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2nd April, 2025.

The Chairman,

The Implementation Committee of the Memorandum of

Understanding between National Agency for Science and

Engineering Infrastructure (NASENI) and University of Abuja.

Dear Sir,

Intelligent Wheel Safety System: AI-Enhanced Tire Safety and Sustainability with Wheel Airbag Technology

BY

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Abstract

This project introduces an innovative Intelligent Wheel Safety System designed to mitigate the consequences of tire bursts and enhance overall road safety. The focal point of the system is the integration of a Wheel Airbag, ingeniously incorporated into the wheel rim and positioned inside the tire. The airbag is meticulously designed as a tube, adapting to the contours of tubeless tires for optimal efficiency. In the event of a tire blowout, a sensor promptly detects the impulse and signals the inflator, initiating the rapid deployment of the airbag. This strategically placed airbag aims to cushion the effects of the tire burst, preserving vehicle balance and allowing the driver critical moments to safely maneuver and park the vehicle. The integration *of artificial intelligence (AI) and computer vision technologies further enhances the system's capabilities by providing real-time analysis of road conditions and tire wear. The project's comprehensive methodology includes the development of an AI algorithm for puncture detection, the design and integration of the Wheel Airbag System, and the implementation of computer vision for analyzing road conditions and monitoring tire wear. A user-friendly interface communicates crucial information to the driver in real-time, ensuring prompt responses to potential risks. Through simulations and testing scenarios, the project evaluates the system's effectiveness in various situations, focusing on safety and environmental impact assessments. The Wheel Airbag Technology, primarily aimed at reducing road traffic accidents caused by tire bursts, presents a promising advancement in intelligent automotive safety systems. The results and discussions derived from this project contribute not only to the field of vehicular safety but also address sustainability concerns through predictive maintenance and environmental impact analyses. The conclusion reflects on the achievements of the Intelligent Wheel Safety System and proposes future directions for continued research and development in intelligent automotive safety.*

1. Introduction

1.1 Background and Motivation

Road traffic accidents continue to pose a significant threat, claiming countless lives and causing severe injuries every minute. Despite efforts by various agencies such as FRSC, VIO, and the Police, the frequency of accidents remains alarmingly high. The motor vehicle, though a marvel of engineering, is a potential hazard, with the tires being a critical point of contact with the ground. Unfortunately, tire-related incidents, particularly blowouts, contribute significantly to highway accidents, especially at high speeds.

The urgency to address the devastating effects of tire bursts has led to the consideration of airbag technology in this project. Traditionally used as a Supplementary Restraint System (SRS) in modern vehicles, the airbag is a flexible membrane designed to inflate upon collision, preventing passengers from pitching forward. In the context of this project, the airbag is adapted to serve as a protective measure during tire bursts, aiming to cushion the impact and provide stability to the vehicle until the driver can safely maneuver it to a stop.

The history of airbags dates back to 1951 when Patrick W. Hetrick patented the device, originally conceived to protect his own family. Early iterations utilized air-filled bladders, evolving over the years with innovations such as the ball-in-tube sensor for crash detection. Major automotive manufacturers, including Mercedes-Benz, Porsche, and Honda, played pivotal roles in the widespread adoption of airbag technology in vehicles. However, the application of airbags to address tire bursts and stabilize vehicles in real-time remains a novel and crucial extension of this technology.

As road safety concerns persist and the need for innovative solutions intensifies, the integration of airbag technology into the wheel, specifically tailored for tire-burst scenarios, emerges as a promising avenue to reduce accidents and enhance overall road safety. This project seeks to build on the legacy of airbag technology, adapting it to address a critical aspect of vehicular safety—tire-related accidents.

1.1.1 Brief overview of current challenges in tire safety

Tire safety remains a critical concern in the realm of road transportation, presenting several challenges that contribute to accidents and pose risks to motorists. Some key challenges include:

1. **Tire Blowouts:** Sudden tire failures, commonly known as blowouts, are a significant challenge leading to loss of control over vehicles. Blowouts often occur unexpectedly, especially at high speeds, resulting in accidents and potential injuries.
2. **Inadequate Maintenance:** Many drivers neglect regular tire maintenance, including checking tire pressure, rotation, and tread wear. Inadequate maintenance can lead to issues such as under inflation, over inflation, and uneven tire wear, increasing the likelihood of tire-related accidents.
3. **Road Hazards:** Roads are often filled with hazards such as potholes, debris, and sharp objects that can damage tires. These hazards contribute to tire punctures and failures, posing safety risks to drivers and passengers.
4. **Adverse Weather Conditions:** Harsh weather conditions, including rain, snow, and extreme temperatures, can impact tire performance. Reduced traction, longer stopping distances, and decreased overall tire effectiveness during adverse weather can lead to accidents.

5. **Lack of Real-time Monitoring:** Traditional tire safety mechanisms often lack real-time monitoring capabilities. Without immediate feedback on tire conditions, drivers may be unaware of potential issues until it's too late, increasing the risk of accidents.
6. **Limited Driver Awareness:** Many drivers may not be adequately educated about the importance of tire safety or may underestimate the potential consequences of neglecting tire maintenance. This lack of awareness contributes to preventable tire-related incidents.

1.1.2 Importance of integrating AI and computer vision for enhanced safety

In the context of automotive safety, the integration of Artificial Intelligence (AI) and computer vision technologies is paramount for several reasons, contributing to an overall enhancement in safety measures:

1. **Real-time Monitoring:**
   - **AI Algorithms for Puncture Detection:** By implementing AI algorithms, the system can analyze real-time data from sensors to detect punctures instantly. This enables timely responses to tire-related issues, preventing accidents caused by blowouts.
2. **Predictive Maintenance:**
   - **Computer Vision for Tire Wear Monitoring:** Computer vision allows for the continuous analysis of tire wear patterns through camera images. This information is crucial for predictive maintenance, notifying drivers and service centers about the condition of tires and potential risks, thus preventing unexpected failures.
3. **Immediate Response to Road Conditions:**
   - **Computer Vision for Road Condition Analysis:** Computer vision can assess road conditions in real-time, identifying hazards such as debris, potholes, or slippery surfaces. AI-driven systems can then alert the driver, enhancing responsiveness and reducing the risk of accidents.
4. **Enhanced Safety Features:**
   - **Integration of AI in Airbag Deployment:** AI can play a crucial role in optimizing the deployment of the Wheel Airbag System. It can analyze various factors, including the severity of the puncture and the speed of the vehicle, to determine the appropriate level of airbag inflation needed for effective stabilization.

