     }
47 }
48
49
50
51
52 bool Speaker_Beep(speaker* speaker, uint16_t length_on_ms, uint16_t length_off_ms, uint8_t
53 numBeeps)
54 {
55     if (speaker->hasFault)
56         return false;
57
58     speaker->timerCounter = 0;
59     speaker->currentNumBeeps = 0;
60
61
62
63
64     speaker->beepLengthOn = length_on_ms * 1000 / __HAL_TIM_GET_AUTORELOAD(speaker->timer);
65     speaker->beepLengthPeriod = speaker->beepLengthOn + length_off_ms * 1000 / __
66         HAL_TIM_GET_AUTORELOAD(speaker->timer);
67     speaker->wantedNumBeeps = numBeeps;
68
69     //speaker->beepLength = length_ms * CLK_SPEED / (speaker->timer->Instance->PSC);
70
71     HAL_TIM_Base_Start_IT(speaker->timer);
72     HAL_TIM_PWM_Start(speaker->timer, TIM_CHANNEL_1);
73     return true;
74 }
75
76 void Speaker_BeepInterrupt(speaker* speaker)
77 {
78     if (speaker->currentNumBeeps < speaker->wantedNumBeeps)
79     {
80
81         if (speaker->timerCounter == speaker->beepLengthOn)
82         {
83             HAL_TIM_PWM_Stop(speaker->timer, TIM_CHANNEL_1);
84             __HAL_TIM_ENABLE(speaker->timer);
85         }
86         else if (speaker->timerCounter >= speaker->beepLengthPeriod)
87         {
88             speaker->currentNumBeeps++;
89             speaker->timerCounter = 0;
90
91             if (speaker->currentNumBeeps < speaker->wantedNumBeeps)
92             {
93                 HAL_TIM_PWM_Start(speaker->timer, TIM_CHANNEL_1);
94             }
95         }
96     }
97     speaker->timerCounter++;
98 }
99
100 else
101 {
102     HAL_TIM_PWM_Stop(speaker->timer, TIM_CHANNEL_1);
103     HAL_TIM_Base_Stop_IT(speaker->timer);
104 }
105
106 void Speaker_SetAutoReload(speaker* speaker, uint16_t value)
107 {

```

```

108     __HAL_TIM_SET_AUTORELOAD(speaker->timer, value);
109     __HAL_TIM_SET_COMPARE(speaker->timer, TIM_CHANNEL_1, value / 2);
110 }

```

Listing 10: Source Code : STM32 Speaker Firmware

```

1 import asyncio
2 import threading
3
4 from bleak import BleakScanner, BleakClient, BleakError
5 from flask import Flask, request, jsonify, render_template
6
7 class BLEManager:
8     # Define UUIDs for BLE Service and Characteristic
9     SERVICE_UUID = "00000000-5EC4-4083-81CD-A10B8D5CF6EC"
10    CHARACTERISTIC_UUID = "00000001-5EC4-4083-81CD-A10B8D5CF6EC"
11    CODE = "0095" # Authentication Code
12
13    def __init__(self):
14        self.devices = []
15        self.client = None
16        self.is_connected = False
17
18        self.loop = asyncio.new_event_loop()
19        self.start_loop()
20
21    def start_loop(self):
22        threading.Thread(target = self._run_loop, daemon = True).start()
23
24    def _run_loop(self):
25        asyncio.set_event_loop(self.loop)
26        self.loop.run_forever()
27
28    def run_async(self, coro):
29        return asyncio.run_coroutine_threadsafe(coro, self.loop)
30
31    async def scan_devices(self):
32        self.devices = []
33        scanned = await BleakScanner.discover()
34
35        self.devices = [
36            {"name": device.name, "address": device.address} for device in scanned if
37            device.name and ("WALL-E" in device.name)
38        ] # Filter BLE Devices
39        return self.devices
40
41    async def connect_device(self, address):
42        """Connect to BLE Device."""
43        if self.client and self.client.is_connected:
44            self.is_connected = True
45            return True
46
47        self.client = BleakClient(address)
48        try:
49            await self.client.connect()
50            await self.client.write_gatt_char(BLEManager.CHARACTERISTIC_UUID,
51                BLEManager.CODE.encode("utf-8"))
52            self.is_connected = self.client.is_connected
53            return self.is_connected
54        except BleakError:
55            self.is_connected = False
56            return False
57
58    async def disconnect_device(self):
59        """Disconnect from BLE Device."""
60        if self.client and self.client.is_connected:
61            await self.client.disconnect()
62            self.is_connected = False
63
64    async def send_cmd(self, cmd):
65        """Schedule Send Command Coroutine Using Button's Custom Command."""

```

