UPGRADE OF THE BLACK BOX SYSTEM FOR VULNERABLE SUBJECTS ON THE ROAD

Abstract

This paper presents the development and implementation of an upgraded black box system aimed at monitoring and ensuring the safety of vulnerable users on the road, primarily focusing on cyclists. The system integrates various sensors to collect data related to user conditions, environmental factors, and vehicle conditions. This iteration addresses previous limitations, including high power consumption and connectivity issues. The paper discusses the initial setup, system implementation, challenges faced, and future directions for improving the system's functionality.

*Keywords:* Black box system; Road safety; Vulnerable road users; Cyclist safety; Sensor integration; Raspberry Pi; Data collection; Environmental monitoring; Lidar technology; Ultrasonic sensors; Remote access; System architecture; Hardware integration; Real-time monitoring; Accident analysis; Data visualization; Future directions; Research methodology; Device usage method; Artificial intelligence in road safety.

1. Introduction to SOTERIA Sensory Kit

**1.1 Background**

The rising importance of road safety, especially for vulnerable road users such as cyclists, has led to the development and implementation of several technological solutions aimed at reducing accidents and fatalities. Cyclists are particularly vulnerable as they are exposed to a wide array of environmental and vehicular risks, lacking the protective barriers that shield occupants in motorized vehicles. In recent years, innovative technologies have been explored to monitor and ensure cyclist safety through data collection and analysis. Black box systems, originally developed for aviation, have increasingly been adapted for use in other forms of transport, including automobiles and bicycles, to monitor safety-related incidents and provide insights that can improve overall road safety infrastructure.

A black box system for cyclists represents a promising tool for addressing the key issues surrounding cyclist safety. By recording environmental data, cyclist behavior, and interactions with vehicles, such systems can contribute to a deeper understanding of accident causes, thus providing data-driven foundations for improved safety regulations and infrastructure development. These systems can also offer valuable information for post-accident analysis, aiding in the determination of liability and the identification of accident trends that may require further intervention.

In urban settings, cyclists face significant challenges, particularly as cities continue to prioritize motorized traffic, often at the expense of bicycle-friendly infrastructure. The introduction of black box systems provides a means of monitoring cycling conditions in real-time, generating critical data that can be utilized by city planners, safety officials, and researchers to make informed decisions regarding cyclist safety enhancements. The integration of sensors, data analytics, and wireless communication has made it possible to monitor real-time conditions that cyclists encounter on the road, creating a feedback loop that can lead to improved safety measures and interventions.

The system discussed in this paper represents an advancement in the integration of black box technology specifically designed for cyclists. This system is equipped with multiple sensors that record environmental conditions, cyclist behavior, and the presence of obstacles, thereby offering a comprehensive overview of cycling conditions. However, despite the progress in developing such systems, they are not without limitations. Sensor inaccuracies, power consumption, and real-time data transmission issues have been identified as challenges that must be addressed to enhance the efficacy and reliability of black box systems for cyclists.

**1.2 Research Problem**

While black box systems hold great potential for improving cyclist safety, several technical issues compromise their effectiveness in real-world applications. The current black box system, although innovative, faces challenges that limit its ability to reliably collect and transmit data. These challenges include sensor inaccuracies, particularly in environmental monitoring and obstacle detection, high power consumption, and issues related to data transmission delays due to poor connectivity in certain environments. The inaccuracy of environmental sensors, such as humidity and temperature sensors, can lead to unreliable data, while unshielded cables contribute to noise interference in ultrasonic sensors used for obstacle detection, resulting in false readings. Moreover, the system's power consumption, despite improvements, still poses a significant barrier to extended usage, particularly during long cycling journeys. Continuous data transmission via the Internet of Things (IoT) also strains battery life and can lead to transmission delays that impede real-time monitoring, which is crucial in preventing accidents.

The purpose of this paper is to address these technical challenges by critically evaluating the current black box system for cyclists. Through a detailed analysis of its strengths and limitations, this paper will offer practical solutions to enhance the system's reliability, efficiency, and accuracy. The overarching goal is to ensure that the black box system evolves into a robust tool that can significantly improve cyclist safety in diverse urban and rural settings.

**1.3 Objectives**

This paper aims to achieve several key objectives in its evaluation of the black box system for cyclist safety:

**Evaluation of Current System Performance:** The first objective is to conduct a thorough evaluation of the current system, detailing both its strengths and its weaknesses. This includes an in-depth analysis of the system architecture, the integration of various sensors, and the reliability of real-time data transmission.

**Identification of Key Technical Limitations:** Through the evaluation process, this paper will identify specific technical limitations that hinder the system's performance. These limitations will be explored in detail, including the causes of sensor inaccuracies, power consumption issues, and data transmission delays.

**Proposing Practical Solutions for Improvement:** Based on the identified challenges, this paper will propose technical solutions aimed at addressing each shortcoming. This will include improvements to sensor accuracy, power efficiency, and data transmission reliability. Particular emphasis will be placed on hardware modifications, such as sensor shielding and PCB (printed circuit board) design, as well as software solutions, such as data compression and hybrid data logging strategies.

**Outlining a Roadmap for Future Development:** Finally, this paper will outline a roadmap for future development to ensure that the black box system continues to evolve in line with the needs of road safety for vulnerable users. This roadmap will include recommendations for integrating emerging technologies, such as artificial intelligence (AI) and machine learning (ML), into the system to provide predictive analytics for accident prevention and personalized safety recommendations for cyclists.

**1.4 Relevance of the Study**

The relevance of this study is underscored by the growing global emphasis on sustainable and safe urban mobility. As cities increasingly prioritize non-motorized forms of transport to reduce carbon emissions and enhance public health, ensuring the safety of cyclists has become a critical concern. Cyclist fatalities and injuries remain a significant issue worldwide, with many accidents resulting from insufficient infrastructure, poor visibility, or dangerous interactions with motor vehicles. In this context, the development of advanced safety technologies, such as black box systems, represents a pivotal step toward protecting cyclists and promoting a more cyclist-friendly urban environment.

Moreover, this study addresses the technical challenges that have thus far limited the widespread adoption of black box systems for cyclists. By proposing viable solutions to these challenges, this paper seeks to contribute to the ongoing refinement of safety technologies that can be deployed in real-world cycling conditions. The integration of black box systems into transportation networks holds the potential to provide actionable insights that can lead to policy changes, infrastructure improvements, and enhanced cyclist safety education, ultimately reducing the risk of accidents and fatalities on the road.

