Enhancing urban cyclist safety through integrated smart backpack system

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ABSTRACT

The increasing adoption of bicycles as a sustainable mode of urban transportation has underscored the urgent need for enhanced safety measures for cyclists. This paper presents the development and implementation of an integrated smart backpack system designed to improve the safety and visibility of urban cyclists. The system leverages advanced technologies, including the ESP32 microcontroller, GPS modules, proximity sensors, and LED lighting, to create a semi-automatic solution that adapts to environmental conditions and cyclist behavior in real-time. Extensive testing under various conditions, including low visibility and adverse weather, demonstrated the system's reliability in enhancing cyclist visibility and reducing accident risks. The smart backpack also features a user-friendly mobile application, providing real-time data on speed, distance, and location, which further contributes to rider safety. The results indicate significant potential for this technology to be widely adopted, offering a practical and effective solution to the growing safety concerns of urban cyclists. This work not only advances the field of wearable safety technologies but also sets the foundation for future innovations in smart transportation systems, contributing to safer and more sustainable urban mobility.

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1. INTRODUCTION

Amid rapid urbanization, the integration of cycling into transportation networks has emerged as a critical strategy for sustainable city living. However, the surge in urban cycling has brought to light a pressing need for enhanced safety measures to protect cyclists amidst the hustle and bustle of city streets [1]. The city of Bogotá, with its vibrant urban landscape and growing cycling community, serves as a poignant case study for the development and implementation of safety technologies [2]-[4]. However, this is not just a local issue but a global concern, as cities worldwide strive to promote cycling as an eco-friendly and efficient means of mobility. Against this backdrop, this paper explores the potential of an integrated smart backpack system to improve urban cyclist safety, aiming to mitigate the risks associated with sharing roads with motorized traffic [5]. The proposed system represents a significant leap forward in harnessing technology to create a safer and more inclusive cycling environment.

Urban areas like Bogotá are grappling with the dual challenges of traffic congestion and high rates of transportation-related accidents, which disproportionately affect cyclists [6]. The unsafe conditions are often exacerbated by a lack of dedicated cycling infrastructure and the erratic behavior of other road users [7].

Improving cyclist safety, therefore, is not only a public health imperative but also a key factor in encouraging more people to choose cycling as a viable mode of daily transportation. Cutting-edge technology holds the key to reducing the dangers faced by urban cyclists. Smart systems and innovations can enhance visibility, communication, and interaction among all road users. This paper delves into the design and functionality of a smart backpack system that could revolutionize cyclist safety by integrating advanced technologies such as collision detection, real-time communication, and enhanced visibility. By addressing these safety concerns, the system has the potential to make cycling a safer and more attractive option for urban commuters.

The research presented in this paper holds broader implications for cities around the world that are striving to integrate cycling into their urban transport networks [8], [9]. As global urbanization continues, the lessons learned from Bogotá's experiences can provide valuable insights for other cities looking to promote environmental sustainability through increased bicycle usage. Insights from these studies can be adapted and implemented in different contexts to create a universal framework for enhancing cycling safety. The integrated smart backpack system discussed in this paper offers a scalable and adaptable solution that can be customized to meet the unique needs of various urban environments. By sharing the findings and recommendations of this study, we aim to contribute to the global conversation on urban sustainability and cyclist safety.

To conduct a thorough analysis of the potential impact of the smart backpack system on urban cyclist safety, this paper adopts a comprehensive research methodology. Information is gathered from various sources, including academic literature, industry reports, and patent filings, to provide a robust foundation for the study. The selection of studies for inclusion in this review is guided by stringent criteria, ensuring that only those with clear empirical findings and innovative perspectives on technology application are considered.

This paper not only assesses the efficacy of the smart backpack system but also identifies its limitations and further research and development. Each component of the system is examined for its adaptability to the urban environment and its potential to gain user acceptance. The comprehensive analysis endeavors to bridge the chasm between research and actionable solutions, presenting a strategic plan for the advancement of technologies that can significantly enhance the safety of urban cyclists. This detailed analysis helps identify the most suitable solutions for each urban setting. Ultimately, the findings of this study are intended to inform and guide policy decisions and technological advancements that will make our cities safer for cyclists and all residents alike. They provide the basis for informed decision-making to shape transportation policies and infrastructure. By integrating these insights, cities can create an environment where cycling is not only feasible but also safe, encouraging more people to embrace this mode of transportation for a sustainable future.