```

64         if not (self.client and self.client.is_connected):
65             return False, "Not Connected to BLE"
66     try:
67         await self.client.write_gatt_char(BLEManager.CHARACTERISTIC_UUID,
68                                         cmd.encode("utf-8"))
69     return True, f"Sent Command: {cmd}"
70 except BleakError as e:
71     return False, f"Error Sending Command: {e}"
72
73 class RobotDriverApp:
74     def __init__(self):
75         self.app = Flask("Robot Driver App")
76         self.ble_manager = BLEManager()
77         self._register_routes()
78
79     def _register_routes(self):
80         @self.app.route("/")
81         def index():
82             return render_template("index.html")
83
84         @self.app.route("/scan", methods = ["GET"])
85         def scan():
86             future = self.ble_manager.run_async(self.ble_manager.scan_devices())
87             devices = future.result(timeout = 30) # Wait for 30 Seconds
88             return jsonify(devices)
89
90         @self.app.route("/connect", methods = ["POST"])
91         def connect():
92             data = request.get_json()
93             if not data or "deviceAddress" not in data:
94                 return jsonify({"error": "No Address Provided"}), 400
95             future =
96                 self.ble_manager.run_async(self.ble_manager.connect_device(data["deviceAddress"]))
97             success = future.result(timeout = 15) # Wait for 15 Seconds
98             return (jsonify({"status": "Connected"})) if success
99                 else (jsonify({"status": "Failed"}), 400))
100
101        @self.app.route("/disconnect", methods = ["GET"])
102        def disconnect():
103            future = self.ble_manager.run_async(self.ble_manager.disconnect_device())
104            future.result(timeout = 10) # Wait for 5 Seconds
105            return jsonify({"status": "Disconnected"})
106
107        @self.app.route("/move", methods = ["POST"])
108        def move():
109            data = request.get_json()
110            if not data or "command" not in data:
111                return jsonify({"error": "No Command Provided"}), 400 # Bad Request
112
113            future = self.ble_manager.run_async(
114                self.ble_manager.send_cmd(data["command"]))
115            )
116            success, message = future.result(timeout = 10) # Wait for 5 Seconds
117
118            if success:
119                return jsonify({"status": "OK", "msg": message})
120            else:
121                return jsonify({"status": "Error", "msg": message}), 400 # Bad Request
122
123        def run(self):
124            self.app.run(host = "0.0.0.0", port = 5000, debug = False)
125
126    if __name__ == "__main__":
127        RobotDriverApp().run()

```

Listing 11: Source Code : Robot Driver App

```

1 from picamera2 import Picamera2
2 from picamera2.encoders import H264Encoder
3 from libcamera import Transform
4

```