5. **Reduced Human Error:**
   - **Automation and Decision Support:** AI systems reduce reliance on human reaction times and decisions. By automating certain safety features and providing decision support to drivers, the integration of AI minimizes the impact of human error on road safety.
6. **Data-driven Insights:**
   - **Data Analysis for Continuous Improvement:** The integration of AI allows for the collection and analysis of vast amounts of data related to tire performance, road conditions, and driving behavior. These insights can be used to continuously improve the system, making it more adaptive and effective over time.
7. **Holistic Safety Approach:**
   - **Combining AI and Airbag Technology:** Integrating AI with airbag technology, specifically tailored for tire safety, provides a holistic approach. It addresses the root causes of accidents by combining real-time monitoring, predictive maintenance, and immediate response mechanisms, thereby enhancing overall safety.

1.2 *Objectives of the Project*

The primary goal is to enhance overall safety by providing real-time alerts, optimizing airbag deployment during tire-related incidents, and contributing to predictive maintenance, ultimately reducing accidents caused by tire failures. However, the specific objectives of the project include:

i. Development of an AI-Enhanced Tire Safety System
ii. Integration of Wheel Airbag Technology
iii. Real-time analysis of road conditions and tire wear using computer vision

1.2.1 Development of an AI-Enhanced Tire Safety System

To develop an AI-Enhanced Tire Safety System that leverages artificial intelligence for real-time monitoring and early detection of potential tire issues, aiming to enhance overall road safety by preventing accidents caused by tire failures. The system will integrate advanced AI algorithms to analyze tire data, predict maintenance needs, and provide timely alerts to drivers, contributing to a proactive approach in mitigating tire-related risks on the road.

1.2.2 Integration of Wheel Airbag Technology

The seamless Integration of Wheel Airbag Technology into the automotive safety system. This involves designing and implementing a wheel-specific airbag system that deploys in response to tire-related incidents, such as blowouts or punctures. The goal is to enhance vehicle stability during emergencies, preventing accidents and providing a crucial safety buffer until the driver can safely maneuver the vehicle to a stop. This integration aims to revolutionize tire safety by mitigating the impact of tire failures and contributing to overall road safety.

1.2.3 Real-time analysis of road conditions and tire wear using computer vision

To implement a real-time analysis system using computer vision technology for assessing both road conditions and tire wear. This involves developing algorithms that analyze camera images to detect potential hazards on the road, such as obstacles or debris, and simultaneously monitor the wear patterns of tires. The goal is to provide drivers with immediate feedback on road conditions and tire health, enhancing overall safety by enabling proactive responses to potential risks and contributing to predictive maintenance practices.

2. LITERATURE REVIEW

2.1 Review of Existing Tire Safety Systems

2.1.1 Evaluation of traditional tire safety mechanisms

Tire safety systems have evolved over the years to address the challenges associated with tire related incidents and enhance overall road safety. A comprehensive review of existing tire safety systems reveals the following key components and advancements:

i. **Tire Pressure Monitoring Systems (TPMS):**

- *Description:* TPMS is a widely adopted technology that monitors tire pressure in real-time.
- *Advantages:* with early warning, TPMS provides early detection of underinflated or overinflated tires, preventing potential accidents. Helps prevent accidents due to underinflated or overinflated tires, improving fuel efficiency and extending tire life.
- *Limitations:* Primarily focuses on pressure levels and may not provide insights into other critical tire conditions. Sensor malfunctions can lead to false readings, affecting the accuracy of the system.

ii. **Anti-lock Braking System (ABS):**

- *Description:* ABS is a safety system that prevents wheel lockup during braking, contributing to vehicle stability.
- *Advantages:* Enhances steering control during emergency braking, reducing the risk of skidding and accidents.
- *Limitations:* While effective in certain scenarios, ABS does not directly address tire blowouts or punctures. iii. **Electronic Stability Control (ESC):**
- *Description:* ESC assists in maintaining vehicle stability by detecting and reducing skidding.
- *Advantages:* Improves vehicle control during sudden maneuvers, reducing the likelihood of rollovers and accidents.
- *Limitations:* Focuses on overall vehicle stability but may not specifically address tire-related issues. iv. **Run-Flat Tire Technology:**
- *Description:* Run-flat tires are designed to continue functioning even after a puncture, allowing the vehicle to be driven for a limited distance at a reduced speed.
- *Advantages:* Enables continued driving after a puncture, reducing the immediate impact of tire failures.
- *Limitations:* Limited driving distance on run-flat tires, and replacement can be more expensive than traditional tires.

v. **Smart Tires with Sensor Integration:**

- *Description:* Smart tires incorporate sensors to monitor various parameters such as temperature, tread wear, and tire health.
- *Advantages:* Provides real-time data for comprehensive tire health assessment, enabling proactive maintenance.

- *Limitations:* Implementation costs and potential complexities in integrating sensor technologies across a fleet of vehicles, may provide a stiffer ride compared to conventional tires. vi. **Tire Inflation Systems:**
- *Description:* Automatic tire inflation systems maintain optimal tire pressure by adjusting it as needed.
- *Advantages:* Improves fuel efficiency, tire longevity, and overall safety by ensuring proper tire pressure.
- *Limitations:* May not address issues related to sudden tire blowouts or provide realtime alerts. vii. **Smart Tire Safety Alarms:**
- *Description:* Alarms integrated into vehicles that alert drivers when tire pressure is below recommended levels.
- *Advantages:* Offers a simple and cost-effective solution to enhance driver awareness regarding tire pressure.
- *Limitations:* Relies on the driver's responsiveness and may not address other critical tire conditions.

2.1.2 Overview of AI applications in automotive safety

The integration of Artificial Intelligence (AI) applications in automotive safety has revolutionized the way vehicles operate, enhancing overall safety standards and mitigating potential risks. AI, with its ability to analyze vast amounts of data in real-time, has found critical applications in predictive maintenance, collision avoidance, and emergency response systems. One notable advancement is the incorporation of AI-driven sensors and cameras for intelligent driver assistance, enabling features like lane departure warnings, automatic emergency braking, and adaptive cruise control. Machine learning algorithms, a subset of AI, empower vehicles to recognize and respond to complex patterns in the environment, contributing to improved hazard detection and accident prevention. Furthermore, AI is instrumental in developing sophisticated airbag systems, such as the Intelligent Wheel Safety System, capable of detecting punctures and deploying airbags with unprecedented precision. As the automotive industry progresses towards autonomous driving, AI algorithms play a pivotal role in decision-making processes, ensuring vehicles can navigate safely through dynamic environments. The ongoing innovation in AI applications continues to redefine automotive safety, promising a future where intelligent systems collaborate seamlessly to safeguard both drivers and pedestrians on the roads.

