Enhancing Cyclist Visibility Using a Smart Reflective Safety Bag with Automated Light Indicators

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ABSTRACT

Cyclist safety during nighttime rides remains a critical challenge due to low visibility and limited signaling capabilities. This study presents the development of a smart reflective safety bag designed to enhance cyclist visibility and communication through sensor-driven automation. The system integrates a Light Dependent Resistor (LDR) for ambient light detection, an MPU6050 accelerometer for braking recognition, and dual signal controls operated via mechanical switches or Bluetooth Low Energy (BLE). An ESP32 Development Module processes sensor inputs and user commands, while the ESP32 C3 Super Mini manages output signals through LED strips and 12V car-grade indicators using the ESP-NOW protocol for reliable wireless communication. Functional testing demonstrated accurate real-time response to low-light conditions, braking events, and directional commands, ensuring adaptive illumination and clear signaling. The smart safety bag combines wearable ergonomics, embedded system integration, and automated feedback, providing a robust, reliable, and user-friendly solution to improve cyclist safety and situational awareness.

Keywords: Embedded Systems, Sensor Node, Output Node, NOW Protocol, LDR, MPU6050, Multiple LEDs

INTRODUCTION

Cycling has become an increasingly favored mode of transportation worldwide due to its sustainability, health benefits, and convenience in congested urban areas. As cities promote active transportation to reduce traffic and environmental impact, more individuals are adopting cycling for commuting and recreation. Despite these benefits, cyclist safety remains a critical challenge, particularly during nighttime rides when reduced visibility and poor lighting conditions significantly elevate the risk of accidents involving vehicles and pedestrians. Traditional passive safety equipment, such as reflective clothing and accessories, rely heavily on external light sources and driver awareness, often providing insufficient protection in complex traffic environments.

In response to these challenges, advancements in embedded systems and sensor technologies have paved the way for active safety solutions that dynamically enhance cyclist visibility and communication. This paper presents the design and development of a smart reflective safety bag tailored specifically for cyclists riding at night. The system leverages multiple sensors and intelligent lighting controls to improve situational awareness and signal cyclist intentions clearly to surrounding road users. Key components include a Light Dependent Resistor (LDR) sensor that continuously monitors ambient light levels to automatically adjust the brightness and activation of LED strips, thereby conserving power during daylight and maximizing visibility after dark. Additionally, an MPU6050 accelerometer is integrated to detect sudden deceleration or braking, triggering a rear-facing brake light to alert trailing vehicles promptly.

Further enhancing its functionality, the safety bag incorporates dual turn signal control mechanisms that combine traditional mechanical switches with modern Bluetooth Low Energy (BLE) connectivity. This dual-control feature allows cyclists to operate turn signals conveniently while riding, using either physical buttons or a paired smartphone, increasing user flexibility and ease of use. Central to the system's operation is the ESP32 development module, which processes sensor inputs and user commands, executes decision algorithms,

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and communicates processed data to the output subsystem via the ESP32's NOW protocol library. This ensures reliable and timely activation of lighting indicators, including white LED illumination for visibility, red brake signals, and blinking turn signals.

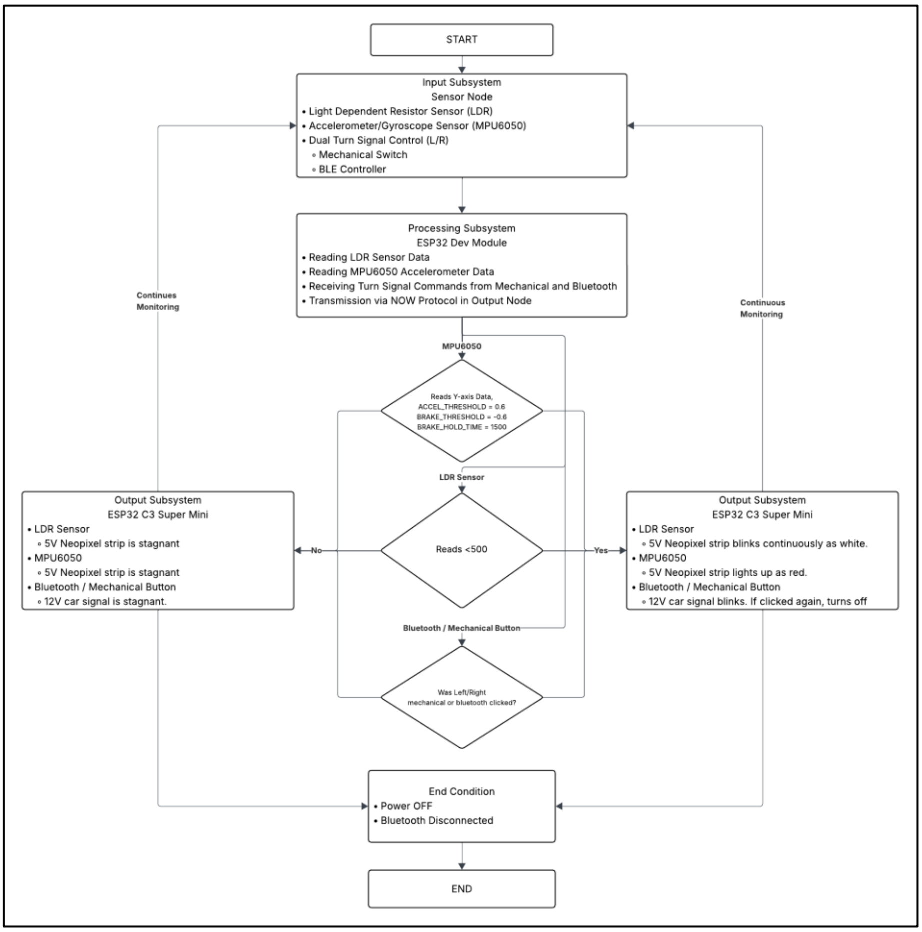
The smart reflective safety bag exemplifies the effective application of embedded system design principles in wearable technology, integrating sensor nodes, processing units, and adaptive output controls into a compact, lightweight, and ergonomic form factor suitable for everyday use. This paper provides an in-depth analysis of the system architecture, sensor integration, control logic, and communication protocols employed, supported by experimental results demonstrating operational effectiveness. It also discusses the broader implications of sensor-driven wearable safety devices in improving urban cycling safety, highlighting potential benefits such as accident reduction, increased rider confidence, and enhanced traffic interaction. Finally, the study identifies current limitations, challenges in sensor accuracy and power management, and explores future development opportunities including integration with smart city infrastructure and enhanced connectivity features.

REVIEW OF RELEVANT THEORY, STUDIES, AND LITERATURE

Theoretical Framework

The development of a smart reflective safety bag for cyclists relies on the integration of **embedded systems**, **sensor technology**, and **actuation mechanisms** to improve visibility and safety during nighttime rides. The system can be conceptually divided into **three main components**: the sensor node, the processing/control node, and the output node.