**1.5 Structure of the Paper**

This paper is organized as follows:

* **Section 2** provides a detailed overview of the current black box system for cyclists, including its system architecture, sensor integration, and key strengths.
* **Section 3** discusses the shortcomings and technical challenges of the system, focusing on sensor inaccuracies, power consumption, and data transmission delays.
* **Section 4** proposes solutions to the identified challenges, including hardware and software modifications, to improve system performance.
* **Section 5** outlines the implementation approach for the proposed solutions, detailing the necessary hardware and software upgrades.
* **Section 6** describes the testing and validation methods that will be employed to assess the effectiveness of the proposed improvements.
* **Section 7** concludes the paper with a summary of the findings and recommendations for future work, focusing on enhancing the reliability and efficiency of the black box system for cyclist safety.

1. State of the art Methodological approach

The current black box system designed for cyclists is an advanced configuration that integrates multiple sensors and processing units, enabling the collection and analysis of environmental and performance data in real time. This system is based on a modular architecture, with components chosen for their ability to handle diverse data streams, process information efficiently, and communicate wirelessly. The system is designed not only to capture a comprehensive range of data but also to transmit this data to cloud-based platforms for real-time monitoring and analysis. In this section, the key components and architecture of the system are examined in detail, followed by an assessment of its operational strengths and the benefits it offers to cyclist safety.

**2.1 System Architecture**

At the heart of the black box system for cyclists is the Portenta H7 microcontroller, a high-performance processing unit chosen for its low power consumption, processing capabilities, and compatibility with various sensor modules. The Portenta H7 acts as the central hub of the system, interfacing with several key sensors that capture a variety of data points critical to understanding a cyclist's interaction with their environment. These sensors include the Nicla Sense Me, a compact environmental sensor that monitors air quality, temperature, and humidity, and ultrasonic sensors for obstacle detection. These sensors communicate with the Portenta H7 via Bluetooth Low Energy (BLE), enabling the system to reduce wiring complexity and energy consumption.

The integration of Global Navigation Satellite System (GNSS) technology is another critical aspect of the system’s architecture. The system employs the MAX-MQ8 GNSS module, which offers multi-constellation satellite support, including GPS, GLONASS, Galileo, and BeiDou. This allows the system to provide highly accurate location data, a crucial feature for both real-time safety monitoring and post-incident analysis. The GNSS module is connected to the Portenta H7 via a serial communication protocol, which ensures low-latency transmission of location data. Additionally, the system uses a portable router to connect to the internet, enabling real-time data uploads to a cloud platform. This allows for continuous monitoring of the cyclist’s environment and performance, as well as the ability to store data for post-ride analysis.

Power is supplied by a high-capacity portable power bank, which is essential for ensuring the system's operation during extended periods of use. The portability of the power bank allows it to be easily mounted on the cyclist's bike or person, ensuring that the system remains operational over long distances and through varying environmental conditions. Power management is a key design consideration, as the system is intended to function for extended periods without requiring frequent recharges. The shift from the previously used Raspberry Pi to the Portenta H7 has significantly improved power efficiency, allowing the system to draw less current while maintaining high processing performance.

One of the core functionalities of the black box system is obstacle detection, which is achieved through the use of ultrasonic sensors. These sensors, which are directly connected to the Portenta H7, are tasked with detecting objects in the cyclist’s path, providing crucial data that could help in preventing collisions. The system is designed to read data from five ultrasonic sensors in intervals of 10 milliseconds, ensuring timely detection of obstacles. The data from these sensors is processed by the Portenta H7 and can be transmitted to the cloud for further analysis, allowing for the detection of potentially hazardous situations in real time.

In addition to environmental and obstacle data, the system collects data on cyclist behaviour and movements using an accelerometer and gyroscope. These sensors are integrated into the Nicla Sense Me module and are capable of detecting changes in speed, orientation, and stability. This information is vital for understanding the cyclist’s behaviour in different riding conditions and can be used to identify potential safety issues, such as sudden swerves or falls.

Once all the data is collected by the various sensors and processed by the Portenta H7, it is transmitted to a cloud-based platform via a portable router. The system’s internet connectivity allows for real-time data uploads, ensuring that the data can be accessed remotely by users, researchers, or authorities. The cloud platform provides tools for visualizing the data and analysing trends, which can be instrumental in improving road safety measures for cyclists. Data transmission occurs at intervals determined by the strength of the internet connection, with a typical upload time of approximately one second. This allows for near real-time monitoring of the cyclist's environment and behaviour, although certain delays may occur due to network limitations.

**2.2 Strengths of the Current System**

The current black box system for cyclists boasts several key strengths that make it an effective tool for improving road safety. One of its most significant strengths is the comprehensive data collection enabled by its integration of multiple sensors. By combining data from environmental sensors, accelerometers, gyroscopes, ultrasonic sensors, and GNSS modules, the system can provide a detailed picture of the cyclist’s environment and behaviour. This data is invaluable for both post-accident analysis and the implementation of preventive safety measures. The inclusion of real-time data collection and transmission capabilities ensures that the system can be used to monitor cyclists continuously, providing immediate insights into their safety conditions.

Another strength of the system is its efficient use of power. The decision to replace the high-power-consuming Raspberry Pi with the Portenta H7 has reduced the system's overall power draw, allowing it to operate for extended periods on a single charge. This is particularly important for cyclists who engage in long-distance rides, as it ensures that the system will remain operational throughout their journey without the need for frequent recharges. Furthermore, the low-power design of the GNSS module and other sensors helps to extend the system’s operational lifespan, making it more practical for real-world use.

The system’s accurate location tracking, enabled by the MAX-MQ8 GNSS module, is another significant advantage. This module supports multiple satellite constellations, ensuring that the system can maintain accurate positioning even in challenging environments, such as urban areas with tall buildings that can obstruct satellite signals. The GNSS module’s high sensitivity and fast time-to-first-fix (TTFF) further enhance its reliability, allowing the system to quickly acquire and maintain a strong satellite signal.

The system’s real-time data transmission capability is also a critical strength. By leveraging IoT technologies, the system can upload data to the cloud in real time, providing continuous monitoring of cyclist safety. This real-time capability is particularly useful for emergency response situations, as it allows for immediate access to critical data following an accident. The system’s cloud connectivity also enables remote access to the data, allowing for collaboration between cyclists, city planners, researchers, and road safety authorities to improve overall road safety measures.