```

5   class CameraDisplay(tk.Frame):
6       SAMPLE_RATE = 1.0 / 50.0 # Update Delay ~20 FPS (1000ms/20 = 50ms)
7       def __init__(self, parent, *args, **kwargs):
8           super().__init__(parent, *args, **kwargs)
9
10          self.filename = ""
11          self.camera = Picamera2() # Init Camera
12
13          self.snapshot_dir: str = os.path.join(os.path.dirname(os.path.abspath(__file__)), "S
14          snapshots")
15          self.video_dir: str = os.path.join(os.path.dirname(os.path.abspath(__file__)), "Videos")
16
17          os.makedirs(self.snapshot_dir, exist_ok = True)
18          os.makedirs(self.video_dir, exist_ok = True)
19
20          # Force RGB888 Output
21          self.config = self.camera.create_video_configuration(
22              main = {
23                  "size": (640, 480), # Default Size
24                  # "size": (1280, 720), # HD
25                  # "size": (1920, 1080), # Full HD
26                  "format": "RGB888"
27              },
28              transform = Transform(hflip = False, vflip = False) # For Tkinter Display
29          )
30          self.image_label = tk.Label(self)
31          self.image_label.pack()
32
33      def start_recording(self):
34          self.camera.configure(self.config)
35          self.camera.start()
36
37          self.filename = f"Recording_{dt.datetime.now().strftime('%Y%m%d_%H%M%S')}"
38          input_file = os.path.join(self.video_dir, f"{self.filename}.h264")
39
40          self.camera.start_recording(H264Encoder(bitrate = 10000000), input_file)
41
42      def stop_recording(self):
43          if self.filename == "":
44              return
45
46          self.camera.stop_recording()
47          self.camera.stop()
48          self.filename = ""
49
50      def take_snapshot(self):
51          if self.filename == "":
52              self.camera.configure(self.config)
53              self.camera.start()
54
55              # Capture Current Frame
56              frame = self.camera.capture_array()
57              if frame is None or frame.size == 0:
58                  print("Failed to Capture Snapshot.")
59                  return
60
61              # Swap Color Channels (BGR -> RGB)
62              frame = frame[..., ::-1]
63
64              snapshot_name = f"Snapshot_{dt.datetime.now().strftime('%Y%m%d_%H%M%S')}.jpg"
65              snapshot_path = os.path.join(self.snapshot_dir, snapshot_name)
66
67              # Convert to PIL Image
68              image = PILImage.fromarray(frame)
69              image.save(snapshot_path) # Save Image
70              print(f"Snapshot Saved to {snapshot_path}")
71
72              if self.filename == "":
73                  self.camera.stop()
74
75      def update(self):

```

```

75     if self.filename == "":
76         return
77
78     frame = self.camera.capture_array()
79     if (frame is not None) and (frame.size != 0):
80         frame = frame[..., ::-1] # BGR -> RGB
81
82     # Convert the PIL Image to an ImageTk.PhotoImage
83     self.image_label.current = ImageTk.PhotoImage(
84         image = PILImage.fromarray(frame) # Convert Numpy Array to PIL.Image
85     )
86     self.image_label.configure(image = self.image_label.current)
87
88 def stop(self):
89     self.camera.close()

```

Listing 12: Source Code : PiCamera Display

```

1  class StripChart:
2      # SAMPLE_RATE = 0.250 # 250 ms
3      SAMPLE_RATE = 1 # 1000 ms
4      def __init__(self, master, conn = None, data_size = 25, ylim = 30):
5          self.master = master
6          self.conn = conn
7          self.fig, self.ax = plt.subplots(figsize = (900 / 100, 755 / 100))
8
9          self.data_size, self.ylim = data_size, ylim
10
11     # Angle Data (Additional Storage Preferred Over DataFrame for Speed)
12     self.sample_data = []
13     self.accelerometer_data = []
14     self.gyroscope_data = []
15     self.complementary_data = []
16
17     # DataFrame for Data Export
18     self.start_time = None
19     self.data_df = pd.DataFrame(
20         columns = [
21             'Time (PST)',
22             'Accelerometer Angle (Deg)',
23             'Gyroscope Angle (Deg)',
24             'Complementary Angle (Deg)'
25         ]
26     )
27
28     self.ax.set_title('Real-Time Angle Strip-Chart')
29     self.ax.grid(True)
30
31     self.ax.set_xlim(
32         0, # Start at 0s
33         # 1.25 * self.data_size * StripChart.SAMPLE_RATE * 0.1
34         1.25 * self.data_size * StripChart.SAMPLE_RATE
35     )
36     self.ax.set_xticks(
37         np.arange(
38             0, # Start at 0s
39             # 1.25 * self.data_size * StripChart.SAMPLE_RATE * 0.1,
40             1.25 * self.data_size * StripChart.SAMPLE_RATE,
41             5 # Set Ticks to 5s Intervals
42         )
43     )
44
45     self.ax.set_ylim(-self.ylim, self.ylim) # Angle Expected to be Between -180 Deg and 180
46     Deg
47     self.ax.set_yticks(np.arange(-self.ylim, self.ylim + 1, 5))
48
49     self.ax.tick_params(axis = 'both', labelsize = 8)
50
51     self.ax.set_xlabel('Time (s)')
52     self.ax.set_ylabel('Angle (Deg)')

```