2. LITERATURE REVIEW

The domain of cyclist safety technology has witnessed a proliferation of innovations aimed at mitigating the risks associated with urban cycling. Traditional measures, such as high-visibility apparel and helmets, remain the cornerstone of personal protection for cyclists [10], [11]. These items, including reflective jackets and LED-equipped gear, are designed to enhance cyclist visibility and offer safety during accidents [12], [13]. Nevertheless, these technologies are fundamentally passive, serving to mitigate rather than prevent incidents, a limitation that has spurred the development of more proactive safety solutions [14], [15].

In response to the need for active safety measures, the cycling community has embraced technologies such as advanced lighting systems and electronic signaling devices [16], [17]. These systems not only light up the cyclist's path but also ensure their visibility to other road users, thus reducing the risk of collisions [18], [19]. Turn signals, integrated into handlebars or wearable devices, facilitate clear communication of the cyclist's intentions, further enhancing safety [20]. Cameras and radar systems complement these solutions by providing cyclists with real-time alerts about approaching vehicles, thereby enhancing situational awareness [21], [22].

The integration of GPS technology has revolutionized urban cycling navigation, offering cyclists a wealth of information to enhance their safety and efficiency [23]. GPS devices, now commonly integrated into bicycle computers or smart watches, provide real-time data on route information, traffic conditions, and road hazards [24]. These devices can recommend alternative routes to avoid high-traffic or areas with poor infrastructure, reducing risk exposure [25]. Additionally, some GPS-enabled devices are linked to mobile apps that enable accident tracking and reporting, contributing to a community-based approach to safety enhancement [26].

Urban cyclists are increasingly embracing wearable technology, particularly smart helmets and connected wearables, to enhance their safety [27]. These devices can monitor vital signs, detect crashes, and automatically alert emergency services to the cyclist's location [28]. Equipped with accelerometers and gyroscopes, these wearables can quickly detect falls and facilitate rapid response, potentially improving outcomes post-accident [29]. Furthermore, the emergence of smart fabrics holds the promise of simultaneously increasing comfort and protection, with sensors that adapt to environmental conditions [30].

The recent advancements in cyclist safety are a big step forward. However, it is important to continuously assess the effectiveness of current technologies in light of changing city landscapes. The innovations in this field need to be adaptable and able to address present safety concerns while also accommodating future urban developments and changes in cyclist behavior. Achieving this requires ongoing research and development driven by technological advancements and a thorough understanding of city dynamics. The objective is to establish a comprehensive system of technologies that will greatly improve overall cyclist safety.

3. PROBLEM STATEMENT

Urban cycling has become an increasingly popular mode of transportation due to its environmental benefits and its role in promoting a healthy lifestyle. However, the rapid growth in cyclist numbers has not been matched by corresponding improvements in road safety infrastructure, leading to a significant rise in cyclist-related accidents, particularly in densely populated cities like Bogotá. The urban environment presents numerous hazards to cyclists, including poor visibility, inadequate lighting on key routes, and the proximity of motorized vehicles, all of which contribute to a heightened risk of collisions and accidents.

Despite the widespread use of traditional safety measures such as high-visibility clothing, helmets, and reflective gear, these solutions are largely reactive, providing protection only after an incident has occurred. This reactive approach fails to address the root causes of many accidents, particularly those resulting from a lack of visibility or communication between cyclists and other road users. As such, there is a critical need for more proactive safety solutions that not only increase the visibility of cyclists but also facilitate better communication and situational awareness on the road.

Moreover, the existing electronic safety systems, while innovative, often lack integration and adaptability. For instance, while GPS-enabled devices can provide route information and alert cyclists to hazards, they do not directly enhance visibility or communication with other road users. Similarly, while LED lighting and electronic signaling devices improve visibility, they do not offer real-time feedback or data that could be used to further enhance cyclist safety. This disjointed approach results in suboptimal safety outcomes, as these technologies do not work together as a cohesive system.

In light of these challenges, there is a pressing need to develop an integrated safety solution that combines the strengths of existing technologies while addressing their limitations. Such a system should enhance cyclist visibility, provide real-time feedback on environmental conditions, and facilitate communication between cyclists and other road users. By addressing these needs, the proposed smart backpack system aims to significantly reduce the risk of accidents and improve overall safety for urban cyclists.

4. METHODS

4.1. System design and architecture

The smart backpack system is designed with a focus on enhancing urban cyclist safety by integrating a variety of sensors and communication modules into a compact and functional wearable device. The core of the system is the ESP32 microcontroller, selected for its robust processing capabilities and dual-mode Bluetooth and Wi-Fi connectivity. The ESP32 serves as the central hub of the system, managing data acquisition from sensors, processing the information, and coordinating the output to various actuators, such as the LED lighting system and the communication interface with the mobile application.