Another notable strength of the system is its modularity and scalability. The use of BLE for sensor communication and the inclusion of a portable router for internet connectivity make the system highly adaptable. It can be easily upgraded with new sensors or additional features without requiring a complete redesign of the system’s architecture. This modularity is essential for ensuring that the system remains relevant as new safety technologies and protocols are developed.

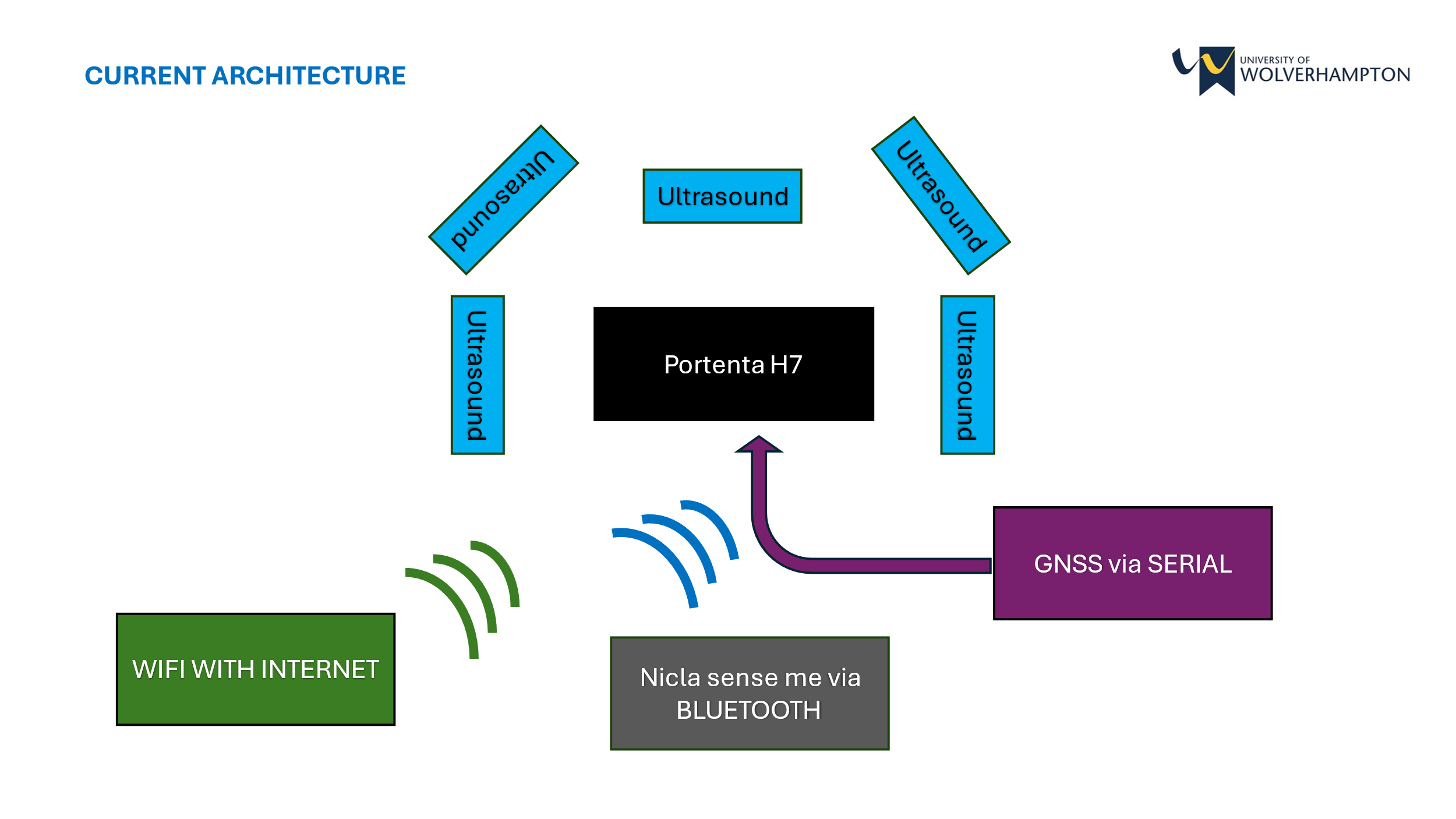
Finally, the system’s data visualization and analysis capabilities provide users with a powerful tool for interpreting the collected data. The cloud-based platform allows for the generation of detailed reports and visualizations that can highlight trends in cyclist behaviour, environmental conditions, and obstacle detection. This information can be used to inform policy decisions, improve cycling infrastructure, and develop targeted safety campaigns aimed at reducing accidents involving cyclists.

**2.3 Limitations in Real-World Use**

Despite its strengths, the current system faces several limitations that need to be addressed to improve its performance in real-world conditions. For instance, while the system’s ultrasonic sensors are effective in detecting obstacles under ideal conditions, they can suffer from inaccuracies in outdoor environments, particularly in situations where there is significant noise interference. This issue is exacerbated by the use of unshielded cables, which are prone to picking up electrical noise, leading to false readings. Additionally, the system’s reliance on continuous data transmission via IoT can result in delays if the internet connection is weak or unstable, reducing its effectiveness in providing real-time monitoring during critical moments.

Another limitation is the occasional inaccuracy of the environmental sensors, particularly with respect to humidity and temperature readings. These sensors have been known to provide false readings at the beginning of the system’s operation, which can compromise the reliability of the data. Additionally, temperature fluctuations due to internal heat generated by the system's components can further distort the readings, particularly during long periods of use.

In summary, while the current black box system for cyclists offers a range of strengths, including comprehensive data collection, power efficiency, accurate location tracking, and real-time monitoring, there are still challenges that must be addressed to optimize its performance in real-world conditions. These challenges, particularly in sensor accuracy and data transmission, will be explored further in subsequent sections, where technical solutions and potential improvements will be proposed.



1. Shortcomings and Technical Challenges  
   While the black box system for cyclists offers significant potential for improving road safety, particularly through its integration of multiple sensors and real-time data transmission, several technical shortcomings hinder its full effectiveness. These challenges primarily revolve around sensor inaccuracies, power consumption, and data transmission delays. Addressing these issues is crucial for ensuring that the system can reliably operate in diverse real-world conditions and deliver the accurate, real-time data required for accident prevention and post-incident analysis.

**3.1 Sensor Inaccuracies**

The performance of the system's sensors is central to its functionality, yet sensor inaccuracies represent a persistent issue, particularly in the areas of environmental monitoring and obstacle detection. These inaccuracies undermine the reliability of the data collected and reduce the system’s ability to provide timely, accurate information in critical situations.