Figure 1. Embedded and Control System Theory



The system operates through the interaction of three primary subsystems: input, processing, and output. The input subsystem collects data from various sensors, including the Light Dependent Resistor (LDR) for ambient light detection, the MPU6050 accelerometer/gyroscope for motion and braking detection, and dual turn signal controls managed via mechanical switches and Bluetooth Low Energy (BLE) communication. These inputs are

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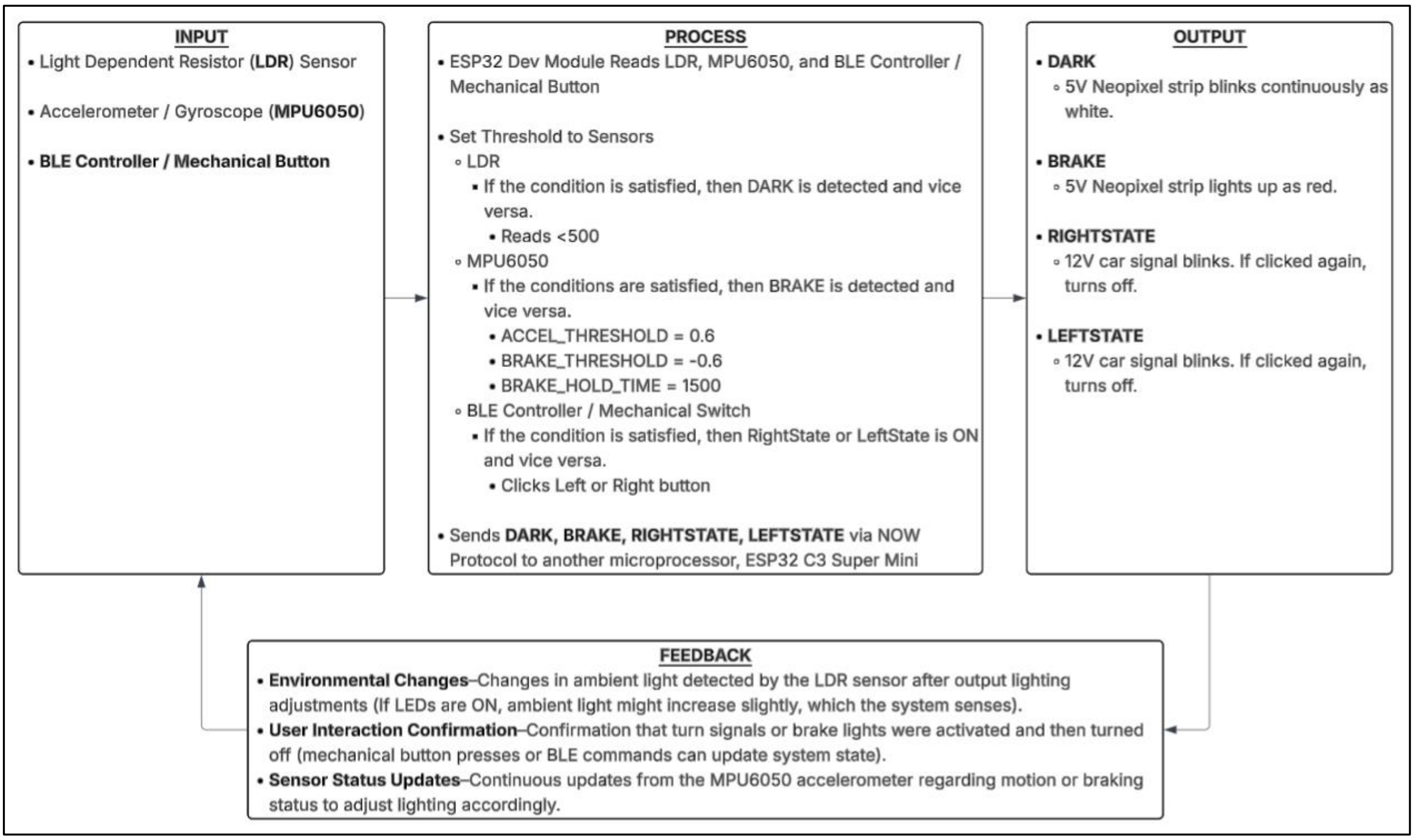
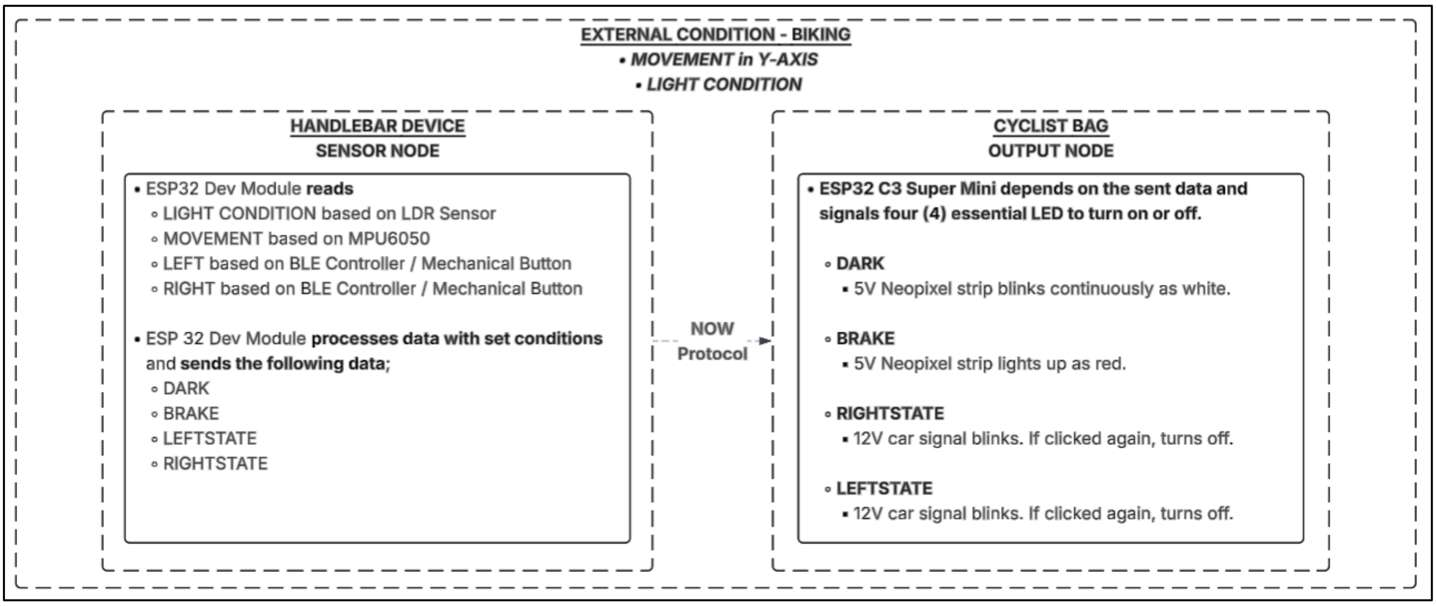
processed by the ESP32 development module, which reads sensor data, interprets user commands, and executes decision logic. Specifically, the system continuously monitors the Y-axis acceleration from the MPU6050 to detect braking events based on predefined thresholds, while the LDR sensor determines lighting conditions to activate or deactivate the LED indicators accordingly. Turn signal commands from both mechanical and Bluetooth inputs are also processed. After processing, the ESP32 Dev Module communicates the control signals and processed data to the output subsystem using the ESP32's NOW protocol library, ensuring efficient and reliable data transmission. The output subsystem then controls LED strips that provide adaptive illumination: white light for visibility in low ambient light, red light signaling during braking, and blinking indicators for turn signals. The system maintains brake light activation for a set duration to ensure clear signaling. Operation continues until power is turned off or the Bluetooth connection is lost, enabling seamless coordination between sensor inputs, processing logic, and output signals to enhance cyclist safety during nighttime rides.