2.2 Wheel Airbag Technology

Wheel Airbag Technology represents a cutting-edge advancement in vehicle safety, specifically addressing the challenges associated with tire blowouts and their potentially catastrophic consequences. This innovative system involves the integration of airbags directly into the wheel, revolutionizing traditional safety measures. The evaluation of Wheel Airbag Technology reveals its key components, functionalities, and potential benefits:

1. **Deployment Mechanism:**
   - **Inflatable Design:** The airbag is seamlessly incorporated into the wheel, residing within the tire itself. Upon detection of a tire blowout or critical pressure loss, the system triggers the airbag's rapid inflation, creating a protective barrier between the tire and the road surface.
2. **Sensor Integration:**
   - **Impulse Recognition:** A sophisticated sensor network is employed to detect sudden changes in tire pressure or unusual vibrations associated with a blowout. The sensor system is finely tuned to respond promptly to these impulses, ensuring swift deployment of the airbag.
3. **Innovative Airbag Structure:**
   - **Tube Design:** The airbag is ingeniously cut and sewn into a tube-like structure, mirroring the shape of the tire. This design ensures optimal coverage and inflation characteristics, effectively supporting the tire and preserving vehicle stability.
4. **Enhanced Stability and Control:**
   - **Balancing Functionality:** Upon deployment, the Wheel Airbag aims to maintain the vehicle's balance during a tire blowout, mitigating the immediate loss of control that often accompanies such incidents. This critical function provides drivers with a valuable window to safely bring the vehicle to a stop.
5. **Integration with AI and Sensors:**
   - **Smart System Integration:** Wheel Airbag Technology often incorporates artificial intelligence and sensor technologies. AI algorithms analyze sensor data in real-time, enhancing the system's responsiveness and allowing for adaptive deployment strategies based on the severity of the tire-related incident.
6. **Preventing Rollovers and Skidding:**

- **Immediate Support:** By cushioning the effects of a blowout, the Wheel Airbag contributes to preventing rollovers, skidding, and other uncontrollable movements. This is particularly significant when the vehicle is traveling at high speeds, where the potential for severe accidents is heightened.

7. **Adaptability to Various Tire Types:**
   - **Tubeless Tire Consideration:** The design of the Wheel Airbag takes into account the prevalent use of tubeless tires, ensuring compatibility with modern tire technologies commonly found in today's vehicles.
8. **Contribution to Overall Vehicle Safety:**
   - **Holistic Safety Approach:** Beyond addressing tire blowouts, the Wheel Airbag System contributes to a holistic approach to vehicle safety. It complements existing safety systems, such as ABS and ESC, by providing an additional layer of protection specifically tailored to tire-related incidents.

2.2.1 Examination of existing airbag systems

Airbag systems have become a cornerstone of modern vehicle safety, significantly reducing the severity of injuries during collisions. Examining existing airbag systems reveals the evolution of this technology, its key components, and ongoing innovations:

i **Origins and Evolution:**

- **Invention by Patrick W. Hetrick:** The concept of the airbag originated in 1951 when Patrick W. Hetrick patented the device. Initially designed to protect his own family, it has since evolved into a critical safety feature in vehicles worldwide.

- **Early Applications:** Early airbag systems trace back to the 1970s, with experimental fleets from major manufacturers such as Ford and General Motors. These systems aimed to provide additional protection to occupants during frontal collisions.

ii. **Components and Deployment:**

- **Flexible Membrane or Envelope:** The core of an airbag system is a flexible membrane or envelope that inflates rapidly upon collision.

- **Crash Detection Sensors:** Integration with crash detection sensors, typically using accelerometers, enables the system to determine the severity and type of impact.
- **Inflator Mechanism:** An inflator mechanism releases gas, usually nitrogen, triggering the rapid inflation of the airbag.
- **Deployment Algorithm:** Algorithms determine the optimal timing and force of airbag deployment based on the crash characteristics.

iii. **Types of Airbags:**

- **Frontal Airbags:** Deploy from the steering wheel or dashboard and provide protection during frontal collisions.
- **Side-Impact Airbags:** Positioned in the doors or seats, these protect occupants during side collisions.
- **Curtain Airbags:** Extend from the roof to protect occupants' heads during side collisions or rollovers.
- **Knee Airbags:** Located below the dashboard, these protect the driver's knees during frontal collisions.

iv. **Innovations and Advancements:**

- **Dual-Stage Airbags:** Introduced to adjust deployment force based on crash severity, reducing the risk of injury.
- **Side Curtain Airbags:** Expanded to provide enhanced protection during side impacts and rollovers.
- **Advanced Sensor Technologies:** Ongoing developments include more sophisticated sensor technologies, such as weight sensors and occupant position sensors, improving the system's ability to tailor deployment to specific scenarios.
- **Pedestrian Airbags:** Some vehicles feature external airbags to protect pedestrians in the event of a collision.

v. **Integration with Vehicle Systems:**

- **Supplemental Restraint System (SRS):** Airbags are integrated into a broader Supplemental Restraint System that may include seatbelt pre-tensioners and other safety features.
- **Collaboration with Other Safety Systems:** Airbag systems often collaborate with other vehicle safety systems, such as ABS and ESC, to provide comprehensive protection in various scenarios.

vi. **Global Mandates and Standards:**

- **Mandatory Installations:** Regulations mandating airbag installations in new vehicles have become widespread globally.
- **Continuous Improvement:** Manufacturers continuously refine airbag systems to meet evolving safety standards and address emerging safety challenges.

vii. **Challenges and Considerations:**

- **Occupant Positioning:** Ensuring optimal protection for occupants of varying sizes and positions remains a challenge.
- **Cost and Weight:** Balancing the cost and weight of airbag systems against their safety benefits is an ongoing consideration for manufacturers.

2.2.2 Identification of key challenges and potential solutions

The challenges and potentials are as follows:

i. Challenges in Current Tire Safety Systems:

The existing tire safety systems face challenges in providing real-time, comprehensive monitoring of tire conditions. Traditional systems, such as TPMS, primarily focus on pressure levels and may not offer insights into other critical factors like tire wear or imminent blowouts. Additionally, there is a dependency on manual checks, which can be inconsistent and may not address sudden tire failures effectively.

ii. A I Algorithm Development for Puncture Detection:

Developing an effective AI algorithm for real-time puncture detection is a key challenge. The algorithm needs to accurately differentiate between normal variations in tire behavior and the onset of a puncture. Fine-tuning the algorithm to operate in diverse driving conditions and adapting to various tire types poses a significant research challenge.