```

53     self.accelerometer_line, = self.ax.plot([], [], linestyle = 'dashed', lw = 1.5, label =
54         'Accelerometer Angle (Deg)', color = 'lightblue')
55     self.gyroscope_line, = self.ax.plot([], [], linestyle = 'dashed', lw = 1.5, label =
56         'Gyroscope Angle (Deg)', color = 'tomato')
57     self.complementary_line, = self.ax.plot([], [], lw = 1.5, label = 'Complementary Angle
58         (Deg)', color = 'purple')
59
59     self.fig.subplots_adjust(bottom = 0.2)
60     self.ax.legend(
61         loc = 'upper center',
62         bbox_to_anchor = (0.5, -0.15), # Position Above Plot with Padding
63         ncol = 3, framealpha = 0.9, # 3 Columns, Transparent Background
64         fontsize = 10,
65     )
66
66     self.canvas = FigureCanvasTkAgg(self.fig, master=self.master)
67     self.canvas_widget = self.canvas.get_tk_widget()
68
68     self.figures_dir: str = os.path.join(os.path.dirname(os.path.abspath(__file__)), "Figures")
69     self.logbook_dir: str = os.path.join(os.path.dirname(os.path.abspath(__file__)), "Logbook")
70
70     os.makedirs(self.figures_dir, exist_ok = True)
71     os.makedirs(self.logbook_dir, exist_ok = True)
72
73
74     def start(self, conn):
75         """Start StripChart."""
76         self.conn = conn
77         self.animation = animation.FuncAnimation(
78             fig = self.fig, # Figure
79             func = self.update, # Update Function
80             frames = self.data_size, # Number of Frames
81             blit = False, # Prevent Re-rendering Entire Plot
82             interval = StripChart.SAMPLE_RATE * 1000, # Delay in ms
83         )
84         self.canvas = FigureCanvasTkAgg(self.fig, master = self.master)
85         self.canvas_widget = self.canvas.get_tk_widget()
86
87     def update(self, frame):
88         """Update StripChart with New Data."""
89         self.rx_angle()
90
91         # Update Plot Data
92         # t_data = [t * 0.1 for t in self.sample_data]
93         t_data = [t for t in self.sample_data]
94         self.accelerometer_line.set_data(t_data, self.accelerometer_data)
95         self.gyroscope_line.set_data(t_data, self.gyroscope_data)
96         self.complementary_line.set_data(t_data, self.complementary_data)
97
98         # Adjust x Limits to Scroll Forward
99         if (len(self.sample_data) > 0) and (self.sample_data[-1] > self.data_size):
100             self.ax.set_xlim(
101                 t_data[0], # Start at First Data Point
102                 # t_data[0] + 1.25 * self.data_size * StripChart.SAMPLE_RATE * 0.1
103                 t_data[0] + 1.25 * self.data_size * StripChart.SAMPLE_RATE
104             ) # Display 25% More Data
105             self.ax.set_xticks(
106                 np.arange(
107                     t_data[0], # Start at First Data Point
108                     # t_data[0] + 1.25 * self.data_size * StripChart.SAMPLE_RATE * 0.1,
109                     t_data[0] + 1.25 * self.data_size * StripChart.SAMPLE_RATE,
110                     5 # Set Ticks to 5s Intervals
111                 )
112             )
113         else:
114             self.ax.set_xlim(
115                 0, # Start at 0s
116                 # 1.25 * self.data_size * StripChart.SAMPLE_RATE * 0.1
117                 1.25 * self.data_size * StripChart.SAMPLE_RATE
118             )

```