Figure 2. Input–Process–Output (IPO) Model



The system integrates multiple sensor inputs to facilitate context-aware signaling and lighting control. It employs a Light Dependent Resistor (LDR) to monitor ambient light intensity, an MPU6050 inertial measurement unit (IMU) comprising an accelerometer and gyroscope to detect motion dynamics, and a Bluetooth Low Energy (BLE) controller or mechanical switch for user-initiated commands. An ESP32 microcontroller module continuously acquires data from these sources and applies predefined threshold criteria to interpret the sensor readings. Specifically, an LDR sensor value below 500 units indicates low-light or "dark" conditions. The MPU6050 outputs are evaluated against acceleration and deceleration thresholds (ACCEL_THRESHOLD = 0.6g, BRAKE_THRESHOLD = -0.6g) sustained over a BRAKE_HOLD_TIME interval of 1500 milliseconds to detect braking events. Concurrently, input from the BLE controller or mechanical switches is used to toggle the system's right or left signaling state upon button actuation. The microcontroller transmits these discrete states—DARK, BRAKE, RIGHTSTATE, and LEFTSTATE—via the NOW communication protocol to a secondary microprocessor, an ESP32 C3 Super Mini, which governs the output actuators. The output control logic activates a 5V Neopixel LED strip to blink white continuously under dark conditions, illuminate solid red to indicate braking, and toggle 12V vehicle turn signal indicators in response to right or left state commands. This design enables automated environmental responsiveness combined with manual signaling inputs, enhancing situational awareness and safety in vehicle or related applications.

Figure 3. Human–Computer Interaction (HCI)



It highlights the human-computer interface within the biking safety system, showing how the cyclist's actions and environmental conditions are translated into digital signals and then back into physical feedback. The handlebar device acts as the input interface, where the human interacts with the computer through sensors and buttons. The cyclist's movement, braking, and turn intentions are captured by the MPU6050 motion sensor, LDR light sensor, and BLE controllers or mechanical buttons. These inputs represent the human side of the interaction, which the ESP32 Dev Module processes into discrete states such as DARK, BRAKE, LEFTSTATE, and RIGHTSTATE. Through the NOW protocol, these signals are transmitted to the cyclist bag, which serves as the output interface. Here, the ESP32 C3 Super Mini interprets the data and activates LED indicators—white blinking lights for darkness, red lights for braking, and car-style signals for left or right turns. This cycle of sensing, processing, and feedback demonstrates the essence of a human-computer interface: the human provides input through natural actions, the computer interprets and processes those signals, and the system responds with clear, real-time outputs that enhance communication and safety on the road.

Framework Summary

The smart reflective safety bag for cyclists is built on the integration of embedded systems, sensor technology, and actuation mechanisms to enhance visibility and safety during nighttime rides. Conceptually, the system is divided into three interconnected components: the sensor node, the processing/control node, and the output node.

Input Subsystem (Sensor Node): Cyclist actions and environmental conditions are captured through multiple sensors and controls. A Light Dependent Resistor (LDR) monitors ambient light, an MPU6050 accelerometer/gyroscope detects motion and braking events, and mechanical switches or Bluetooth Low Energy (BLE) controllers provide manual turn signal inputs.

Processing Subsystem (Output Node): The ESP32 Dev Module continuously reads sensor data, applies threshold criteria, and interprets user commands. It identifies low-light conditions, braking events based on Y-axis acceleration thresholds, and toggles left/right signaling states. These discrete states—DARK, BRAKE, LEFTSTATE, RIGHTSTATE—are transmitted via the ESP32's NOW protocol for reliable communication.

Output Subsystem (Actuation Node): The ESP32 C3 Super Mini governs LED-based outputs to provide real-time feedback. A 5V Neopixel strip blinks white under dark conditions, illuminates red during braking, and 12V car-style indicators blink for left or right turns. These outputs ensure adaptive illumination and clear signaling to surrounding vehicles and pedestrians.

Human–Computer Interaction (HCI): The system exemplifies a dynamic human-computer interface where natural human actions (movement, braking, signaling) are sensed, processed, and translated into digital signals. These signals are then converted into physical feedback through LED indicators, creating a seamless loop of input → processing → output that improves communication, situational awareness, and cyclist safety.

RELATED LITERATURE

This section presents a comprehensive review of existing theories, studies, and technological developments related to cyclist safety, visibility enhancement, and wearable embedded systems. As cycling continues to gain prominence as a sustainable and efficient mode of transportation, numerous researchers and organizations have explored strategies to mitigate the risks faced by cyclists, particularly during nighttime and low-visibility conditions. These efforts span a wide range of approaches, including passive safety apparel, active lighting systems, intelligent signaling devices, and sensor-based situational awareness technologies.

The reviewed literature encompasses both non-technological and technology-driven solutions, such as reflective clothing, safety education programs, LED-enhanced wearables, gesture-based signaling systems, GPS-assisted indicators, and Internet of Things (IoT)-enabled safety equipment. While these studies have contributed valuable insights into improving cyclist visibility, perception, and communication with other road users, many existing solutions focus on isolated safety features or are limited to specific form factors such as vests, jackets, helmets, or bicycles themselves. Furthermore, several systems rely heavily on manual user input or single-sensor configurations, which may reduce responsiveness in dynamic traffic environments.

In addition, prior research has often treated lighting control, braking detection, and turn signaling as independent functions rather than as an integrated safety system. Few studies have explored the combination of ambient light sensing, motion-based brake detection, and flexible turn signal control within a single, wearable platform that is both ergonomic and suitable for everyday use. Limitations related to automation, real-time responsiveness, power efficiency, and adaptability to varying environmental conditions remain evident in many existing designs.

Guided by these gaps, the current study reviews relevant literature to identify the strengths and shortcomings of previous approaches and to establish the need for a more integrated, sensor-driven solution. This review serves as the foundation for the development of a smart reflective safety bag for cyclists, which combines LDR-based lighting automation, accelerometer-activated braking signals, and dual turn signal control using embedded systems and wireless communication. By synthesizing insights from prior studies, this section justifies the proposed system and highlights its contribution to advancing wearable safety technologies for urban cycling.

Table 1. Comparison Matrix of Related Studies and Current Research

Study	Sensor(s) / Method Used	Platform / Technology	Key Feature(s)	Gap Addressed by This Study
Benea et al. (2019)	Visual perception testing	Reflective vest color evaluation	Analyzed effect of reflective vest color on cyclist visibility at night	Focused only on passive visibility; lacks active lighting, automation, braking detection, and signaling integration
League of American Bicyclists (2010)	Safety education framework	Training programs and guidelines	Promotes cyclist safety awareness and best practices	Non-technological approach; does not provide real-time, sensor-based visibility or signaling

				support
Limb & Collyer (2023)	Behavioral perception analysis	Psychological and social research	Examined how safety attire affects cyclist dehumanization	Addresses social perception only; no embedded system, lighting control, or safety signaling implementation
Nourbakhshrezaei et al. (2023)	Multi-sensor situational awareness	Intelligent safety system	Use intelligent systems to enhance cyclist awareness in traffic	System-level focus; does not implement a compact, wearable, bag-based solution with lighting and signaling automation
Sankhe & Rodrigues (2018)	User interaction sensors	Microcontroller-based smart backpack	LED-integrated backpack for user safety	Lacks automatic light adaptation, braking detection, and wireless dual-control signaling features
Shabakouh (2021)	LED control mechanisms	Smart LED bike jacket	Wearable LED jacket to increase cyclist visibility	Rely on manual or static lighting; no sensor-driven automation or motion-based brake signaling
Tai & Hu (2017)	Gesture / motion sensors	Natural user interface-based vest	Gesture-based cyclists turn signaling	Limited to gesture control; does not include ambient light detection, brake sensing, or bag-based implementation
Tsai et al. (2021)	IoT sensors	IoT-enabled bicycle helmet	Multifunctional helmet with IoT safety features	Helmet-centric design; does not enhance rear visibility or torso-mounted signaling using adaptive LEDs
Usha et al. (2021)	GPS (offline navigation)	Microcontroller-based indicator system	Automatic turn indicators using GPS navigation	GPS-dependent and route-based; lacks real-time motion sensing, braking detection, and adaptive lighting
Wood et al. (2010)	Human visibility perception tests	Experimental visibility study	Identified mismatch between perceived and actual cyclist visibility	Observational study only; does not propose or implement an active technological safety solution
Reñido et al. (2026)	LDR, MPU6050, mechanical switches, BLE	ESP32 Dev Module, ESP32 C3, ESP-NOW	Automatic lighting based on ambient light, accelerometer-activated brake light, dual turn-signal control, distributed	Addresses the lack of an integrated, wearable, bag-based safety system that combines ambient light automation, motion-based brake detection, and

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			ESP32 architecture	flexible turn signaling using a low-cost embedded platform

METHODOLOGY

This study employed a developmental and experimental research methodology focused on the design, implementation, and evaluation of a smart reflective safety bag for cyclists. The methodology integrates embedded system development, sensor-based data acquisition, wireless communication, and functional testing to assess the effectiveness of the proposed system in enhancing cyclist visibility and signaling during nighttime and low-light conditions.