**3.1.1 Environmental Sensors**

The system’s environmental sensors, which monitor factors such as air quality, temperature, and humidity, are susceptible to inaccuracies that compromise data quality. One notable issue arises with the humidity sensor, which has been observed to report false readings, especially during the initial stages of the system's operation. These inaccuracies may be the result of sensor calibration issues or environmental noise that interferes with the sensor’s operation. Humidity data is particularly prone to showing unreliable values at the beginning of a cycling journey, which can distort the overall dataset and make it difficult to use the information for real-time monitoring or long-term analysis.

Similarly, the system’s temperature sensor has been noted to fluctuate, particularly when the internal components of the system generate heat. The enclosure housing the system’s components can lead to a build-up of heat, which in turn affects the temperature sensor’s readings. These temperature variations do not always reflect the actual external environment, which is the primary focus of the sensor. This problem not only affects the accuracy of real-time temperature monitoring but also undermines the integrity of long-term datasets that rely on consistent sensor performance.

**3.1.2 Obstacle Detection**

In terms of obstacle detection, the black box system relies on ultrasonic sensors to identify potential hazards in the cyclist's path. These sensors, while useful in controlled environments, often struggle with reliability in outdoor settings. The main issue stems from the use of unshielded cables to connect the ultrasonic sensors to the Portenta H7 processing unit. Unshielded cables are particularly vulnerable to electrical noise interference, which can lead to false readings or the failure to detect obstacles accurately. This is a critical limitation, as obstacle detection is a key feature intended to help cyclists avoid collisions with vehicles or other objects.

In outdoor environments, particularly those with high levels of ambient noise or electromagnetic interference, the sensors can produce erratic readings, misidentifying obstacles or failing to detect them altogether. This compromises the system’s ability to provide accurate, real-time feedback to cyclists about their surroundings, which is vital for accident prevention.

**3.2 Power Consumption and Efficiency**

Despite improvements in power efficiency through the replacement of the Raspberry Pi with the Portenta H7, the system still faces significant challenges related to power consumption, particularly when it comes to sustaining long-term operations. While the system's power bank allows for portability and extended use, the continuous data transmission to the IoT platform, especially during long cycling journeys, places a heavy demand on battery life. As the system constantly transmits data, the power consumption remains high, which reduces the operational lifespan of the system and necessitates frequent recharging.

This limitation is particularly problematic for cyclists engaged in long-distance travel, where maintaining power over extended periods is crucial. If the system's power is depleted mid-journey, not only is real-time monitoring lost, but critical data related to the latter part of the journey may also be unavailable for post-ride analysis. This diminishes the effectiveness of the black box system as a continuous safety and data collection tool.

Although the shift to the Portenta H7 has yielded improvements in power efficiency, there is still a need for further optimization to ensure that the system can function effectively over long durations. The absence of power-saving features, such as sleep modes for sensors not in active use, further exacerbates the system’s power consumption issues. Incorporating power-saving techniques could extend the battery life and ensure the system remains operational for longer periods.

**3.3 Connectivity and Data Transmission Delays**

One of the core strengths of the black box system is its ability to transmit data in real-time via IoT to a cloud platform. However, in practice, this capability is often hindered by connectivity issues and data transmission delays. The system experiences delays of up to one second in transmitting data to the cloud, which can be significant in time-sensitive situations, such as when a cyclist is in imminent danger.

The primary cause of these delays is the dependence on internet connectivity, which can fluctuate based on the cyclist’s location. In urban environments with strong and stable internet connections, the system performs adequately. However, in areas with poor or intermittent connectivity, such as rural roads or areas with significant signal interference, the system’s real-time monitoring capabilities are compromised. These connectivity issues result in delayed uploads to the cloud, meaning that the data is not always available for immediate analysis. This delay can prove critical in situations where real-time data is needed for emergency response or to prevent an accident.

Moreover, the system’s reliance on continuous data transmission, rather than local data storage, exacerbates these issues. In the event of connectivity loss, there is a risk that data may be lost or delayed, which reduces the overall reliability of the system.

In summary, the black box system for cyclists, while innovative and capable of delivering valuable data, is constrained by several technical challenges. Sensor inaccuracies, particularly in environmental monitoring and obstacle detection, diminish the reliability of the data collected. Power consumption remains a critical issue, limiting the system’s operational lifespan during long cycling journeys. Additionally, connectivity issues and data transmission delays hinder the system’s ability to provide real-time monitoring, particularly in areas with poor internet connectivity. These challenges highlight the need for further improvements to ensure that the system can operate reliably and efficiently in real-world conditions.

4. Possible Solution Implementation

The current black box system for cyclists, while offering significant potential for enhancing road safety, faces several key technical challenges that limit its full effectiveness. These include sensor inaccuracies, power consumption inefficiencies, and data transmission delays. To address these issues, a comprehensive approach that incorporates both hardware and software improvements is essential. This section proposes several solutions aimed at mitigating these challenges, thereby optimizing the system’s performance in real-world conditions. Each proposed solution is grounded in both theoretical concepts and practical applications, ensuring the system can function reliably and efficiently while providing real-time safety benefits to cyclists.

**4.1 Improving Sensor Accuracy**

One of the most critical areas requiring improvement in the black box system is sensor accuracy, particularly in environmental monitoring and obstacle detection. As discussed in previous sections, the humidity and temperature sensors tend to report false or fluctuating readings, especially during the system's initial operation, and the ultrasonic sensors used for obstacle detection are prone to inaccuracies due to electrical noise interference. These sensor issues must be addressed to ensure the system can reliably collect accurate data under a variety of conditions.

**4.1.1 Calibration and External Placement of Environmental Sensors**

Sensor calibration is a well-established method for improving the accuracy of sensor readings. Calibration involves comparing sensor outputs with known reference values and adjusting the sensor's algorithm or hardware configuration to ensure it produces accurate data. In the context of the black box system, recalibrating the humidity and temperature sensors prior to deployment can help mitigate false readings, especially during the system's initial operation. This recalibration process would involve subjecting the sensors to a range of controlled environmental conditions and adjusting their response to match known values.

However, recalibration alone may not be sufficient to address all sensor inaccuracies, particularly those caused by the build-up of heat inside the system’s enclosure. The internal heat generated by the processing unit and other components can lead to distorted temperature readings, as the sensor detects the heat from within the enclosure rather than the external environment. To solve this issue, it is proposed that the environmental sensors be placed outside the main enclosure, in a position where they are directly exposed to the external atmosphere. By isolating the sensors from the internal heat sources, the system can ensure that the readings reflect actual external conditions rather than internal temperature fluctuations.