The system architecture is built around three key components: the sensor suite, the processing unit, and the communication modules. The sensor suite includes the BH1750 light sensor, which measures ambient light levels and triggers the LED lights when the cyclist enters low-visibility conditions. The MPU-6050 accelerometer and gyroscope module monitors the cyclist's movements, detecting sudden accelerations or decelerations that might indicate an emergency, such as a fall or abrupt stop. Additionally, the NEO-6M GPS module provides real-time location data, allowing the system to track the cyclist's route and provide location-based services through the mobile application.

Data flow within the system begins with the sensor suite continuously monitoring the cyclist's environment and movements. The ESP32 collects this raw data and processes it using predefined algorithms to determine the appropriate response. For instance, if the BH1750 sensor detects low light levels, the microcontroller immediately activates the LED lighting system to increase the cyclist's visibility. Similarly, if the MPU-6050 detects a sharp deceleration, the system can trigger a visual alert, such as flashing the LEDs in a specific pattern to signal an emergency. The processed data, including GPS coordinates, is then transmitted via Bluetooth to the mobile application, where it is displayed to the user in real-time.

The system's architecture also emphasizes modularity and expandability. The components are interconnected through standard communication protocols such as I2C for the sensors and universal asynchronous receiver/transmitter (UART) for the GPS module, allowing for easy integration of additional sensors or actuators if needed. The use of the ESP32's dual-core processing capability ensures that the system can handle multiple tasks simultaneously without compromising performance. One core is dedicated to managing sensor data and system logic, while the other handles communication tasks, ensuring that data transmission to the mobile application remains smooth and uninterrupted.

The system is designed with energy efficiency in mind. The power requirements of the ESP32 and the sensors are carefully managed to maximize battery life without sacrificing functionality. The LED lighting system, for instance, is programmed to operate in an energy-saving mode during the daytime or when the cyclist is stationary. The overall architecture of the smart backpack ensures that it is both powerful and efficient, capable of significantly enhancing cyclist safety in urban environments while maintaining a compact and user-friendly form factor.

4.2. Component integration

The successful operation of the smart backpack system hinges on the seamless integration of various sensors, modules, and actuators, each playing a critical role in enhancing the safety of urban cyclists. The integration process was meticulously planned to ensure that all components worked in harmony, with particular attention given to physical layout, wiring, and communication protocols. The primary components integrated into the system include the BH1750 light sensor, MPU-6050 accelerometer, and gyroscope, NEO-6M GPS module, and the LED lighting system, all orchestrated by the ESP32 microcontroller.

The BH1750 light sensor was selected for its precision in measuring ambient light levels, a critical factor for activating LED lighting in low-visibility conditions. The sensor was mounted on the top section of the backpack, ensuring unobstructed exposure to environmental light. Wiring was routed internally to connect the sensor to the ESP32 via the I2C bus, chosen for its simplicity and reliability in handling data transmission between multiple sensors. This configuration allowed the microcontroller to continuously monitor light levels and trigger the LED system as needed without delay, enhancing the cyclist's visibility during dusk, dawn, or under low-light conditions such as tunnels.

The MPU-6050 accelerometer and gyroscope module were integrated to monitor the cyclist's motion, providing real-time data on acceleration, orientation, and sudden movements. This module was strategically placed near the center of the backpack, aligning with the cyclist's center of gravity for accurate motion detection. The MPU-6050 was also connected to the ESP32 via the I2C interface, enabling efficient data collection and processing. The microcontroller used this data to detect potential emergencies, such as sudden stops or falls and responded by activating the LED lights in a flashing pattern, signaling to nearby road users that the cyclist may be in distress.

The NEO-6M GPS module was integrated to provide accurate location tracking and navigation capabilities. Positioned on the exterior of the backpack to ensure optimal satellite reception, the GPS module was connected to the ESP32 through a UART interface. This setup allowed for the efficient transmission of GPS data to the microcontroller, which was then relayed to the mobile application via Bluetooth. The GPS data was crucial not only for real-time tracking but also for logging routes and providing location-based alerts, thereby enhancing the overall safety and situational awareness of the cyclist.