The research followed a prototype-based development approach, wherein a functional wearable safety system was designed, assembled, programmed, and tested. The system was iteratively developed through stages of hardware integration, firmware programming, and functional validation. Experimental testing was conducted to evaluate sensor responsiveness, system reliability, and the correctness of lighting and signaling outputs under various conditions

The system was assembled and programmed to continuously monitor the distance between the vehicle and nearby obstacles. When an object was detected within the predefined safety threshold, the system automatically restricted forward motion and activated visual and auditory alerts to prevent collision. Testing was conducted under controlled indoor conditions to evaluate obstacle detection accuracy, motor response, Bluetooth control reliability, and alert activation behavior. This approach enabled systematic assessment of the system's collision prevention capability, operational performance, and overall safety.

Figure 4. Waterfall Model

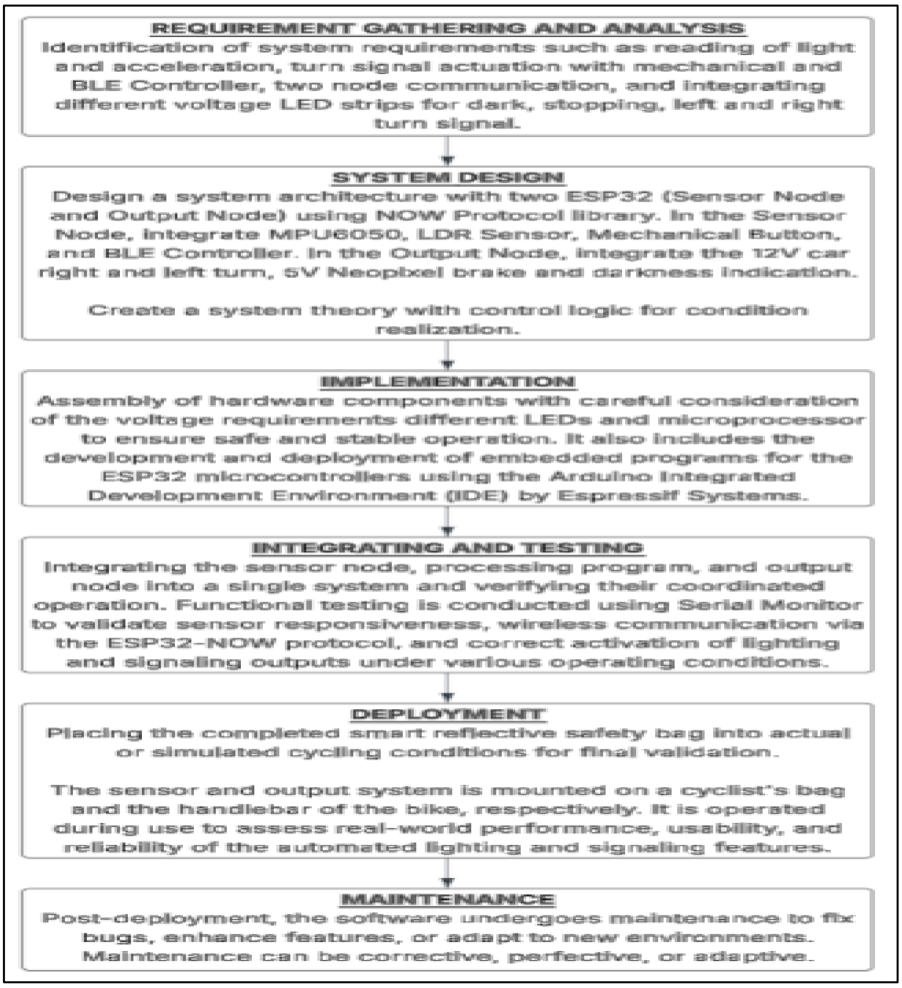

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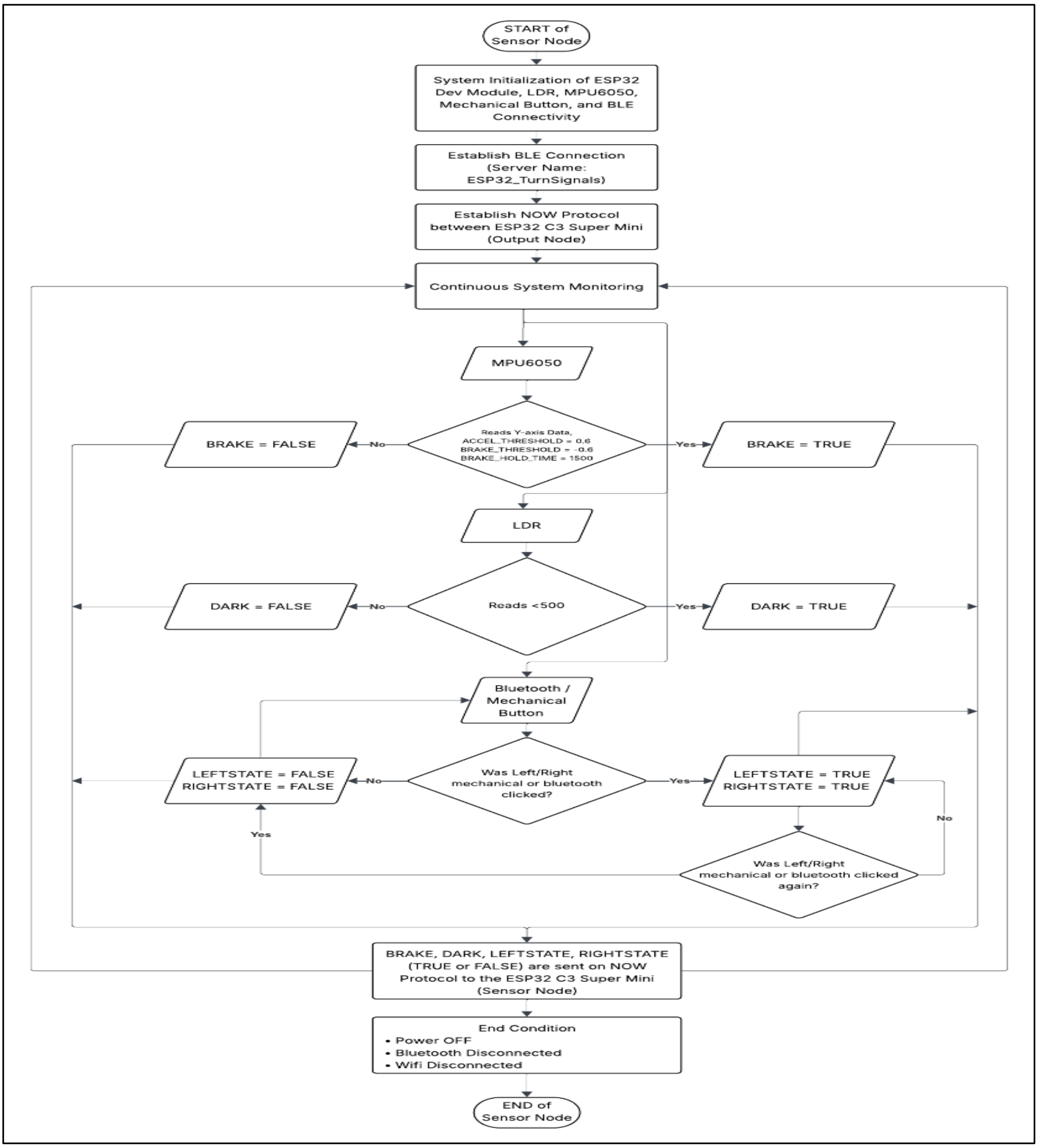
Figure 4 illustrates the Waterfall Model used in the development of smart reflective safety bag for cyclists. The process begins with Requirement Gathering and Analysis, where system needs such as sensor inputs, signaling methods, wireless communication, and voltage considerations are identified. This is followed by System Design, which defines the overall architecture, including the separation of sensor and output nodes, selection of components, and development of control logic.