Additionally, the implementation of more sophisticated sensors with higher sensitivity and faster response times could further improve the accuracy of the environmental data. Advanced humidity and temperature sensors with better resolution and accuracy would be less prone to the fluctuations that have been observed in the current system, especially in the early stages of operation. These sensors are available in the market, offering low power consumption and small form factors, making them suitable for integration into the black box system without significantly increasing power consumption or system size.

**4.1.2 Shielding and PCB Design for Obstacle Detection**

The issue of false readings in the system’s obstacle detection capabilities is largely due to the unshielded cables used to connect the ultrasonic sensors to the processing unit. These unshielded cables are highly susceptible to electrical noise interference, which can distort the signals sent between the sensors and the processing unit, leading to inaccurate or unreliable data. This issue is especially problematic in outdoor environments, where varying levels of electromagnetic interference (EMI) from power lines, vehicles, or even other electronic devices can further exacerbate the problem.

To address this challenge, it is recommended that the cables connecting the ultrasonic sensors be shielded. Shielding involves encasing the cables in conductive material that can block or attenuate external electromagnetic signals, thus preventing them from interfering with the sensor's data transmission. Shielded cables are commonly used in environments where data integrity is critical, such as industrial automation and telecommunications. By implementing high-quality shielded cables in the black box system, the accuracy of the ultrasonic sensors can be significantly improved, reducing the likelihood of false readings due to EMI.

In addition to shielding the cables, transitioning to a printed circuit board (PCB) design that integrates the sensors directly into the board could further enhance signal integrity. A well-designed PCB can minimize the length of the connections between components, reducing the potential for electrical noise to interfere with sensor signals. Additionally, PCBs can be designed with specific layers dedicated to grounding and noise reduction, which can help filter out unwanted signals and improve overall system stability. PCB designs also offer the advantage of compactness, which could help reduce the overall size and weight of the black box system, making it more practical for cyclists.

By combining shielding with a robust PCB design, the system’s obstacle detection capabilities can be significantly enhanced. The ultrasonic sensors will be able to reliably detect obstacles in the cyclist's path, providing accurate and timely feedback to the cyclist, which is crucial for accident prevention.

**4.2 Optimizing Power Consumption**

Power consumption remains one of the most significant challenges for the black box system, particularly in scenarios where cyclists are engaged in long-distance rides. The system’s reliance on continuous data transmission via IoT, along with the power demands of its various sensors and processing units, places a heavy burden on the portable power bank, reducing the system’s operational lifespan. To address this issue, a multi-pronged approach is proposed that includes the implementation of power-saving techniques, the incorporation of energy-harvesting technologies, and the optimization of system components for lower power consumption.

**4.2.1 Implementation of Sleep Modes**

One of the most effective ways to reduce power consumption in electronic systems is through the use of sleep modes. Sleep modes allow components that are not actively in use to enter a low-power state, reducing their energy consumption while maintaining the ability to quickly resume full operation when needed. This approach is widely used in mobile devices, embedded systems, and other battery-powered applications to extend battery life without compromising performance.

In the context of the black box system, sleep modes could be applied to several components, including the GNSS module and the environmental sensors. For example, the GNSS module could switch to a low-power mode when the cyclist is stationary, as there would be no need to continuously update location data in this state. Similarly, the environmental sensors could enter a low-power state when the cyclist is in a stable environment where significant changes in temperature or humidity are unlikely to occur. These sleep modes could be automatically managed by the Portenta H7 processing unit, which would activate or deactivate components based on real-time data and system needs.

Additionally, the Portenta H7 itself is capable of entering various low-power states, which could further reduce the system’s overall power consumption. The Portenta H7 supports dynamic voltage and frequency scaling (DVFS), a technique that adjusts the power consumption of the processing unit based on the current workload. By dynamically reducing the clock speed and voltage of the processor during periods of low activity, the system can conserve power without compromising its ability to perform critical tasks when needed.

**4.2.2 Energy Harvesting Technologies**

Another promising solution for extending the operational lifespan of the black box system is the incorporation of energy-harvesting technologies. Energy harvesting refers to the process of capturing and converting ambient energy from the environment into usable electrical energy, which can be used to supplement or recharge the system’s power supply. This approach is particularly attractive for applications where access to conventional power sources is limited, such as in portable or wearable electronics.

In the case of the black box system, solar panels could be integrated into the cyclist’s helmet or bike frame to capture solar energy and convert it into electrical power. Advances in photovoltaic technology have made it possible to develop lightweight, flexible solar panels that can be seamlessly integrated into various surfaces without adding significant weight or bulk. These solar panels could be used to recharge the power bank during daylight hours, extending the system’s operational time and reducing the need for frequent manual recharging.

Additionally, kinetic energy harvesting is another option that could be explored. Kinetic energy harvesters convert mechanical energy from movement into electrical energy. In the context of cycling, the pedaling motion or vibrations from the road surface could be used to generate electricity, which could then be stored in the power bank or used to directly power the system. While the amount of energy generated from kinetic harvesting may be relatively small, it could provide a useful supplementary power source that reduces the overall drain on the battery.

**4.2.3 Optimization of System Components**

Beyond implementing sleep modes and energy-harvesting technologies, further power optimization can be achieved by selecting more energy-efficient components and optimizing the system’s overall design. The transition from the Raspberry Pi to the Portenta H7 has already yielded significant improvements in power consumption, but additional gains can be made by refining the selection of sensors and other peripheral components.

For instance, the use of ultra-low-power sensors that consume minimal energy during operation could help reduce the system's overall power draw. Many modern environmental sensors are designed specifically for battery-powered applications and feature power consumption rates as low as a few microamps during active operation. By selecting sensors that prioritize energy efficiency, the system can maintain its functionality while significantly reducing its power requirements.

Furthermore, the software running on the Portenta H7 could be optimized to minimize unnecessary power consumption. This includes optimizing data acquisition routines, reducing the frequency of sensor polling when environmental conditions are stable, and minimizing the amount of data processed and transmitted. Efficient software algorithms can significantly reduce the system’s workload, allowing it to operate more efficiently while conserving power.

**4.3 Enhancing Data Transmission Efficiency**

The ability to transmit data in real-time is one of the black box system’s key features, but as noted earlier, connectivity issues and data transmission delays can hinder its effectiveness, particularly in areas with poor or intermittent internet connectivity. To address this issue, several solutions are proposed to enhance the system’s data transmission efficiency, including the implementation of a hybrid data logging approach, the use of data compression algorithms, and the integration of more robust communication protocols.