The LED lighting system, a vital component of the safety mechanism, was integrated along the exterior of the backpack in a pattern designed to maximize visibility. The LEDs were connected to the ESP32 through MOSFET drivers, which were necessary due to the higher current requirements of the LEDs compared to the microcontroller's output capacity. The MOSFETs acted as switches, allowing the ESP32 to control the LEDs' operation based on inputs from the light sensor and accelerometer. The wiring was carefully routed through the backpack's structure, with protective insulation to prevent damage from wear and tear or environmental exposure. This integration ensured that the lighting system could operate reliably under various conditions, enhancing the cyclist's visibility at all times.

4.3. Software development

The software development process was key in ensuring the seamless interaction between hardware components and the user interface. The primary objectives of the software were to efficiently manage sensor data, facilitate real-time decision-making, and provide an intuitive user experience through a mobile application. The development process involved the use of MIT AppInventor for the creation of the mobile application and Arduino IDE for programming the ESP32 microcontroller, which serves as the system's core.

The Arduino IDE was utilized to develop the firmware for the ESP32 microcontroller, responsible for managing the data flow between sensors, processing this data, and controlling the outputs. The software was written in C/C++, leveraging the extensive libraries available for the ESP32 platform. Key functionalities such as reading data from the BH1750 light sensor, MPU-6050 accelerometer, and NEO-6M GPS module were implemented using respective libraries like "Wire.h" for I2C communication and software "Serial.h" for GPS data handling. The firmware also included routines for controlling the LED lighting system through the use of MOSFET drivers, enabling dynamic responses based on real-time sensor data.

A critical component of the software was the implementation of algorithms for sensor fusion and data processing. Sensor fusion was necessary to combine data from the accelerometer and gyroscope in the MPU-6050 module, providing more accurate and reliable information about the cyclist's movements. This was achieved using a complementary filter algorithm, which merged the accelerometer data to detect sudden stops or falls and the gyroscope data to monitor orientation changes. The processed data was then used to trigger specific responses, such as activating the LED lights in a flashing pattern to signal an emergency. Additionally, the software was designed to periodically check the light levels using the BH1750 sensor and adjust the LED brightness accordingly to ensure optimal visibility under varying environmental conditions.

The mobile application, developed using MIT AppInventor, served as the user interface for the smart backpack system. MIT AppInventor was chosen for its simplicity and ability to quickly prototype and develop applications for Android devices. The application was designed to display real-time data such as the cyclist's speed, distance traveled, current location, and light levels (Figure 1). The Bluetooth communication between the ESP32 and the mobile application was handled using the "BluetoothClient" component in AppInventor, which facilitated the seamless exchange of data. The application also provided the user with control over certain system parameters, such as setting thresholds for light levels that would trigger the LED lights or choosing to activate a silent mode where only critical alerts are displayed.

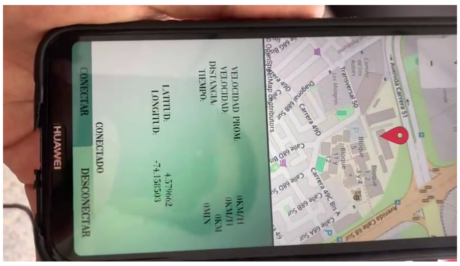

Figure 1. Application on Android smartphone

In addition to real-time data display, the mobile application included a feature for logging ride data, which allowed cyclists to review their performance metrics and routes after their journey. This feature was implemented using the "TinyDB" component in AppInventor, which stored data locally on the user's device. The application also incorporated safety features such as sending automatic alerts to emergency contacts in the event of a detected fall, leveraging the accelerometer data processed by the ESP32. The overall design of the software prioritized responsiveness, user-friendliness, and the integration of safety-critical functions, ensuring that the smart backpack system could effectively enhance the safety of urban cyclists.

The software development process also included rigorous testing and debugging phases, where both the firmware and the mobile application were iteratively refined based on feedback from field tests. The system's performance was evaluated in real-world cycling conditions, ensuring that the algorithms could handle the dynamic nature of urban environments. Any issues related to sensor accuracy, data transmission latency, or user interface responsiveness were addressed during these phases, leading to a robust and reliable software system that meets the safety and usability requirements of the smart backpack.

4.4. Prototyping

The prototyping and fabrication phase of the smart backpack system was a critical step in transforming the conceptual design into a functional, physical product. This process involved careful selection of materials, meticulous design of the printed circuit board (PCB) layout, and iterative fabrication of the prototype to ensure it met the desired performance and safety standards. The primary goals were to create a durable, weather-resistant, and ergonomically sound product that could reliably house the electronic components while maintaining user comfort and functionality.