```

119         self.ax.set_xticks(
120             np.arange(
121                 0, # Start at 0s
122                 # 1.25 * self.data_size * StripChart.SAMPLE_RATE * 0.1,
123                 1.25 * self.data_size * StripChart.SAMPLE_RATE,
124                 5 # Set Ticks to 5s Intervals
125             )
126         )
127
128     def stop(self):
129         """Set Connection to None and Stop Updating."""
130         if self.conn is not None:
131             self.conn.close()
132             self.conn = None
133
134         fig_name = f"Angle_Data_{dt.datetime.now().strftime('%Y%m%d_%H%M%S')}"
135         self.save_logs(fig_name)
136         self.save_fig(fig_name)
137
138     def rx_angle(self):
139         """Read Angle Data from Serial Connection."""
140         def read_serial():
141             """Read Data from Serial Connection."""
142             if (self.conn is not None):
143                 return str(self.conn.readline().decode('ascii')).strip('\r').strip('\n'))
144             else:
145                 return None
146
147         if self.conn is None:
148             return
149
150         try:
151             self.conn.write(b'A')
152         except serial.SerialException:
153             self.conn.reconnect()
154
155         try:
156             arduinoStream: list = str(read_serial()).rstrip('\r').split(' ')
157             if len(arduinoStream) != 3:
158                 raise ValueError
159
160             accelerometer_angle = float(arduinoStream[0])
161             gyroscope_angle = float(arduinoStream[1])
162             complementary_angle = float(arduinoStream[2])
163
164             print(f"Accelerometer Angle: {accelerometer_angle} Deg")
165             print(f"Gyroscope Angle: {gyroscope_angle} Deg")
166             print(f"Complementary Angle: {complementary_angle} Deg")
167
168             # Append Data
169             new_sample = (self.sample_data[-1] + 1) if self.sample_data else 0
170
171             self.sample_data.append(new_sample)
172             self.accelerometer_data.append(accelerometer_angle)
173             self.gyroscope_data.append(gyroscope_angle)
174             self.complementary_data.append(complementary_angle)
175
176             self.start_time = dt.datetime.now(pytz.timezone('US/Pacific')) if self.start_time is
177             None else self.start_time
178
179             if self.data_df.empty:
180                 self.data_df = pd.DataFrame({
181                     'Time (PST)': self.start_time,
182                     'Accelerometer Angle (Deg)': accelerometer_angle,
183                     'Gyroscope Angle (Deg)': gyroscope_angle,
184                     'Complementary Angle (Deg)': complementary_angle
185                 }, index = [0])
186             else:
187                 self.data_df = pd.concat([
188                     self.data_df,
189                     pd.DataFrame([{
```

```

189         'Time (PST)': self.start_time + dt.timedelta(seconds = new_sample),
190         'Accelerometer Angle (Deg)': accelerometer_angle,
191         'Gyroscope Angle (Deg)': gyroscope_angle,
192         'Complementary Angle (Deg)': complementary_angle
193     }]], ignore_index = True
194 )
195
196 except serial.SerialException:
197     self.conn.reconnect()
198 except ValueError as value_error: # Parse Error
199     display("Parse Error:", str(value_error))
200
201 # Limit Size to Trailing Data
202 self.sample_data = self.sample_data[-self.data_size:]
203 self.accelerometer_data = self.accelerometer_data[-self.data_size:]
204 self.gyroscope_data = self.gyroscope_data[-self.data_size:]
205 self.complementary_data = self.complementary_data[-self.data_size:]
206
207 def save_fig(self, fig_name) :
208     """Save Figure to File."""
209     file_path = os.path.join(self.figures_dir, f"{fig_name}.jpg")
210
211     self.fig.savefig(file_path, format = 'jpg', dpi = 800)
212     print(f"Figure Saved to {file_path}")
213
214 def save_logs(self, file_name):
215     """Save Data to CSV File."""
216     file_path = os.path.join(self.logbook_dir, f"{file_name}.csv")
217
218     csv_df = self.data_df.copy()
219     csv_df['Time (PST)'] = self.data_df['Time (PST)'].dt.strftime('%Y-%m-%d %H:%M:%S')
220     csv_df.to_csv(file_path, index = False)
221
222     print(f"Data Exported to {file_path}\n\nData Preview:\n")
223     display(self.data_df.head(2))
224     display("-----")
225     display(self.data_df.tail(2))

```

Listing 13: Source Code : Python Stripchart