**4.3.1 Hybrid Data Logging Approach**

One of the primary challenges with continuous data transmission is the reliance on stable internet connectivity. In situations where the cyclist is traveling through areas with weak or no connectivity, the system may experience delays in uploading data to the cloud, resulting in gaps in the data that can compromise both real-time monitoring and post-incident analysis. To mitigate this issue, a hybrid data logging approach is proposed.

In a hybrid data logging system, data is stored locally on a secure digital (SD) card in addition to being transmitted to the cloud. This ensures that, even if the internet connection is lost, the system continues to log all data locally without interruption. Once the internet connection is restored, the locally stored data can be uploaded to the cloud, ensuring that no data is lost due to connectivity issues. This approach allows the system to maintain full data integrity while still benefiting from the advantages of real-time monitoring when connectivity is available.

Additionally, the hybrid approach offers the flexibility to adjust the frequency of cloud uploads based on the strength of the internet connection. In areas with strong connectivity, data can be uploaded frequently to support real-time monitoring. In areas with poor connectivity, data uploads can be delayed until a stronger connection is available, reducing the likelihood of transmission delays and data loss.

**4.3.2 Data Compression Algorithms**

Another solution to improve data transmission efficiency is the implementation of data compression algorithms. Data compression involves reducing the size of the data being transmitted by encoding it in a more compact form. Compression can significantly reduce the bandwidth required for data transmission, which is particularly useful in situations where the internet connection is weak or slow.

In the context of the black box system, data compression could be applied to the sensor data before it is transmitted to the cloud. For example, sensor readings that do not change significantly over time (such as stable temperature or humidity readings) could be compressed by storing only the changes rather than transmitting the same data repeatedly. Additionally, compression techniques such as Huffman coding or run-length encoding could be used to reduce the size of the data packets, making transmission more efficient and reducing the overall load on the system’s communication channels.

By compressing the data before transmission, the system can reduce the likelihood of transmission delays and minimize the amount of data lost due to weak or intermittent connectivity. This approach is particularly useful in scenarios where the system is operating in rural or remote areas, where internet connectivity may be less reliable.

**4.3.3 Robust Communication Protocols**

To further enhance data transmission efficiency, the system could be upgraded to use more robust communication protocols that are better suited to dealing with fluctuating network conditions. For example, message queuing telemetry transport (MQTT) is a lightweight messaging protocol designed for constrained devices and low-bandwidth, high-latency networks. MQTT is particularly well-suited for IoT applications, as it is optimized for real-time data transmission while minimizing the overhead required for communication.

In the black box system, MQTT could be used to transmit sensor data to the cloud in a more efficient and reliable manner. The protocol's publish-subscribe architecture allows for more flexible data transmission, ensuring that data is transmitted only when necessary and minimizing unnecessary bandwidth usage. Furthermore, MQTT supports quality of service (QoS) levels that can be tailored to the system’s specific needs. For example, a higher QoS level could be used to ensure that critical safety data is reliably delivered, even in the event of network disruptions.

Additionally, the system could benefit from using error-correcting codes (ECC) to enhance the reliability of data transmission. ECCs are mathematical algorithms that add redundancy to transmitted data, allowing the receiver to detect and correct errors that may occur during transmission. This can significantly improve the reliability of data transmission, especially in noisy or unreliable communication environments. By implementing ECCs, the black box system can reduce the likelihood of data corruption or loss during transmission, ensuring that the data received by the cloud platform is accurate and complete.

**4.4 AI and Predictive Analytics for Accident Prevention**

One of the most promising directions for the future development of the black box system is the integration of artificial intelligence (AI) and machine learning (ML) algorithms. AI-driven systems have the potential to analyze sensor data in real-time, identifying patterns and behaviors that may indicate a heightened risk of accidents. By leveraging predictive analytics, the system could alert cyclists or connected infrastructure to potential dangers before an accident occurs, significantly enhancing cyclist safety.

**4.4.1 Real-Time Data Analysis Using AI**

AI algorithms are particularly well-suited to analyzing large, complex datasets in real-time. In the context of the black box system, AI could be used to process data from the various sensors and identify patterns associated with risky behaviors or hazardous environmental conditions. For example, the AI system could monitor accelerometer and gyroscope data to detect sudden changes in speed or orientation, which may indicate that the cyclist is swerving or losing control. Similarly, AI could analyze ultrasonic sensor data to identify obstacles that pose an imminent threat to the cyclist’s safety.

By processing this data in real-time, the AI system could provide immediate feedback to the cyclist, alerting them to potential dangers and recommending corrective actions. For example, if the system detects that the cyclist is approaching a hazardous intersection or a vehicle is rapidly approaching from behind, it could issue an audible or visual warning, giving the cyclist time to adjust their behavior and avoid an accident.

Additionally, AI could be used to analyze historical data collected by the black box system, identifying trends and patterns that may not be immediately apparent through manual analysis. For example, the AI system could identify recurring environmental factors or behaviors that are consistently associated with accidents, allowing for targeted interventions aimed at mitigating these risks.

**4.4.2 Personalized Safety Recommendations**

Another key advantage of AI is its ability to adapt to individual users. By analyzing data from a specific cyclist over time, the AI system could learn their unique riding patterns and behaviors, allowing it to provide personalized safety recommendations. For example, if the AI system detects that a particular cyclist tends to ride at high speeds through busy intersections, it could issue personalized warnings or suggest alternative routes that are safer.

Personalized safety recommendations could also be tailored to the cyclist’s environment. For example, the system could provide warnings about specific road hazards based on real-time environmental data, such as poor visibility due to fog or icy conditions on the road. These personalized alerts could help cyclists make more informed decisions about their riding behavior, reducing the risk of accidents.

**4.4.3 Machine Learning for Continuous Improvement**

Machine learning (ML), a subset of AI, offers the potential for continuous improvement in the black box system’s accident prevention capabilities. ML algorithms can be trained on large datasets of cycling behavior and accident data, allowing them to improve their predictive accuracy over time. As the system collects more data from cyclists in real-world conditions, the ML models can be continuously refined, making the system increasingly adept at identifying risky behaviors and predicting accidents.

One potential application of ML in the black box system is the development of predictive models that can forecast the likelihood of an accident based on real-time data inputs. For example, an ML model could be trained to predict the probability of a collision based on factors such as the cyclist’s speed, proximity to obstacles, and road conditions. If the system detects that the probability of an accident exceeds a certain threshold, it could issue a warning to the cyclist, allowing them to take preventive action before the accident occurs.