Potential Solutions:

- Conducting extensive data collection and analysis to train the AI model on diverse scenarios.
- Implementing machine learning techniques for pattern recognition to enhance accuracy.
- Integrating sensor fusion approaches for more robust puncture detection.

iii. Integration of Wheel Airbag with Vehicle Systems:

Seamlessly integrating the Wheel Airbag System with the vehicle's existing safety systems presents a technological challenge. Ensuring the airbag's timely and appropriate deployment in response to tire-related incidents, without interfering with other safety mechanisms, requires a careful balance.

Potential Solutions:

- Conducting rigorous testing and simulations to optimize the integration of the airbag with ABS, ESC, and other safety features.
- Developing smart algorithms that can adaptively coordinate the deployment of various safety systems based on real-time sensor data.

iv. User Interface Design for Real-Time Feedback:

Designing an intuitive user interface that provides real-time feedback to the driver poses a design challenge. The interface should convey critical information about tire conditions, airbag deployment status, and recommended actions in a way that is easily comprehensible during driving.

Potential Solutions:

- Collaborating with user experience (UX) designers to create a dashboard layout that prioritizes essential information.

- Implementing user-friendly alerts and warnings, possibly utilizing visual and auditory cues for effective communication.

v. Environmental Impact Assessment:

Assessing the environmental impact of the Intelligent Wheel Safety System, particularly concerning the use of airbags, is a critical challenge. Balancing safety improvements with sustainable materials and disposal practices is essential.

Potential Solutions:

- Conducting life cycle assessments to evaluate the overall environmental impact of the system.
- Exploring eco-friendly materials for airbag construction and considering recycling options for end-of-life components.

vi. Cost-Effectiveness and Market Adoption:

Achieving cost-effectiveness and widespread market adoption of the Intelligent Wheel Safety System may be challenging. Balancing the additional manufacturing costs against the perceived safety benefits and persuading consumers to adopt this technology is a market-driven challenge.

Potential Solutions:

- Collaborating with automotive manufacturers to explore cost-effective production methods.
- Implementing awareness campaigns highlighting the long-term safety and economic benefits to encourage consumer adoption.

*2.3 **Computer Vision in Automotive Safety***

Computer vision has emerged as a transformative technology in automotive safety, revolutionizing how vehicles perceive and interact with their surroundings. By leveraging advanced algorithms and image processing techniques, computer vision systems analyze visual data from cameras and sensors to enhance safety in various ways. These applications include real-time detection of obstacles, lane departure warnings, pedestrian recognition, and adaptive cruise control. In the context of automotive safety, computer vision contributes to accident prevention, improves driver assistance systems, and lays the foundation for the development of autonomous vehicles. Its ability to interpret visual information in complex environments makes computer vision a critical component in shaping the future of safer and more intelligent transportation systems.

2.3.1 Applications of computer vision in road condition analysis

Computer vision, as a core component of the Intelligent Wheel Safety System, brings about transformative applications in analyzing road conditions. These applications are pivotal for ensuring AI-enhanced tire safety and sustainability in conjunction with Wheel Airbag Technology:

i. **Surface Anomaly Detection:**
   - *Objective:* Identify irregularities on road surfaces that may pose risks to tires.
   - *Application:* Computer vision analyzes real-time images to detect potholes, debris, or uneven surfaces, triggering timely responses from the Intelligent Wheel Safety System to mitigate potential tire damage.

ii. **Traction Assessment:**
   - *Objective:* Evaluate road traction levels to optimize tire performance.
   - *Application:* Computer vision assesses the texture and wetness of the road, providing data for AI algorithms to adjust tire dynamics and optimize the deployment of the Wheel Airbag System for enhanced vehicle stability.

iii. **Obstacle Recognition:**
   - *Objective:* Detect and classify obstacles on the road that may impact tire safety.
   - *Application:* Computer vision identifies objects such as fallen branches or road debris, enabling the Intelligent Wheel Safety System to anticipate and prepare for potential tire-related challenges.

iv. **Dynamic Road Sign Interpretation:**
   - *Objective:* Interpret road signs and markings for informed driving decisions.
   - *Application:* Computer vision deciphers traffic signs, lane markings, and signals, contributing to the overall intelligence of the system. This

information aids in proactive adjustments to tire settings for different road conditions.

v. **Adaptive Cruise Control Integration:**

- *Objective:* Seamlessly integrate road condition data with adaptive cruise control.

Application: Computer vision collaborates with adaptive cruise control systems, using road condition analysis to optimize speed and maintain safe following distances, contributing to overall tire and vehicle safety.

vi. **Real-time Weather Response:**

- *Objective:* Respond to changing weather conditions affecting road surfaces.
- *Application:* Computer vision monitors weather patterns, enabling the Intelligent Wheel Safety System to adapt tire settings in anticipation of rain, snow, or other weather-related challenges.

vii. **Road Surface Temperature Assessment:**

- *Objective:* Evaluate road surface temperature for tire grip optimization.
- *Application:* Computer vision provides insights into road surface temperature, allowing the system to adjust tire parameters to enhance traction and prevent issues like skidding in extreme temperature conditions.

viii. **Predictive Maintenance Insights:**

- *Objective:* Gather data for predictive tire maintenance based on road conditions.
- *Application:* Computer vision, in combination with AI algorithms, analyzes road conditions to provide predictive insights into tire wear. This information contributes to proactive maintenance strategies, extending tire lifespan and sustainability.

2.3.2 Use of AI for predictive maintenance in tires

i. **Tire Wear Prediction:**

- *Objective:* Anticipate and address tire wear before it becomes a safety concern.

- *AI Application:* Machine learning algorithms analyze historical tire wear patterns, driving behavior, and road conditions to predict future wear. This proactive approach ensures timely tire replacements, preventing potential blowouts.

ii. **Anomaly Detection in Tire Behavior:**

Objective: Identify abnormal tire behavior indicative of potential issues.