The Implementation phase involves assembling the hardware components and developing the embedded programs for the ESP32 microcontrollers. Next, Integrating and Testing ensures that all system components operate cohesively, validating sensor accuracy, wireless communication reliability, and correct lighting and signaling behavior under various conditions. The Deployment phase places the completed system into actual or simulated cycling environments to evaluate real-world performance, usability, and reliability. Finally, Maintenance addresses post-deployment improvements, including bug fixes, feature enhancements, and system adaptations, ensuring long-term functionality and sustainability of the proposed solution.

Figure 5. System Flowchart for Sensor Node



The operational logic of the sensor node system is structured around an ESP32 Dev Module, which serves as the central microcontroller for initializing and managing peripheral components. Upon system startup, the ESP32 initializes the Light Dependent Resistor (LDR), MPU6050 accelerometer and gyroscope module, mechanical push-button interface, and Bluetooth Low Energy (BLE) stack. BLE connectivity is established with a designated server identifier ("ESP32_TurnSignals"), while the ESP-NOW protocol is concurrently configured to enable low-latency peer-to-peer communication with the output node, an ESP32 C3 Super Mini.

Once initialized, the system enters a continuous monitoring phase. The MPU6050 module captures Y-axis acceleration data to detect braking events. A braking condition is asserted when the measured acceleration exceeds the defined threshold of 0.6 g and persists for a duration longer than 500 milliseconds. If these criteria are met, the system sets the BRAKE flag to TRUE; otherwise, it remains FALSE.

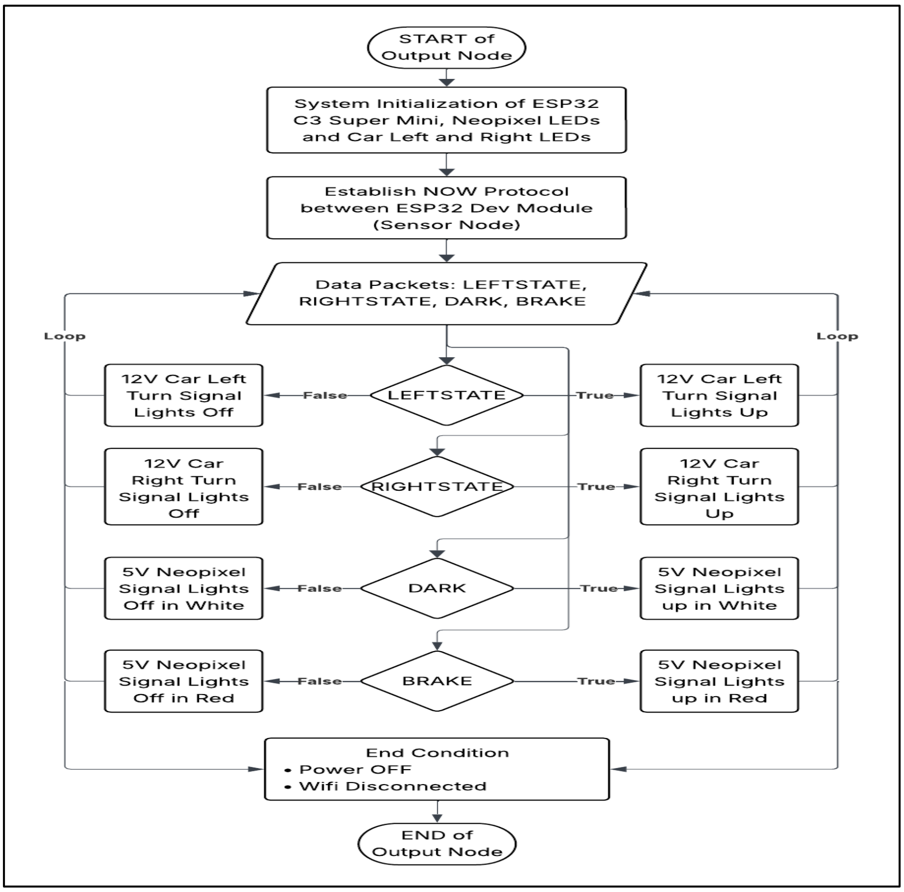
Ambient light conditions are assessed using the LDR sensor. A reading below 500 lux is interpreted as a low-light environment, prompting the system to set the DARK flag to TRUE. If the light intensity remains above this threshold, the flag is set to FALSE. This binary evaluation enables the system to adapt its signaling behavior based on environmental lighting.

Directional signaling is facilitated through both mechanical button presses and BLE-based user input. A single activation of either input method toggles the corresponding directional state (LEFTSTATE or RIGHTSTATE) to TRUE. A subsequent activation resets the state to FALSE, thereby implementing a toggle mechanism for left and right turn signals.

The evaluated Boolean states—BRAKE, DARK, LEFTSTATE, and RIGHTSTATE—are transmitted via the ESP-NOW protocol to the ESP32 C3 Super Mini output node. This node is responsible for interpreting the received data and executing corresponding output actions, such as activating visual indicators.

The system terminates operation under any of the following conditions: manual power-off and thus cuts all operation on BLE and Wi-Fi.

Figure 6. System Flowchart for Output Node



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The output node of the vehicle lighting system is implemented using an ESP32 C3 Super Mini microcontroller. Upon initialization, the system activates its onboard components, including Neopixel LEDs and 12V car-grade left and right turn signal lights. Concurrently, the ESP-NOW protocol is established to enable wireless communication with the sensor node, which is based on an ESP32 Dev Module.

The system continuously listens to incoming data packets transmitted via ESP-NOW. These packets contain four Boolean flags: LEFTSTATE, RIGHTSTATE, DARK, and BRAKE, each representing a specific operational condition derived from sensor inputs and user interactions at the sensor node.

Upon receipt of a data packet, the output node evaluates each flag to determine the appropriate lighting response:

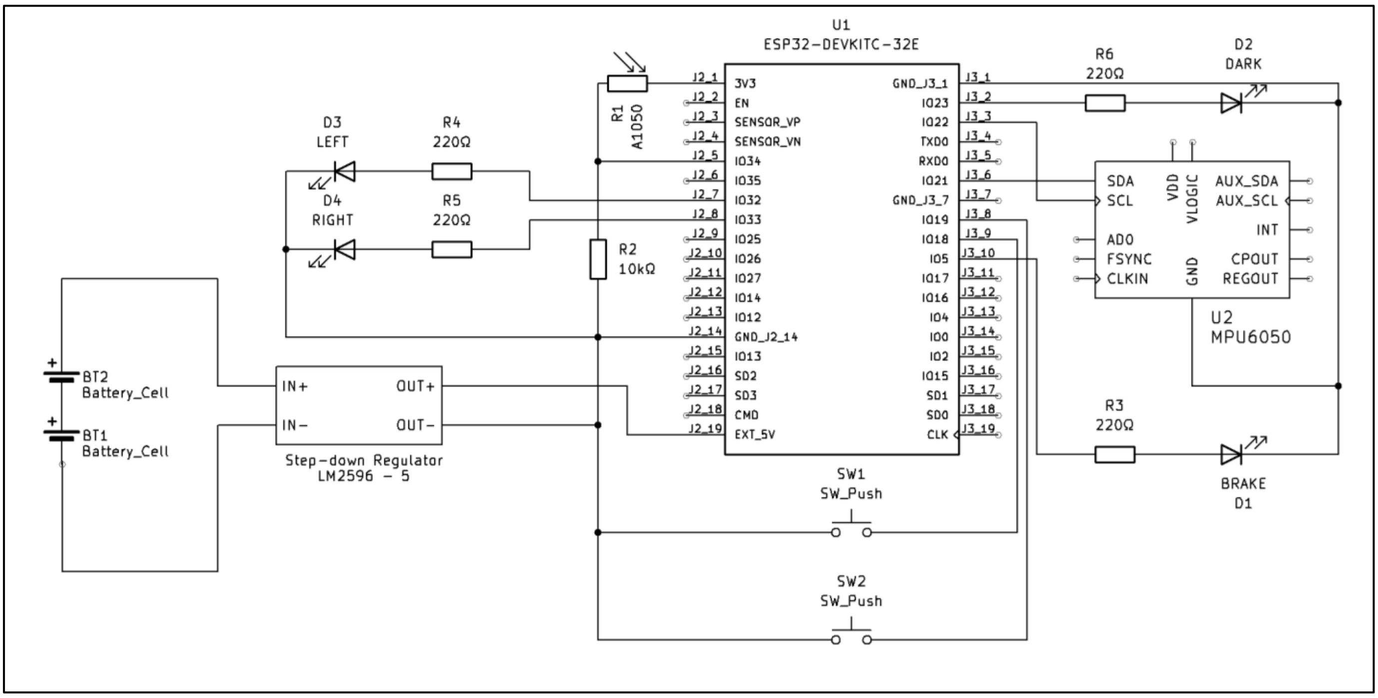
If LEFTSTATE is TRUE, the system activates the 12V left turn signal lights; if FALSE, the lights remain off. Similarly, a TRUE value for RIGHTSTATE triggers the 12V right turn signal lights, while a FALSE value deactivates them.

The DARK flag governs the behavior of the Neopixel LEDs in white. When DARK is TRUE, the Neopixel signal lights illuminate in white to enhance visibility under low-light conditions. If FALSE, the white Neopixel lights are turned off.

The BRAKE flag controls the Neopixel LEDs in red. A TRUE value indicates a braking event, prompting the system to illuminate the red Neopixel lights. Conversely, a FALSE value results in the red lights being turned off.

Same as on the sensor node, the system terminates operation under any of the following conditions: manual power-off and thus cuts all operation on BLE and Wi-Fi.

Figure 7. Schematic Diagram on Sensor Node

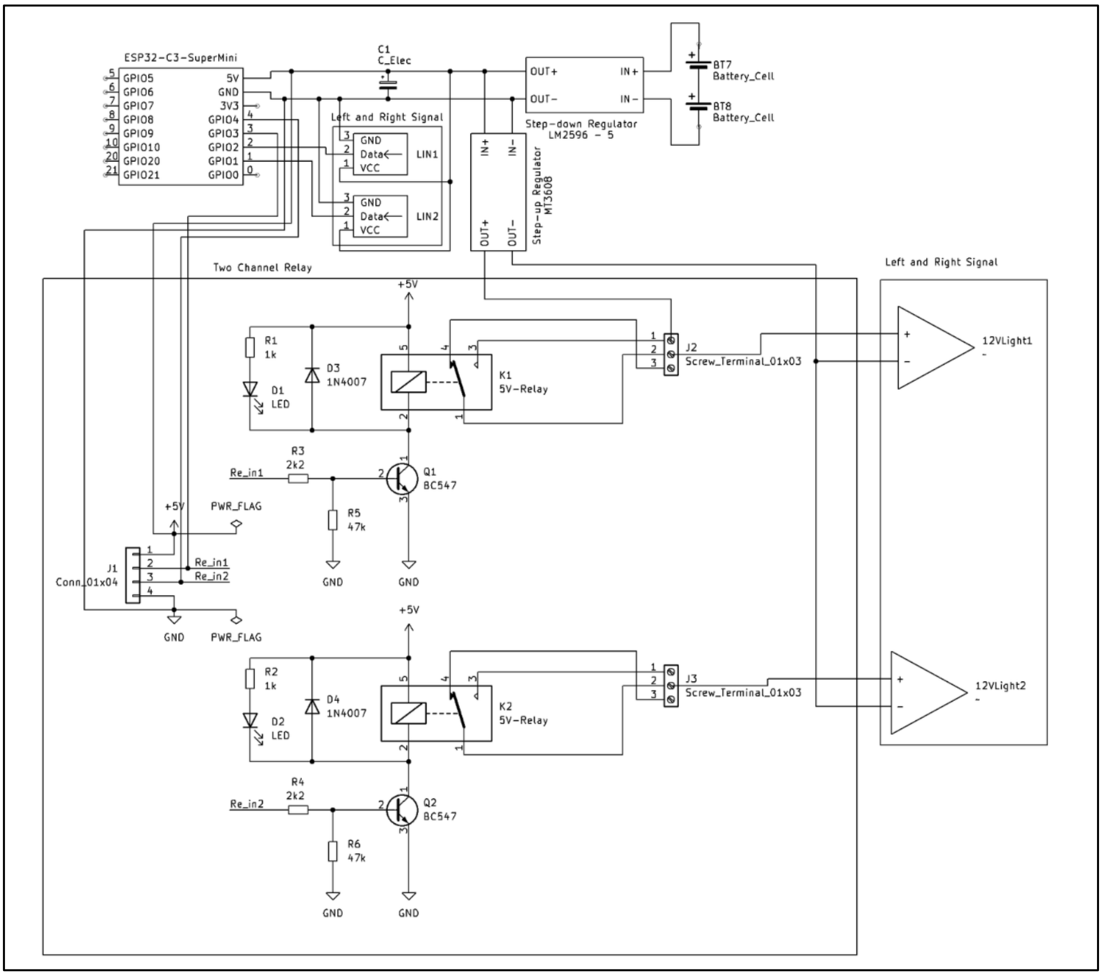


The input stage of the system is designed to provide stable power and reliable sensor signals to the ESP32-DEVKITC-32E microcontroller. Two battery cells connected in series serve as the primary energy source, delivering a raw voltage that is regulated by the LM2596 step-down converter. This regulator ensures a consistent 5V supply to the ESP32 and its peripheral components, protecting them from voltage fluctuations.

Ambient light detection is achieved through the LDR sensor, which is interfaced with GPIO34 of the ESP32. A 10kΩ pull-down resistor is connected to the sensor output to prevent floating values and stabilize the input signal. Motion sensing is provided by the MPU6050 module, which communicates with the ESP32 via the I²C bus through the SDA and SCL lines. The primary function centers on acceleration data for braking detection.

Manual inputs are incorporated through two push buttons connected to GPIO pins. These switches enable the assertion of left and right directional states, complementing the sensor-based inputs. Collectively, the input subsystem establishes the foundation of the intelligent signaling system, allowing the ESP32 to process environmental conditions, motion data, and user commands in a unified manner.

Figure 8. Schematic Diagram on Output Node



This schematic illustrates the output node of a signal-controlled lighting system, designed to activate two 12V and two 5V lights based on wireless input from a sensor node. The core of the circuit is the ESP32-C3-SuperMini, which receives Boolean flags—such as LEFTSTATE, RIGHTSTATE, BRAKE, DARK—via ESP-NOW communication. These flags determine whether the left or right light, brake and darkness light indicator should be activated.