Furthermore, ML algorithms could be used to adapt the system’s safety recommendations based on feedback from cyclists. For example, if cyclists consistently respond positively to certain types of warnings (e.g., slowing down when warned about obstacles), the system could prioritize those warnings in future interactions. Conversely, if certain warnings are frequently ignored, the system could adjust its algorithms to make the warnings more effective.

In conclusion, the proposed solutions for addressing the technical challenges of the black box system for cyclists are comprehensive and multi-faceted. By improving sensor accuracy through calibration, shielding, and PCB design, the system can provide more reliable data. Power consumption can be optimized through the use of sleep modes, energy-harvesting technologies, and more efficient components. Data transmission efficiency can be enhanced through hybrid data logging, data compression, and robust communication protocols. Finally, the integration of AI and predictive analytics offers the potential to transform the system into a proactive tool for accident prevention, providing real-time alerts and personalized safety recommendations to cyclists.

These proposed solutions, when implemented, will significantly enhance the reliability, efficiency, and overall performance of the black box system, making it a more effective tool for improving cyclist safety in diverse real-world environments.

1. Implementation Approach

The proposed solutions outlined in the previous section provide a comprehensive framework for addressing the technical challenges currently faced by the black box system for cyclists. However, the successful realization of these improvements depends on careful planning and execution across both hardware and software domains. This section will delve into the practical implementation strategies required to enhance sensor accuracy, optimize power consumption, improve data transmission, and integrate artificial intelligence (AI) for predictive analytics. By mapping out the necessary steps, this section aims to provide a clear roadmap for upgrading the system and ensuring that it meets the evolving needs of cyclist safety.

**5.1 Hardware Modifications**

The proposed hardware modifications play a crucial role in addressing sensor inaccuracies, power inefficiencies, and the limitations in obstacle detection. To implement these changes, careful attention must be paid to the selection of components, redesign of the system’s architecture, and testing of new configurations in real-world environments.

**5.1.1 Sensor Calibration and External Placement**

One of the first hardware modifications involves recalibrating the system's environmental sensors and placing them outside the main enclosure. Sensor calibration can be accomplished by subjecting the sensors to a range of controlled environmental conditions in a laboratory setting. For instance, the temperature and humidity sensors can be exposed to known conditions using climate control equipment. This allows the system to establish reference points and fine-tune the sensors’ response curves to minimize inaccuracies. Once recalibrated, these sensors will need to be placed in locations that minimize the influence of internal heat generated by the system's components.

The physical placement of sensors can be achieved by redesigning the enclosure to accommodate external mounts for the temperature and humidity sensors. For example, a small extension or port on the enclosure can be used to house the sensors, ensuring they remain shielded from environmental hazards such as rain or debris while still maintaining exposure to external atmospheric conditions. The redesign must also account for the mechanical stability of the sensors during the cyclist's ride, ensuring that vibrations or shocks do not negatively impact sensor performance.

**5.1.2 Shielded Cables and PCB Redesign for Ultrasonic Sensors**

To address the issue of inaccurate obstacle detection due to noise interference, it is crucial to implement shielded cables for the ultrasonic sensors. These cables can be sourced from suppliers that specialize in noise-resistant materials, which include conductive shields to block electromagnetic interference. In practice, the system’s wiring should be replaced with shielded alternatives, ensuring that all connections between the ultrasonic sensors and the Portenta H7 processing unit are properly insulated from external electrical noise sources.

Additionally, transitioning to a printed circuit board (PCB) design will further enhance the reliability of data transmission from the sensors. The PCB design process should focus on minimizing the length of signal paths between components, as shorter paths reduce the likelihood of signal degradation. Moreover, incorporating dedicated ground planes into the PCB design will help shield sensitive components from noise interference. Advanced PCB design software, such as Altium Designer or KiCad, can be used to model and simulate the board layout before fabrication, ensuring optimal performance.

Once the PCB is fabricated, the system can be assembled and tested in both laboratory and field conditions to verify that the shielded cables and new PCB design have eliminated the sensor inaccuracies. This testing will involve subjecting the system to various noise sources (such as those found in urban environments) to confirm that the ultrasonic sensors reliably detect obstacles without producing false readings.

**5.1.3 Integration of Energy Harvesting Technologies**

To extend the system's operational lifespan, the integration of energy-harvesting technologies—such as solar panels and kinetic energy harvesters—will be a key focus. The implementation begins with selecting appropriate photovoltaic (solar) panels, which should be lightweight and flexible enough to be mounted on the cyclist's helmet or bike frame. These panels can be sourced from manufacturers that specialize in portable and flexible solar technologies, such as PowerFilm or SunPower.

The next step involves integrating the solar panels into the power supply system. This requires connecting the panels to a power management module capable of regulating the input from solar energy and directing it to the system's battery. The module must handle varying sunlight conditions and ensure that excess energy is stored in the power bank for later use. Testing will be required to ensure that the solar panels provide a meaningful extension to the battery life under typical cycling conditions, particularly during long rides in daylight hours.

Kinetic energy harvesters, which convert mechanical energy from the cyclist’s movements into electrical power, can also be integrated. These harvesters can be mounted on the bike’s wheels or frame, capturing energy from pedaling or road vibrations. Similar to the solar panels, the harvested energy will be directed to the power management module. While kinetic harvesters tend to generate smaller amounts of power compared to solar panels, they provide an additional source of energy, particularly useful in cloudy or low-light conditions.

**5.2 Software and AI Integration**

In addition to the hardware upgrades, implementing the proposed software enhancements and AI-driven analytics is vital for optimizing data transmission and enhancing the system's predictive safety capabilities. This will involve both the development of new software algorithms and the integration of machine learning models that can process data in real-time to identify potential safety risks.

**5.2.1 Implementing Sleep Modes and Power-Saving Algorithms**

One of the most effective ways to reduce power consumption in the black box system is to implement software-driven power-saving algorithms that place system components into low-power sleep modes when they are not in use. This implementation begins with identifying the components that can be powered down during periods of inactivity, such as the GNSS module when the cyclist is stationary or the environmental sensors when conditions remain stable.

The software running on the Portenta H7 processing unit can be modified to dynamically manage the power states of the system's components. Using built-in power management libraries (such as Arduino’s Low Power library for microcontrollers), the system can monitor its operational state and automatically trigger sleep modes when possible. For example, the software could periodically check the cyclist’s speed and, if the cyclist is stationary for more than a few seconds, place the GNSS module into a low-power state until movement resumes.