- *AI Application:* Continuous monitoring by AI algorithms allows for the detection of deviations from expected tire performance. Unusual patterns, such as vibrations or temperature changes, trigger alerts for further inspection or intervention.

iii. **Dynamic Pressure Optimization:**

- *Objective:* Optimize tire pressure based on predictive insights.
- *AI Application:* AI algorithms assess historical pressure data, driving conditions, and road characteristics to dynamically adjust tire pressure. This proactive optimization enhances fuel efficiency, extends tire life, and contributes to overall sustainability.

iv. **Weather-Responsive Tire Settings:**

- *Objective:* Preemptively adapt tire settings to changing weather conditions.
- *AI Application:* AI analyzes weather forecasts and historical data to predict upcoming weather patterns. This information guides the Intelligent Wheel Safety System in adjusting tire parameters, ensuring optimal performance in rain, snow, or varying temperatures.

v. **Adaptive Traction Control:**

- *Objective:* Enhance traction control based on predictive analytics.
- *AI Application:* Machine learning algorithms analyze historical data on road surface conditions and tire behavior to predict traction requirements. The system adapts in real-time, optimizing Wheel Airbag deployment and vehicle stability in anticipation of challenging road surfaces.

vi. **Early Puncture Detection:**

- *Objective:* Detect punctures before they pose a safety risk.
- *AI Application:* AI algorithms process data from tire sensors, assessing factors such as pressure changes and temperature fluctuations. Predictive

analytics enable the system to identify subtle indicators of punctures, triggering early warnings or interventions.

- vii. **Route-Specific Tire Adjustments:**

  Objective: Tailor tire settings based on the predicted characteristics of the upcoming route.

- *AI Application:* Analyzing historical route data and current traffic conditions, AI algorithms predict the demands on the tires. The system adjusts parameters such as tire pressure and airbag deployment in anticipation of specific road challenges.

vii. **Data-Driven Decision-Making:**

- *Objective:* Utilize AI-driven insights for informed decision-making.
- *AI Application:* The system employs AI to analyze a vast array of data, including road conditions, tire health, and historical incidents. Informed by this analysis, the Intelligent Wheel Safety System makes data-driven decisions to optimize tire safety and overall vehicular performance.

METHODOLOGY

2.4 AI Algorithm for Puncture Detection

In the pursuit of elevating tire safety within the Intelligent Wheel System, the development of an advanced AI algorithm for puncture detection takes center stage. This algorithm, a critical component of the project, aims to employ machine learning techniques to enable real-time identification of punctures and abnormalities in tire behavior. By leveraging extensive datasets and refining the algorithm's capacity for pattern recognition, the system strives to provide swift and accurate detection of punctures, triggering timely interventions to mitigate potential safety risks. This segment of the project embodies a crucial stride towards the overarching goal of fostering a safer and more sustainable driving experience through AI-enhanced tire safety within the Intelligent Wheel System.

2.4.1 Selection of AI model(s) for real-time puncture detection

Choosing the right artificial intelligence (AI) models is pivotal in achieving real-time puncture detection within the Intelligent Wheel Safety System. The project aims to evaluate and select AI models that demonstrate high accuracy, efficiency, and adaptability to varying driving conditions. Machine learning algorithms, such as Convolutional Neural Networks (CNNs) and Recurrent Neural Networks (RNNs), will be considered for their capabilities in image analysis and sequential data processing, respectively.

1. **Convolutional Neural Networks (CNNs):**
   - *Strengths:*
     - Exceptional Image Analysis: CNNs excel in image recognition tasks, making them suitable for processing visual data from tire sensors and cameras.
     - Hierarchical Feature Extraction: CNNs automatically learn hierarchical features, allowing for the identification of intricate patterns associated with punctures.
   - *Application:* CNNs will be explored for their efficacy in analyzing images captured by sensors mounted on or around the tire, enabling real-time detection of punctures based on visual cues.
2. **Recurrent Neural Networks (RNNs):**
   - *Strengths:*
     - Sequential Data Processing: RNNs are proficient in handling sequential data, making them suitable for analyzing time-series data related to tire behavior.
     - Contextual Understanding: RNNs retain memory of past states, facilitating a contextual understanding of dynamic changes in tire conditions.
   - *Application:* RNNs will be considered for their ability to analyze temporal patterns in tire sensor data, allowing for the identification of subtle changes indicative of punctures over time.
3. **Hybrid Models:**
   - *Strengths:*

- Combining Strengths: Hybrid models, integrating aspects of both CNNs and RNNs, can leverage the strengths of each architecture for a more comprehensive approach.
- Improved Generalization: Hybrid models may enhance the system's ability to generalize across diverse driving conditions and puncture scenarios.

- *Application:* Hybrid models will be explored to capitalize on the strengths of both CNNs and RNNs, providing a robust solution for real-time puncture detection that encompasses both visual and sequential data.

4. **Transfer Learning Approaches:**
   - *Strengths:*
     - Knowledge Transfer: Transfer learning allows the model to leverage pretrained weights and architectures, accelerating the learning process.
     - Adaptability: Models pre-trained on large datasets can adapt well to specific tasks with limited labeled data.
   - *Application:* Transfer learning techniques will be investigated to capitalize on models trained on extensive datasets, tailoring them to the specific task of puncture detection in the Intelligent Wheel Safety System.

2.4.2 Training and validation processes

The success of the AI algorithm for real-time puncture detection within the Intelligent Wheel Safety System hinges on robust training and validation processes. This section outlines the key steps and methodologies involved in preparing and refining the algorithm for optimal performance:

i. Data Collection and Preprocessing:

- Dataset Compilation:
  - Gather diverse datasets encompassing various puncture scenarios, road conditions, and tire types.
- Data Augmentation:
  - Enhance dataset variability through augmentation techniques, ensuring the model's adaptability to different real-world conditions.

ii. Model Selection and Initialization:

- Architecture Choice:
   - Select the chosen AI model(s) based on the evaluation of CNNs, RNNs, hybrid models, and transfer learning approaches.
- Model Initialization:
   - Initialize model weights using pre-trained models or random weights, depending on the chosen architecture.

iii. Training Phase:

- Input Encoding:
   - Encode input data, incorporating visual and sequential features from tire sensors and cameras.
- Loss Function Selection:
   - Choose an appropriate loss function that aligns with the nature of puncture detection, optimizing model training.
- Optimization Algorithm:
   - Implement optimization algorithms (e.g., Adam, SGD) to minimize the chosen loss function and update model weights.
- Hyper parameter Tuning:
   - Iteratively adjust hyper parameters, such as learning rate and batch size, to optimize model convergence.

iv. Validation and Fine-Tuning:

- Validation Dataset Split:
   - Reserve a portion of the dataset for validation to assess the model's generalization performance.
- Early Stopping:
   - Implement early stopping mechanisms based on validation performance to prevent overfitting.
- Fine-Tuning Strategies:

- Fine-tune the model based on validation feedback, adjusting parameters for improved performance.

v. Performance Evaluation:

- Metrics Selection:
  - Choose evaluation metrics (e.g., precision, recall, F1-score) relevant to puncture detection accuracy and false positive/negative rates.
- Confusion Matrix Analysis:
  - Analyze confusion matrices to understand the model's performance across different puncture scenarios.

vi. Iterative Optimization:

- Feedback Loop:
  - Establish an iterative feedback loop, incorporating insights from model performance, user feedback, and real-world testing.
- Continuous Improvement:
  - Implement updates and optimizations to the algorithm based on ongoing evaluations and emerging challenges.

vii. Real-world Testing:

- Simulation Scenarios:
  - Subject the model to simulated scenarios replicating real-world puncture incidents and diverse driving conditions.
- On-road Testing:
  - Conduct on-road tests to validate the algorithm's effectiveness in real-time puncture detection.

2.5 Wheel Airbag System Design

The Wheel Airbag System, a key element within the Intelligent Wheel Safety System, aims to revolutionize tire safety by mitigating the impact of blowouts and enhancing vehicle stability. This chapter provides a comprehensive exploration of the design considerations, calculations, and fabrication processes involved in the development of the Wheel Airbag.

i. Analysis of the Wheel Airbag:

The Wheel Airbag, distinct in construction and location from occupant airbags, is meticulously analyzed to meet the specific demands of tire safety. Unlike traditional airbags, it is crafted from a robust woven nylon fabric with strategically minimized vent holes to endure the weight of the vehicle for an extended period.

i. Material and Construction:

- **Material:** Woven nylon fabric
- **Vent Holes:** Minimized for enhanced weight-bearing capacity

- **ii. Metric Tyre Size Consideration:**

Considering a typical P-metric passenger car tire with the size designation P205/60HR15:

- P: Passenger
- 205: Tyre width in millimeters
- 60: Ratio of height to width
- HR: Radial construction, High-speed capability
- 15: Wheel diameter in inches

- **iii. Wheel Airbag Dimensions Calculation:**

The Wheel Airbag mirrors the tube's shape in the tire and is sized based on the metric tyre-size designation. Calculations involve determining Section Width (SW) and Section Height (SH):

SW = 205 mm

SH = 60% of SW = 123 mm

ii. Determining the Size of the Wheel Airbag:

- **Inflation Consideration:** The wheel airbag, when inflated, should be about twice the size of the tire for optimal effectiveness.
- **Design Parameters:**

  $Wa=SWWa=SW$

  $Ha=2SHHa=2SH$
- **Calculated Sizes:**

  Inflated Airbag Section Width (Wa) = 270 mm

  Inflated Airbag Section Height (Ha) = 246 mm

iii. Overall Diameter Calculations:

Overall Diameter of the Tyre (ODt):

$ODt=2SH+RDODt=2SH+RD$ $ODt=626mmODt=626mm$

Overall Diameter of Wheel Airbag (ODa):

$ODa=2Ha+RDODa=2Ha+RD$ $ODa=872mmODa=872mm$

iv. Fabrication Process:

- **Die Cutting:** The nylon fabric is die-cut to precise dimensions before the inflation process.
- **Sewing:** Internal and external sewing is carried out to form two sides of the airbag.
- **Inflation and Inspection:** The airbag is inflated and thoroughly inspected for imperfections.

2.5.1 Specification of airbag components

The airbag components within the Intelligent Wheel Safety System are engineered with precision and reliability to ensure effective deployment in the event of a tire blowout. Each component plays a vital role in cushioning the impact, stabilizing the vehicle, and enhancing overall safety.
Below are the detailed specifications for key airbag components:

i. **Airbag Material:**

- **Material Type:** Woven Nylon Fabric
- **Characteristics:**
  - High tensile strength for structural integrity
  - Resilience to withstand vehicle weight
  - Minimized vent holes for enhanced durability

ii. **Inflation Mechanism:**

- **Inflation Medium:** Compressed Gas (e.g., Nitrogen)
- **Deployment Trigger:**
  - Activated by tire pressure sensors detecting sudden changes
  - Real-time data analysis for rapid response

iii. **Internal Structure:**

- **Sewing Method:**
  - Double-sided sewing for structural integrity
  - Internal reinforcement for enhanced stability during deployment

iv. **Deployment Sensor:**

- **Type:** Accelerometer and Pressure Sensors
- **Functionality:**
  - Accelerometer detects sudden deceleration indicative of a blowout
  - Pressure sensors monitor tire pressure changes in real-time

v. **Deployment Control Unit:**

- **Processing Unit:** Microcontroller or FPGA
- **Functions:**
  - Receives signals from deployment sensor
  - Initiates inflation mechanism
  - Coordinates with the Intelligent Wheel Safety System

vi. **Safety Features:**

- **Built-in Redundancy:**

- Dual sensors for increased reliability
- Backup inflation mechanism in case of primary system failure

vii. Testing and Inspection:

- **Quality Assurance:** Stringent testing procedures for each component
- **Imperfection Inspection:** Pre and post-inflation inspections to identify any defects

viii. Integration with Vehicle Systems:

- **Communication Protocol:** Compatible with the vehicle's communication system
- **Seamless Integration:** Ensures coordinated response with other safety systems **ix.**

Environmental Considerations:

- **Temperature Range:** Designed to operate within a specified temperature range
- **Material Resistance:** Resistant to environmental factors such as moisture and UV exposure

x. Compliance Standards:

- **Regulatory Compliance:** Adheres to relevant automotive safety standards
- **Testing Certifications:** Compliance with industry safety testing certifications

2.5.2 Integration with the vehicle's existing systems

Seamless integration of the Intelligent Wheel Safety System, including the Wheel Airbag, with the vehicle's existing systems is crucial for ensuring optimal performance, real-time responsiveness, and coordination with other safety features. The integration process involves interfacing the Wheel Airbag system with various onboard components and communication systems. Below are key aspects of the integration process:

i. **Communication Protocols:**

- **CAN Bus Integration:**
  - Utilize Controller Area Network (CAN) bus communication for real-time data exchange.
  - Enable the Wheel Airbag system to communicate with the vehicle's Electronic Control Unit (ECU) and other safety modules.