The selection of materials was driven by the need for durability, flexibility, and waterproofing. The outer shell of the backpack was constructed using a high-quality, water-resistant fabric, chosen for its ability to protect the electronic components from environmental factors such as rain and dust. This fabric was reinforced with additional layers at critical points, such as the base and seams, to enhance durability and resistance to wear and tear. The interior of the backpack was lined with shock-absorbing foam, strategically placed to protect the delicate electronic components, including the PCB and battery pack, from mechanical shocks and impacts during use. Yumbolon foam was selected for this purpose due to its lightweight yet highly protective properties, ensuring that the backpack remained comfortable to wear while providing adequate protection for the electronics.

Designing the PCB layout was a complex task that required careful consideration of the spatial constraints within the backpack, as well as the need to minimize electrical interference between components. The PCB was divided into two main sections: one dedicated to power management and the other to signal processing and communication. The power management section included the lithium-ion battery pack, a voltage regulator, and MOSFETs for controlling the LED lights. The signal processing section housed the ESP32 microcontroller, along with the connections for the BH1750 light sensor, MPU-6050 accelerometer, and NEO-6M GPS module. The layout was optimized to reduce the length of critical signal paths, thereby minimizing potential noise and interference. Additionally, the PCB was designed with oversized copper traces in the power section to handle the higher currents required by the LEDs, ensuring reliable operation under all conditions.

The fabrication of the prototype involved several iterations, each addressing specific challenges encountered during the development process. One of the primary challenges was ensuring the waterproofing of the backpack without compromising the accessibility of the electronic components for maintenance and upgrades. This was achieved by designing a sealed compartment for the electronics, with waterproof zippers and silicone gaskets around cable entry points. The sealed compartment could be easily accessed by the user for battery replacement or software updates, without exposing the electronics to moisture. Another challenge was managing the heat generated by the electronic components, particularly the LEDs and the power management circuitry. To address this, the PCB was designed with thermal vias and heat sinks, which effectively dissipated heat away from the critical components, maintaining the system's stability and prolonging the lifespan of the electronics.

Throughout the prototyping process, extensive testing was conducted to validate the design under real-world conditions. The prototype was subjected to environmental stress tests, including exposure to extreme temperatures, humidity, and mechanical shocks, to ensure it could withstand the rigors of daily urban cycling. Additionally, the ergonomic design of the backpack was tested with users to ensure that it was comfortable to wear for extended periods, even with the added weight of the electronics. Feedback from these tests was used to refine the design, resulting in a final prototype that balanced durability, functionality, and user comfort.

4.5. Testing and validation

The testing and validation phase was crucial in ensuring that the smart backpack system met the required safety and performance standards for urban cyclists. This phase involved a series of rigorous tests designed to evaluate the system's functionality under various environmental and operational conditions. The primary areas of focus during testing included the responsiveness of the LED lighting system, the accuracy of the GPS module, the reliability of the sensor data, and the overall battery life. Each component was subjected to specific tests to validate its performance, and the system as a whole was tested in real-world cycling conditions to ensure its effectiveness in enhancing cyclist safety.

The LED lighting system was tested for responsiveness to changes in ambient light levels, as detected by the BH1750 light sensor. These tests were conducted in both controlled laboratory settings and real-world environments with varying lighting conditions, such as during nighttime, in tunnels, and under streetlights (Figure 2). The system's ability to adjust the brightness of the LEDs in real-time was evaluated by measuring the response time from the moment the sensor detected a change in light level to when the LEDs adjusted their brightness. The results demonstrated that the system could effectively enhance visibility in low-light conditions, with a response time well within the acceptable range for ensuring cyclist safety.

Figure 2. Illumination system in low light conditions in the environment

The NEO-6M GPS module was subjected to accuracy tests to validate its ability to provide precise location data. These tests were conducted by comparing the GPS data logged by the smart backpack with reference data obtained from a high-precision GPS device. The tests included both stationary measurements and dynamic testing during cycling to assess the module's performance in tracking the cyclist's movement. The results showed that the GPS module provided accurate location data with minimal deviation, making it reliable for real-time tracking and navigation purposes. Additionally, the GPS module's ability to maintain a stable connection with satellites in various urban environments, including areas with tall buildings and dense tree cover, was evaluated, and it was found to perform reliably in most conditions.

Sensor reliability was another critical area of testing, particularly for the MPU-6050 accelerometer and gyroscope module, which plays a key role in detecting sudden movements, such as falls or abrupt stops. The sensor was tested for accuracy and consistency in detecting and reporting acceleration and orientation changes. This involved subjecting the backpack to a series of simulated falls and abrupt movements to determine how quickly and accurately the sensor data was processed by the ESP32 microcontroller. The testing confirmed that the sensor reliably detected these events and triggered the appropriate safety responses, such as flashing the LEDs in a specific pattern to signal an emergency.