Power is supplied by four battery cells (BT5 to BT8), connected in series to provide sufficient voltage for the relays and lighting devices. A step-down regulator (LM2596) converts this raw voltage to a stable 5V output, which powers the ESP32 and the relay control circuitry. The ESP32 outputs control signals through GPIO 3 and 4 pins, which are routed to the bases of two BC547 NPN transistors (Q1 and Q2) via 1kΩ resistors (R1 and R2). These transistors act as switches, allowing current to flow through the relay coils when activated. These inputs are conditioned by 47kΩ resistors (R5 and R6) to ensure proper biasing and signal integrity. External connections are made via screw terminals (J2 and J3), allowing the 12V lights to be easily wired into the system.

Each relay (K1 and K2) is part of a two-channel 5V relay module. When energized, the relay closes its normally open contact, allowing 12V power to reach either 12VLight1 or 12VLight2, depending on which relay is triggered. Flyback diodes (D3 and D4, 1N4007) are placed across the relay coils to protect the transistors from voltage spikes caused by coil discharge. Indicator LEDs (D1 and D2), paired with 2.2kΩ resistors (R3 and R4), provide visual feedback when each relay is active.

LIN1 and LIN2 represent the Neopixel LED strips. They are controlled via GPIO 1 and 2 of the ESP32 C3 Super Mini. Both strips are connected to the 5V and GND of the microprocessor.

Hardware Implementation and Circuit Configuration

The system is composed of two primary nodes: a sensor node mounted on the bicycle handlebar and an output node embedded in the cyclist’s bag. The sensor node utilizes an ESP32-DEVKITC-32E microcontroller, interfaced with an MPU6050 accelerometer/gyroscope, an ALS-PT19 light sensor, mechanical push buttons, and a BLE controller. These components are powered by a regulated 5V supply derived from a series of battery cells and an LM2596 step-down converter. The output node features an ESP32-C3 Super Mini microcontroller, which controls two 12V car signal lights via relay modules and drives two 5V Neopixel LED strips for brake and darkness indication. Both nodes are connected via the ESP-NOW protocol, enabling low-latency wireless communication without the need for external Wi-Fi infrastructure.

Software Development

Firmware for both ESP32 microcontrollers was developed using the Arduino IDE with support from the ESP-NOW and Wire libraries. The sensor node continuously monitors environmental and user inputs, including light intensity, acceleration along the Y-axis, and directional commands from mechanical or BLE interfaces. Threshold conditions are defined for each input: ambient light below 500 lux triggers the DARK state, acceleration values exceeding ±0.6 g for at least 1500ms trigger the BRAKE state, and button presses toggle LEFTSTATE and RIGHTSTATE flags. These Boolean states are transmitted wirelessly to the output node. The output node interprets the received data and activates corresponding lighting outputs: Neopixel strips for brake and darkness indication, and relay-driven 12V signals for left and right turns.

System Testing and Evaluation

Functional testing was conducted to verify the correct operation of each subsystem. Sensor responsiveness was validated using controlled light and motion conditions, while push button inputs were tested for debounce accuracy and state toggling. Output responses were observed under simulated cycling scenarios to confirm correct activation of Neopixel strips and 12V signal lights. All tests confirmed that the system met its design objectives for responsiveness and reliability.

Data Collection and Analysis

Output activation events were recorded to assess timing accuracy and consistency across multiple trials. The data was tabulated and visualized to identify trends, validate threshold settings, and confirm system reliability. Results demonstrated that the system consistently responded to environmental and user inputs with minimal delay, supporting its suitability for real-world deployment in cyclist safety applications.

RESULTS

The developed system successfully integrated sensor inputs, wireless communication, and output actuation to provide reliable signaling functions during testing.

[1] The LDR sensor consistently detected ambient light levels, with values below the defined threshold (<500) triggering the DARK state. In this condition, the Neopixel strip responded by blinking continuously in white, enhancing visibility in low-light environments.

[2] The MPU6050 accelerometer accurately measured motion along the Y-axis, and braking events were detected when acceleration values exceeded the set thresholds (ACCEL_THRESHOLD = 0.6,

BRAKE_THRESHOLD = –0.6, BRAKE_HOLD_TIME = 1500 ms). When braking was identified, the Neopixel strip illuminated in red, providing a clear visual indication of deceleration.

[3] Manual inputs through mechanical push buttons and BLE commands were also validated. Pressing the left or right button activated the corresponding directional state, causing the 12V car signal lights to blink. A second press correctly deactivated the signal, confirming proper toggling behavior.

[4] Wireless communication between the ESP32-DEVKITC-32E sensor node and the ESP32-C3 Super Mini output node via the ESP-NOW protocol was stable, with negligible latency observed during repeated trials.

Overall, the system demonstrated accurate sensor detection, responsive wireless transmission, and reliable output activation. The coordinated operation of Neopixel strips and 12V car signals provided clear visual feedback for braking, darkness, and directional intent. These results confirm that the smart signaling system functioned as intended, offering real-time responsiveness and dependable performance under simulated cycling conditions.

Requirements

The functional requirements of the smart signaling system focus on its ability to detect environmental conditions, interpret motion data, and respond to user inputs for safe and reliable signaling. The LDR sensor continuously monitors ambient light levels, triggering the DARK state when readings fall below the defined threshold. The MPU6050 accelerometer/gyroscope provides real-time motion data, enabling detection of braking events when acceleration values exceed preset limits. Manual directional control is achieved through mechanical push buttons or BLE commands, which toggle LEFTSTATE and RIGHTSTATE signals. The ESP32 Dev Module sensor node processes all sensor readings and user inputs, transmitting Boolean states (DARK, BRAKE, LEFTSTATE, RIGHTSTATE) via the ESP-NOW protocol to the ESP32-C3 Super Mini output node. The output node activates corresponding indicators: Neopixel LED strips for brake and darkness signals, and relay-driven 12V car lights for left and right turn signals. The regulated 5V supply from the LM2596 step-down converter and the 12V supply from the MT3060 step-up converter controls the higher voltage turn signal via relay ensures stable operation of all components.

Non-functional requirements emphasize responsiveness, safety, and reliability. The system continuously evaluates sensor inputs and updates outputs in real time, ensuring immediate feedback to environmental changes and user commands. Visual indicators through Neopixel strips provide clear and distinct signaling for braking and darkness, while 12V car lights deliver reliable directional cues. Wireless communication via ESP-NOW is required to maintain low-latency transmission between nodes without dependence on external Wi-Fi infrastructure. The system must operate efficiently under varying power conditions, with stable voltage regulation to protect microcontrollers and peripheral components. Overall, the design prioritizes dependable performance, consistent safety feedback, and seamless integration of sensor and user inputs into coordinated signaling outputs.