ii. **Sensor Fusion:**

- **Integration of Sensor Data:**
  - Fuse data from the Wheel Airbag's deployment sensors with information from existing vehicle sensors.
  - Collaborate with the Anti-lock Braking System (ABS), Electronic Stability Control (ESC), and other safety sensors for a comprehensive understanding of the vehicle's dynamics.

iii. **ECU Coordination:**

- **Incorporate into Vehicle's ECU Logic:**
  - Ensure that the Wheel Airbag system's deployment control unit coordinates seamlessly with the vehicle's main ECU.
  - Collaborate with the ECU to prioritize safety interventions and optimize vehicle stability during a tire-related incident.

iv. **Data Processing and Analysis:**

- **Integration with Onboard Computers:**
  - Interface with the vehicle's onboard computers for real-time data processing and analysis.
  - Leverage the processing power of the vehicle's computing infrastructure to enhance the Wheel Airbag system's responsiveness.

v. **Communication with Driver Assistance Systems:**

- **Coordinate with Advanced Driver Assistance Systems (ADAS):**
    - Collaborate with ADAS components such as Lane Departure Warning and Collision Avoidance systems.
    - Share relevant data to enhance the overall safety suite and provide a more comprehensive safety response.

vi. **User Interface Integration:**

- **Display and Alert Systems:**
    - Integrate with the vehicle's dashboard display for real-time feedback on tire conditions.
    - Coordinate with existing alert systems to communicate critical information to the driver seamlessly.

vii. **Onboard Diagnostics (OBD) Integration:**

- **OBD-II Compatibility:**
    - Ensure compatibility with the OBD-II standard for diagnostic communication.
    - Facilitate system monitoring, diagnostics, and reporting in line with industry standards.

viii. **Power Management Integration:**

- **Optimized Power Consumption:**
    - Coordinate with the vehicle's power management system to optimize power consumption during normal operation and standby modes.
    - Implement power-saving measures to ensure minimal impact on the vehicle's overall energy efficiency.

ix. **Redundancy and Fail-Safe Mechanisms:**

- **Redundant Systems Integration:**
    - Integrate redundant systems to enhance reliability.

- Implement fail-safe mechanisms that can independently initiate safety measures in the event of a communication breakdown or system failure.

x. **Regulatory Compliance:**

- **Adherence to Safety Standards:**
  - Ensure that the integration meets regulatory safety standards and guidelines.
  - Collaborate with relevant authorities to certify the Intelligent Wheel Safety System's compliance.

2.6 Computer Vision Implementation

2.6.1 Selection of computer vision algorithms for road condition analysis

In the integration of computer vision within the Intelligent Wheel Safety System, the choice of algorithms for road condition analysis is paramount. Various computer vision techniques can be employed to interpret visual data captured by cameras mounted on the vehicle. The selection is driven by the need for accurate and real-time assessment of road conditions, ensuring timely responses to potential hazards. Below are key computer vision algorithms chosen for road condition analysis.

i. **Object Detection:**

- **Objective:**
  - Recognition and localization of specific objects on the road, such as vehicles, pedestrians, and debris.
- **Benefits:**
  - Enhances situational awareness, allowing the system to react to potential obstacles or dangers.

ii. **Optical Flow Analysis:**

- **Objective:**
  - Estimation of motion patterns of objects within the camera's field of view.

- **Benefits:**
  - Enables the system to gauge the speed and movement of surrounding elements, aiding in predictive analysis.

iii. Depth Estimation:

- **Objective:**
  - Determination of the distance to objects in the scene.
- **Benefits:**
  - Enhances the system's understanding of spatial relationships, crucial for assessing potential collision risks.

iv. Road Surface Quality Analysis:

- **Objective:**
  - Assessment of road surface conditions, including potholes, cracks, or uneven terrain.
- **Benefits:**
  - Contributes to predictive maintenance by identifying potential risks to tire health and overall vehicle stability.

v. Dynamic Object Tracking:

- **Objective:**
  - Continuous tracking of moving objects in the scene.
- **Benefits:**
  - Facilitates anticipatory responses to the behavior of other road users, enhancing overall safety.

vi. Image Enhancement and Preprocessing:

- **Objective:**
  - Improving the quality of captured images for better analysis.
- **Benefits:**

- Enhances the system's ability to extract meaningful information under varying lighting and environmental conditions.

vii. Machine Learning-based Anomaly Detection:

- **Objective:**
  - Identification of abnormal patterns or events in the visual data.
- **Benefits:**
  - Adds a layer of intelligence to the system, allowing it to recognize and respond to unexpected road conditions.

3. SYSTEM INTEGRATION

3.1 Integration of AI, Wheel Airbag, and Computer Vision Systems

The seamless integration of Artificial Intelligence (AI), Wheel Airbag, and Computer Vision systems represents a pivotal advancement in automotive safety within the Intelligent Wheel Safety System. This holistic approach converges cutting-edge technologies to create a comprehensive safety framework capable of not only responding to critical incidents but also proactively assessing and mitigating potential risks.

The integration begins with the fusion of AI algorithms and machine learning models into the system's core. AI acts as the brain of the operation, processing vast datasets generated by sensors and cameras. These algorithms play a dual role, driving the decision-making process for the Wheel Airbag's deployment and facilitating real-time analysis of road conditions through the Computer Vision system.

The Wheel Airbag system, designed to cushion the impact of tire blowouts, is intricately woven into this integration. Triggered by AI algorithms assessing sudden changes in tire pressure or abnormal behavior, the Wheel Airbag deploys rapidly, assuming the shape of the tire tube. The deployment is not just a reactive measure; it is orchestrated by predictive algorithms that anticipate and respond to potential blowouts, enhancing vehicle stability during critical moments.

Simultaneously, the Computer Vision system contributes by continuously analyzing the visual landscape. Semantic segmentation, object detection, and lane detection algorithms provide a detailed understanding of the road environment. This visual intelligence informs the AI system about the context in which the vehicle operates. For instance, recognizing obstacles, understanding lane boundaries, and interpreting road signs all feed into the AI's decision-making process.

The coordination between these systems is facilitated by a sophisticated communication protocol, ensuring the exchange of critical information in real-time. As the AI system detects a potential hazard through the analysis of sensor data and computer vision input, it communicates with the Wheel Airbag system to prepare for a rapid response. This collaboration is not limited to crisis scenarios; it extends to predictive maintenance strategies based on Computer Vision's analysis of road conditions and tire wear.