Battery life testing was conducted to ensure that the smart backpack could operate for extended periods without requiring frequent recharging, which is essential for practical use in urban cycling. The system's power consumption was measured under different operating conditions, including continuous LED operation, GPS tracking, and Bluetooth communication with the mobile application. The tests were designed to simulate typical usage scenarios to determine the expected battery life under normal conditions. The results indicated that the backpack could operate for a full day of cycling (approximately 8-10 hours) on a single charge, with power-saving modes available to extend battery life further when full functionality was not required.

4.6. Data collection and analysis

The data collection and analysis phase was essential for evaluating the performance of the smart backpack system under real-world conditions. This process involved gathering data from various sensors during field tests, processing the raw data to extract meaningful insights, and analyzing the results to assess the system's effectiveness in enhancing cyclist safety. The data collected provided valuable feedback on the system's functionality, including sensor accuracy, system responsiveness, and overall user experience.

During the field tests, data was collected from the BH1750 light sensor, MPU-6050 accelerometer and gyroscope, and NEO-6M GPS module, all of which were logged by the ESP32 microcontroller (Figure 3). The microcontroller continuously monitored the sensor outputs, logging data at predefined intervals to ensure a comprehensive dataset. The light sensor data provided insights into the ambient light conditions encountered during the tests, while the accelerometer and gyroscope data captured the cyclist's movements, including any sudden changes in velocity or orientation. GPS data was logged to track the cyclist's route, speed, and location, which was essential for assessing the system's real-time tracking capabilities.

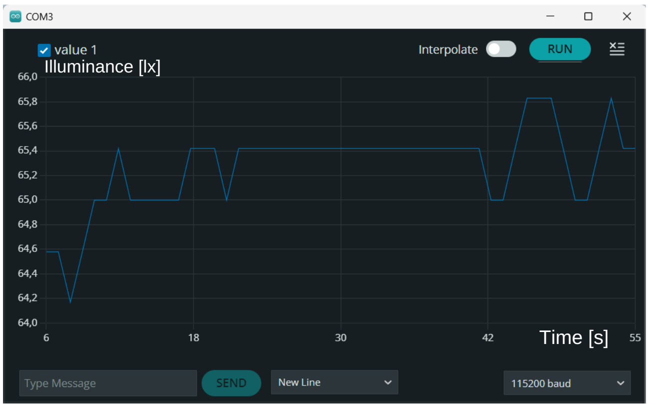

Figure 3. BH1750 light sensor recording in medium-low light conditions

The raw data collected from the sensors was processed using algorithms implemented in the firmware of the ESP32 microcontroller. For instance, the data from the MPU-6050 was processed using a complementary filter to combine accelerometer and gyroscope readings, providing a more accurate representation of the cyclist's movements. This processed data was used to identify significant events, such as sudden stops or falls, which were then marked in the dataset for further analysis (Figure 4). The GPS data was processed to calculate the distance traveled, and average speed, and identify any deviations from the planned route, which could indicate areas where the cyclist faced challenges, such as poor road conditions or high traffic.

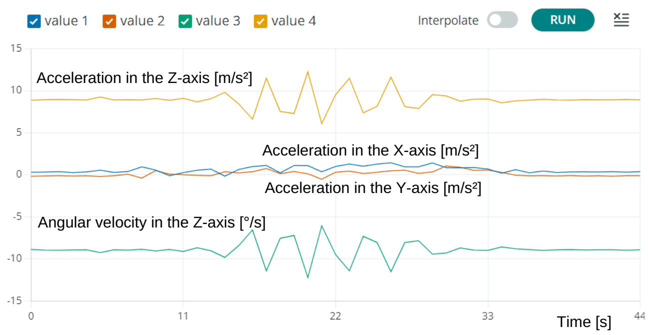

Figure 4. MPU-6050 sensor recording during speed change, acceleration, and turning tests

The analysis of the collected data involved both quantitative and qualitative methods. Quantitative analysis was performed using statistical tools to evaluate the reliability and accuracy of the sensor data. For example, the standard deviation of the light sensor readings was calculated to assess the sensor's consistency in different lighting conditions. Similarly, the accuracy of the GPS module was evaluated by comparing the logged data against a reference GPS device, calculating the average error in position and speed. The accelerometer and gyroscope data were analyzed to detect patterns that could indicate unsafe conditions, such as sudden decelerations that might precede a fall. These statistical analyses provided a clear picture of the system's performance and highlighted areas for potential improvement.