Table 2. Components, Variables, and Operational Responses

Variable / Component	**Type (Input / Output)**	**Parameter Measured / Controlled**	**Condition or range**	**System Response / Action**
ESP32 Dev Module (Sensor Node)	Microcontroller	Processes sensor inputs and user commands	Operates at 5V logic, continuous loop evaluation	Reads LDR, MPU6050, and button/BLE inputs; transmits DARK, BRAKE, LEFTSTATE, RIGHTSTATE via

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				ESP-NOW
Photoresistor Sensor	Input	Ambient light intensity	Threshold: < 500 (low-light condition)	Sends DARK state to ESP32; triggers Neopixel strip to blink white continuously
MPU6050 Accelerometer / Gyroscope	Input	Motion and braking detection	ACCEL_THRESHOLD = 0.6; BRAKE_THRESHOLD = –0.6; BRAKE_HOLD_TIME = 1500 ms	Sends BRAKE state to ESP32; triggers Neopixel strip to light up red
Mechanical Push Buttons / BLE Controller	Input	User directional commands (Left/Right)	Toggle ON/OFF with button press or BLE click	Sends LEFTSTATE or RIGHTSTATE to ESP32; activates corresponding 12V car signal light
ESP32-C3 Super Mini (Output Node)	Microcontroller	Receives states via ESP-NOW	Operates at 5V logic, continuous loop evaluation	Interprets DARK, BRAKE, LEFTSTATE, RIGHTSTATE; drives Neopixel strips and relay outputs
5V Neopixel LED Strips	Output	Visual signaling (Darkness / Brake)	5V supply; continuous blinking white or solid red	Provides visibility in darkness (white blink) and braking indication (red illumination)
12V Car Signal Lights	Output	Left and right directional signals	Relay switching; ON/OFF toggle	Blinks left or right signal when activated; turns off on second press
LM2596 Buck Regulator	Power Supply	Voltage regulation	Converts battery pack voltage to stable 5V	Provides regulated power to ESP32 boards and output devices
MT3608 Boost Converter	Power Supply	Voltage regulation (boost converter)	Input: 2–24V; Output adjusted to 12V for 12V Car Signal Lights	Supplies 12V to the Car Signal Light
Relay Module (2-Channel)	Output Control	Switching of 12V car lights	5V coil activation via transistor drivers	Closes contacts to power 12V lights when LEFTSTATE or RIGHTSTATE is true
Battery Pack (2 Cells) – 3.7V Li-On	Power Source	Provides raw voltage	Nominal 7.4V	Supplies energy to regulator, ESP32 boards, sensors, and

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14500 750mA				output devices

Table 3. Test Conditions, Expected Responses, and Verification Results

Test #	Input Condition	Observed Output	Expected Output	Pass / Fail	Remarks / Behavior Explanation
1	No ambient darkness, no braking, no turn signal input	LEDs OFF, turn signals OFF, buzzer OFF	System remains idle	Pass	Bag waits for conditions requiring activation; no unnecessary illumination
2	Ambient light below threshold (< 500 lux)	White LEDs ON, turn signals OFF, buzzer OFF	Low-light visibility activated	Pass	Automatic light activation works correctly in dark conditions
3	Sudden deceleration detected (Y-axis acceleration ≤ -0.6g for ≥ 500 ms)	Red brake LEDs ON, buzzer ON, turn signals unchanged	Brake signaling triggered	Pass	Accelerometer-based braking detection functions correctly
4	Simultaneous darkness and braking	White LEDs ON, Red brake LEDs ON, buzzer ON	Both light signals active simultaneously	Pass	Multiple sensor inputs handled properly
5	Left turn signal activated via mechanical switch	Left turn LEDs blink, right LEDs OFF, other lights as per environment	Turn signal indicates LEFT	Pass	Manual turn signaling operates correctly
6	Right turn signal activated via BLE command	Right turn LEDs blink, left LEDs OFF, other lights as per environment	Turn signal indicates RIGHT	Pass	Wireless turn signal control functions reliably
7	Both turn signals toggled rapidly	LEDs respond correctly with no erratic blinking	Stable turn signal control	Pass	System handles rapid user input without malfunction
8	Continuous low-light condition without braking	White LEDs remain ON	Sustained visibility maintained	Pass	LDR-based automation supports long-term operation
9	Manual power OFF	All LEDs OFF, buzzer OFF, BLE disconnected	Safe shutdown	Pass	No residual operation: system safely powered down
10	Power ON in low light near obstacle (braking not detected)	White LEDs ON, red LEDs OFF, turn signals OFF	Defaults to safe visibility mode	Pass	Safe startup behavior confirmed; no false brake activation

11	Power ON, braking detected immediately	White LEDs ON, red LEDs ON, buzzer ON	Automatic brake signal upon startup	Pass	System correctly interprets initial sensor readings
12	Obstacle detected while riding (dynamic testing)	Brake LEDs ON if deceleration occurs, turn signals responsive, white LEDs ON in dark	Dynamic safety response functional	Pass	Integrated sensor response tested in realistic scenarios

The results confirm that the Smart Reflective Safety Bag for Cyclists effectively enhances rider safety by prioritizing environmental sensing and automated signaling over manual control inputs when necessary. The system responds to low-light conditions, sudden braking, and directional commands, demonstrating accurate implementation of sensor-driven decision logic.

The immediate activation of the white LEDs in dark environments and red brake LEDs during sudden deceleration, along with responsive turn signal operation, reflects proper application of real-time control principles. Continuous monitoring of ambient light via the LDR and motion through the MPU6050 ensures rapid feedback and adaptive signaling, which are essential for maintaining visibility and alerting surrounding road users.

Furthermore, the integration of dual turn signal control—through mechanical buttons and Bluetooth Low Energy (BLE) connectivity—provides a simple, intuitive, and flexible user interface while maintaining system safety. The successful execution of all test scenarios indicates that the system is dependable, responsive, and suitable for practical cycling applications, enhancing both rider confidence and overall traffic safety.

DISCUSSION

The Smart Reflective Safety Bag for Cyclists successfully met its design objectives by providing accurate environmental sensing and timely signaling to enhance rider safety. The LDR-based ambient light detection reliably measured surrounding lighting conditions, activating white LEDs in low-light environments and conserving power during daylight. The MPU6050 accelerometer consistently detected sudden deceleration or braking events, triggering red brake LEDs and buzzer alerts without delay. Minor calibration adjustments were required to ensure threshold sensitivity, but once tuned, the system responded instantly and accurately, demonstrating both precision and speed in critical situations.

The integration of visual, auditory, and wireless feedback contributed to an effective human–computer interface. White Neopixel LEDs, red brake lights, and 12V turn signals provided clear cues to surrounding traffic, while Bluetooth Low Energy (BLE) connectivity allowed remote operation of turn signals through a smartphone application. The combination of manual and automated controls ensured that rider commands were respected without compromising safety, particularly during braking or low-light scenarios.

Sensor reliability was consistently high, with ambient lighting, surface reflectivity, or rider motion having negligible impact on system performance. Some hardware limitations were noted, such as occasional BLE disconnection during low battery conditions or minor delays in turn signal toggling, but these did not compromise overall safety.

The automatic response to braking and low-light conditions effectively prevented potential accidents, while dual turn signal functionality enhanced rider communication with surrounding vehicles. The system's thresholds and logic can be adjusted to suit different environments or cycling conditions, demonstrating versatility and adaptability. Overall, the Smart Reflective Safety Bag provides a robust, responsive, and intuitive solution for improving cyclist visibility and safety during nighttime rides.

CONCLUSION AND RECOMMENDATIONS

The system reliably activated white LEDs under low-light conditions, illuminated red brake lights during sudden deceleration detected by the MPU6050, and allowed left/right signaling through both mechanical buttons and Bluetooth Low Energy (BLE) control. These features collectively improved rider safety, situational awareness, and communication with surrounding road users.

All sensors and modules—LDR, MPU6050, and ESP32 microcontrollers—performed consistently across various test scenarios, accurately detecting environmental lighting, braking events, and user commands. Minor issues, such as occasional BLE disconnections or slight delays in turn signal response, were negligible and did not compromise overall safety. The Li-ion rechargeable battery supplied sufficient power for continuous operation, though the absence of a 2S BMS means users must manually monitor battery health and charging safety.

It is recommended that future iterations include optional battery management features to improve reliability, enhance BLE connectivity for stable smartphone control, and explore additional safety features such as GPS-based navigation or collision warning. The system’s architecture is flexible and can be adapted for other wearable cycling devices or smart safety gear.

In conclusion, the Smart Reflective Safety Bag is a safe, reliable, and user-friendly solution for improving cyclist visibility and signaling at night. Its integration of sensor-driven automation and embedded systems demonstrates a strong foundation for future development in smart urban cycling safety.

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