Another critical aspect of power-saving algorithms involves optimizing data polling intervals. For components such as environmental sensors, reducing the frequency of sensor readings when environmental conditions are stable can reduce unnecessary power consumption. The software should be programmed to adjust the polling frequency dynamically based on real-time conditions, ensuring that the system only collects data when significant changes occur.

**5.2.2 Hybrid Data Logging and Data Compression**

To address the challenges of data transmission delays and connectivity issues, the implementation of a hybrid data logging system is essential. This will require modifying the system’s software to store data locally on an SD card when internet connectivity is weak or unavailable, ensuring no data is lost. The software should be capable of detecting the status of the internet connection and seamlessly switching between real-time data uploads and local storage when necessary.

The stored data can then be uploaded to the cloud once the connection is re-established. This requires implementing an efficient file transfer protocol to minimize bandwidth usage during large data uploads. Protocols such as MQTT (Message Queuing Telemetry Transport), which is designed for low-bandwidth IoT applications, can be integrated into the software to handle data uploads efficiently.

In addition, data compression algorithms will be implemented to reduce the size of the transmitted data packets. These algorithms can be based on well-established compression techniques such as Huffman coding or run-length encoding, which compresses repeated or stable sensor readings into smaller data segments. The implementation of compression will help reduce the bandwidth required for data transmission, improving the system's performance in areas with limited internet connectivity.

**5.2.3 AI and Predictive Analytics**

The integration of AI and machine learning into the black box system represents a significant step forward in enhancing its predictive safety capabilities. This implementation will involve both real-time data analysis and the development of machine learning models that can identify patterns in the cyclist’s behavior or the surrounding environment that may indicate a potential accident.

First, the system’s software must be updated to collect and process the necessary data for AI analysis. This includes real-time data from the accelerometer, gyroscope, and ultrasonic sensors, which can be fed into an AI model designed to detect risky behaviors such as sudden swerves or rapid deceleration. The AI model could be trained using a dataset of known cycling behaviors and accident scenarios, allowing it to predict the likelihood of an accident based on current conditions.

Once trained, the AI model can be deployed on the Portenta H7 processing unit or on the cloud platform, depending on the available processing power. For real-time applications, the model should run locally on the Portenta H7, ensuring that immediate feedback can be provided to the cyclist in the form of audible or visual alerts. These alerts could be triggered when the system detects behaviors or environmental conditions that significantly increase the risk of an accident, giving the cyclist the opportunity to adjust their riding behavior.

The system should also be designed to continually update and improve the AI model based on new data collected during rides. By incorporating machine learning algorithms capable of self-improvement, the system can become more adept at identifying potential safety risks over time. This continuous learning approach will ensure that the black box system remains effective as cyclists encounter new and varied conditions on the road.

**5.3 Testing and Validation**

After implementing the proposed hardware and software upgrades, rigorous testing and validation must be conducted to ensure the system functions as intended. Testing will occur in both laboratory and real-world settings, with a focus on validating sensor accuracy, power efficiency, data transmission reliability, and AI-driven safety alerts.

Initial testing should occur in controlled environments, where the performance of individual components can be closely monitored. For instance, the new environmental sensor placements and recalibrations can be tested in a climate-controlled chamber to ensure accurate readings across a range of temperatures and humidity levels. Similarly, the obstacle detection system can be tested in a noise-controlled environment to verify that the shielded cables and PCB design have eliminated interference.

Following laboratory tests, field testing will involve mounting the system on a bike and conducting real-world trials on urban streets and rural roads. These tests will evaluate how well the system performs under actual cycling conditions, including variable internet connectivity, changing environmental factors, and diverse road surfaces. Data collected during these tests will be analyzed to verify that the system accurately detects obstacles, monitors environmental conditions, and provides timely feedback to the cyclist.

Finally, user feedback should be incorporated into the validation process. Cyclists who test the system should provide input on the effectiveness of the AI alerts, the clarity of the data visualizations, and the overall usability of the system. This feedback will be invaluable for refining the system and ensuring it meets the practical needs of its users.

In summary, the successful implementation of these solutions will result in a significantly improved black box system that addresses the key technical challenges of sensor accuracy, power consumption, and data transmission. With the addition of AI-driven predictive analytics, the system will not only monitor cyclist safety but also proactively prevent accidents, marking a major advancement in cyclist safety technology.

1. Testing and Validation

The implementation of the proposed solutions for improving the black box system must be followed by rigorous testing and validation to ensure that the enhancements perform as expected in both controlled and real-world environments. Testing will be conducted in two primary phases: laboratory testing and field testing, each designed to validate specific aspects of the system's performance.

**6.1 Laboratory Testing**

The initial phase of testing will take place in a controlled laboratory environment. The goal is to isolate and evaluate the performance of individual system components, including sensor accuracy, power efficiency, and data transmission. For example, the recalibrated environmental sensors will be tested in a climate-controlled chamber to verify their accuracy across varying temperatures and humidity levels. Similarly, the effectiveness of shielded cables and the redesigned printed circuit board (PCB) for ultrasonic sensors will be assessed in an environment with simulated electromagnetic interference, ensuring that noise interference is minimized or eliminated. Power consumption will also be measured under various operating conditions to confirm that the sleep modes and energy-harvesting technologies function as intended.

**6.2 Field Testing**

Once laboratory tests confirm the viability of the hardware and software modifications, the system will undergo extensive field testing. This involves mounting the system on a bicycle and conducting tests in real-world cycling environments, including both urban and rural settings. During field tests, the system’s ability to accurately monitor environmental conditions, detect obstacles, and provide real-time feedback through AI-driven predictive analytics will be closely monitored. Data will be collected on system reliability, power consumption over long rides, and connectivity performance in areas with fluctuating network strength.

By combining laboratory and field testing, the validation process will ensure that the system improvements not only work in theory but also translate effectively to practical use, delivering enhanced safety and functionality to cyclists.

1. Future Work

This paper has presented a comprehensive evaluation of the current black box system for cyclist safety, addressing its key limitations in sensor accuracy, power consumption, and data transmission. Proposed solutions, including hardware improvements, AI integration, and optimized power management, have been outlined to enhance system reliability and performance. Future work will focus on refining these implementations, particularly the use of AI for predictive analytics and the adoption of energy-harvesting technologies. Further testing and real-world trials will be essential to ensure the system’s adaptability and effectiveness in diverse cycling environments, with the goal of improving road safety for cyclists.

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