In addition to quantitative analysis, qualitative feedback from test participants was gathered to assess the system's usability and effectiveness. Cyclists who participated in the field tests were asked to provide feedback on their experience using the smart backpack, including the responsiveness of the lighting system, the accuracy of the GPS tracking, and the comfort of the backpack during use. This feedback was analyzed to identify any usability issues that were not evident from the sensor data alone, such as difficulties in interacting with the mobile application or discomfort caused by the placement of certain components.

The combined results from the quantitative and qualitative analyses were used to refine the system and inform future development efforts. The data demonstrated that the smart backpack system was effective in enhancing cyclist safety by improving visibility, providing accurate location tracking, and responding appropriately to sudden movements. However, the analysis also revealed areas where the system could be further optimized, such as improving the energy efficiency of the LED lighting system or enhancing the user interface of the mobile application. These insights will guide future iterations of the smart backpack system, ensuring that it continues to meet the needs of urban cyclists in increasingly complex environments.

5. RESULTS AND DISCUSSION

5.1. Lighting system performance

The LED lighting system, controlled by the BH1750 light sensor, performed exceptionally well in adjusting to varying ambient light conditions. During field tests, the system consistently responded to changes in light levels, such as transitioning from daylight to tunnels or underpasses, by automatically adjusting the brightness of the LEDs. The response time of the lighting system was found to be within milliseconds, ensuring that the cyclist's visibility was maintained at all times. This real-time adjustment significantly enhanced the cyclist's visibility to other road users, especially in low-light conditions. The feedback from cyclists confirmed that the lighting system was effective in alerting drivers and pedestrians to their presence, thereby reducing the risk of accidents. However, the tests also revealed that the system's battery consumption increased significantly when operating at maximum brightness for extended periods. This finding suggests the need for further optimization of the power management system, possibly by integrating more energy-efficient LEDs or enhancing the power-saving algorithms.

5.2. GPS accuracy and tracking

The GPS module's performance was evaluated based on its ability to accurately track the cyclist's location and provide reliable navigation data. The field tests indicated that the NEO-6M GPS module maintained a high level of accuracy, with an average positional error of less than 2 meters, even in urban environments with dense buildings and trees. The GPS system was particularly effective in tracking the cyclist's route and speed, providing valuable data that was integrated with the mobile application for real-time monitoring. This level of accuracy is critical for urban cyclists who rely on precise navigation to avoid hazardous areas or plan efficient routes. Despite the overall positive results, occasional signal drops were observed in areas with very high-rise buildings or underpasses, where satellite visibility was obstructed. Addressing these limitations might involve exploring alternative positioning technologies, such as integrating inertial navigation systems (INS) to complement the GPS data and provide continuous location tracking in environments where GPS alone is insufficient.

5.3. Sensor reliability and system responsiveness

The MPU-6050 accelerometer and gyroscope module proved to be reliable in detecting sudden movements and changes in orientation, which are indicative of potential accidents or falls. The sensor data was processed in real-time by the ESP32 microcontroller, which then triggered the LED lights to flash in a specific pattern to alert nearby vehicles and pedestrians of the cyclist's emergency. The system's responsiveness was validated through a series of simulated fall tests, where the time from sensor detection to LED activation was consistently less than 200 milliseconds. This rapid response time is crucial in preventing secondary accidents by making other road users immediately aware of the cyclist's situation. However, the testing phase also highlighted the need for fine-tuning the sensitivity thresholds of the accelerometer, as some false positives were recorded during normal cycling activities, such as abrupt stops or sharp turns. These findings suggest that further calibration of the sensor thresholds could improve the system's accuracy in distinguishing between actual emergencies and normal cycling dynamics.

5.4. User experience and battery life

Feedback from test participants regarding the overall user experience was largely positive. Cyclists appreciated the system's unobtrusive design and the seamless integration of safety features that did not interfere with their riding experience. The mobile application, developed using MIT AppInventor, was praised for its intuitive interface and the real-time display of critical data such as speed, distance, and location. However, some users reported issues with Bluetooth connectivity, particularly in maintaining a stable connection between the mobile device and the ESP32 microcontroller during long rides. This issue highlights the need for further optimization of the Bluetooth communication protocols to ensure consistent performance.

Battery life tests revealed that the system could operate continuously for approximately 8 hours under typical usage conditions, which includes moderate LED usage and periodic GPS tracking. While this battery life is sufficient for most daily commutes, it may fall short for longer rides or when the system operates at full capacity, such as in consistently low-light conditions. This finding indicates the need for future improvements in power efficiency, such as incorporating a larger battery or implementing more aggressive power-saving features to extend the operational time without compromising the system's safety functions.

5.5. Discussion of overall system performance

Overall, the smart backpack system demonstrated its potential to significantly enhance urban cyclist safety through a combination of proactive safety features and real-time data integration. The LED lighting system, GPS tracking, and sensor-based hazard detection all performed reliably under various test conditions, validating the system's design and functionality. However, the testing phase also revealed areas where further refinement is necessary, particularly in power management, sensor calibration, and Bluetooth connectivity. Addressing these challenges will be critical in future iterations of the smart backpack system to ensure it meets the needs of urban cyclists in increasingly complex and demanding environments.

The positive feedback from test participants, combined with the quantitative data collected, suggests that the smart backpack system could be a valuable addition to existing cyclist safety measures. By integrating multiple technologies into a single, user-friendly device, this system offers a comprehensive solution to the challenges faced by urban cyclists, particularly in environments with high traffic density and variable lighting conditions. Future development efforts will focus on optimizing the system's performance, expanding its feature set, and conducting broader field tests to further validate its effectiveness and adaptability.

The findings of this study hold significant implications for urban cyclist safety, addressing critical challenges related to visibility, communication, and real-time hazard detection. Unlike traditional safety measures, which are predominantly reactive, the proposed smart backpack system integrates proactive technologies that dynamically adapt to environmental conditions, providing a scalable and autonomous solution for accident prevention. This research aligns with the broader scientific consensus that wearable and intelligent transportation systems can significantly enhance road safety, complementing previous studies that emphasize the importance of cyclist visibility and situational awareness. However, our results also introduce a novel approach by integrating multiple sensor-based safety mechanisms into a single, compact system, demonstrating its feasibility for large-scale urban deployment. These findings contribute to the growing body of research on smart mobility solutions, reinforcing the role of real-time data processing and adaptive safety measures in reducing cyclist vulnerability in high-traffic environments.

6. CONCLUSION

The development of the smart backpack system represents a significant advancement in the pursuit of enhanced safety for urban cyclists. Through the integration of advanced sensors, real-time data processing, and responsive LED lighting, the system addresses critical safety challenges faced by cyclists in complex urban environments. The field tests demonstrated that the system effectively improves visibility, provides accurate GPS-based tracking, and rapidly responds to potential hazards, thereby reducing the risk of accidents. The positive feedback from users further validates the system's practical applicability, highlighting its unobtrusive design and the seamless integration of safety features that do not interfere with the riding experience. However, the testing phase also identified areas for further improvement, particularly in terms of power management, sensor calibration, and Bluetooth connectivity, which will be crucial in refining the system for broader deployment.

Looking forward, the smart backpack system holds great potential for widespread adoption among urban cyclists, particularly as cities continue to evolve and the need for robust safety solutions becomes increasingly urgent. The system's modular and expandable design allows for future enhancements, such as integrating additional sensors or developing more sophisticated data analytics capabilities, to further improve its effectiveness. Moreover, the insights gained from this project provide a valuable foundation for future research and development in the field of wearable safety technology. By continuing to refine and expand upon the current design, there is potential to create a comprehensive safety solution that not only protects cyclists but also contributes to the broader goal of sustainable and safe urban mobility. Ultimately, this project underscores the importance of proactive safety measures and the role of technology in addressing the challenges faced by vulnerable road users.

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AUTHOR CONTRIBUTIONS STATEMENT

All authors reviewed and approved the final version of the manuscript.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Fredy Martínez	✓				✓				✓		✓	✓	✓	✓
Sergio Gómez		✓				✓		✓		✓				
Daniel Mejía			✓	✓		✓	✓		✓					

C : **C**onceptualization	I : **I**nvestigation	Vi : **Vi**sualization
M : **M**ethodology	R : **R**esources	Su : **Su**pervision
So : **So**ftware	D : **D**ata Curation	P : **P**roject administration
Va : **Va**lidation	O : Writing - **O**riginal Draft	Fu : **Fu**nding acquisition
Fo : **Fo**rmal analysis	E : Writing - Review & **E**diting	

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Authors state no conflict of interest.

INFORMED CONSENT

This study does not involve human participants, personal data, or identifiable individual information. Therefore, the requirement for informed consent does not apply.

ETHICAL APPROVAL

This study does not involve human participants or animal subjects. Therefore, ethical approval is not applicable.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, Fredy Martínez, upon reasonable request.

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