The result is a symbiotic relationship where each system complements the others, creating a dynamic safety net for the vehicle. In the event of a blowout, the Wheel Airbag deploys with precision, guided by insights from both AI predictions and real-time Computer Vision assessments. Moreover, the continuous monitoring of road conditions by the Computer Vision system contributes valuable data to AI algorithms, enabling the system to anticipate and prevent potential issues.

3.2 Ensuring seamless communication between systems

To guarantee optimal functionality and response within the Intelligent Wheel Safety System, a robust communication architecture has been meticulously designed. This involves the establishment of seamless communication channels between the AI algorithms, Wheel Airbag deployment system, and Computer Vision module. The technical aspects ensuring this cohesion are:

i. **Standardized Protocols:**
    - Implementation of industry-standard communication protocols such as MQTT or Web Socket to facilitate efficient data exchange.
    - Adoption of standardized data formats to ensure uniformity in information representation.

ii. **Real-time Data Exchange:**

- Utilization of real-time data streaming mechanisms to enable instantaneous communication between the AI algorithms, Wheel Airbag system, and Computer Vision module.
- Integration of data pipelines to facilitate continuous flow of information. iii. **Interoperability Measures:**
- Implementation of interoperability standards, such as OPC UA, to ensure seamless integration and communication between diverse systems.
- Adoption of open-source communication frameworks to enhance compatibility. iv. **Redundancy Mechanisms:**
- Incorporation of redundant communication pathways to mitigate the impact of potential system failures or network disruptions.
- Duplication of critical communication nodes to ensure uninterrupted data flow.

v. **Data Synchronization:**

- Implementation of synchronized data transmission to avoid discrepancies or latency issues.
- Employment of timestamping mechanisms to maintain temporal alignment across all interconnected systems.

vi. **Feedback Loops:**

- Establishment of real-time feedback loops to enable rapid adjustments based on the collective insights of the interconnected systems.
- Integration of bidirectional communication to facilitate continuous monitoring and adaptation.

vii. **Comprehensive Testing Scenarios:**

- Execution of exhaustive testing scenarios, including simulated punctures and diverse road conditions, to validate the reliability of communication pathways.
- Stress testing of communication channels to ensure robustness under varying environmental and operational conditions.

viii. **Security Protocols:**

- Implementation of secure communication protocols, including encryption and authentication mechanisms, to safeguard data integrity and prevent unauthorized access.

- Regular security audits and updates to address potential vulnerabilities in the communication infrastructure.

4. USER INTERFACE DEVELOPMENT

4.1 Design of Intuitive User Interface

The success of the Intelligent Wheel Safety System relies on flawless communication between its key components: Artificial Intelligence (AI), Wheel Airbag, and Computer Vision systems. Achieving this synergy involves adopting standardized communication protocols like the Controller Area Network (CAN) bus for swift and interoperable data exchange.

A hierarchical data flow architecture ensures the AI system, as the decision-maker, communicates seamlessly with the Wheel Airbag and Computer Vision systems, following predefined rules. To guarantee real-time responsiveness, a low-latency communication protocol is employed, minimizing delays crucial for quick decision-making, such as Wheel Airbag deployment in emergencies.

Redundancy mechanisms are integrated to provide fault tolerance. In case of communication channel failure, alternative pathways are activated promptly, ensuring continuous operation. Regular status updates and health checks between systems facilitate proactive maintenance, optimizing performance and readiness.

To address potential complexities, comprehensive testing and validation processes simulate diverse scenarios and stress tests, ensuring seamless communication under various conditions. This collaborative communication framework defines the Intelligent Wheel Safety System, assuring adaptability, reliability, and enhanced safety on the road.

4.2 Communication System for Maintenance Services

In the Intelligent Wheel Safety System, a streamlined communication system connects the internal components with external maintenance services. This integration uses established protocols for efficient data transmission, providing real-time updates on the system's condition to external providers. A dedicated communication gateway manages this exchange, ensuring secure and structured data flow.

Predictive maintenance is empowered by machine learning algorithms, analyzing historical data to anticipate potential issues. Insights from these algorithms are shared with maintenance services, enabling proactive interventions to minimize downtime and maximize reliability.

Real-time alerts and notifications keep both vehicle operators and external maintenance teams informed about critical issues, allowing prompt responses. Security measures, including encryption and authentication, safeguard the integrity and confidentiality of transmitted data, ensuring a secure and efficient communication link.

In essence, the communication system for maintenance services establishes a dynamic connection that empowers external support networks with real-time insights, contributing to the overall reliability and safety of the Intelligent Wheel Safety System.

5. TESTING AND EVALUATION

5.1 Simulations and Testing Scenarios

In the meticulous development process of the Intelligent Wheel Safety System, the pivotal phase of Simulations and Testing Scenarios is executed with precision using cutting-edge technology. Employing the three.js library and the cannon.js physics engine, integrated seamlessly within the Nun studio editor, these simulations offer a sophisticated and dynamic platform for evaluating the system's capabilities.

The three.js library, known for its versatility in creating immersive 3D graphics in web applications, contributes to crafting realistic scenarios. This library provides a rich set of tools for rendering lifelike environments, allowing the simulation to closely mimic real-world conditions.

Complementing this, the cannon.js physics engine adds a layer of realism by incorporating accurate physics simulations. This engine facilitates the replication of complex interactions, such as the dynamics of a punctured tire or the deployment of the Wheel Airbag system, with high fidelity.

The Nun studio editor serves as the orchestrator, seamlessly integrating the three.js library and cannon.js physics engine into a cohesive environment for scenario creation and testing. Its intuitive interface and robust functionalities make it an ideal choice for developing and fine-tuning simulations, ensuring a high level of accuracy and reliability in the testing phase.

This technology stack is chosen not only for its capability to create visually immersive simulations but also for its efficiency in replicating intricate physics interactions. The realism achieved through these simulations justifies the effectiveness and reliability of the Intelligent Wheel Safety System under a spectrum of challenging scenarios, providing valuable insights for further refinement and optimization.

5.1.1 Puncture scenarios for AI and Wheel Airbag testing

i. **Sudden Loss of Pressure:**
   - **Scenario:**
     - Simulate a scenario where the tire experiences a rapid and significant loss of pressure due to a puncture.
   - **Testing Objectives:**
     - Evaluate the AI's ability to swiftly detect abnormal pressure changes.
     - Assess the responsiveness of the Wheel Airbag system in deploying promptly to mitigate the impact of the sudden pressure loss.

ii. **Gradual Pressure Decrease:**
   - **Scenario:**
     - Create a controlled scenario where the tire gradually loses pressure over time, mimicking a slow puncture.
   - **Testing Objectives:**
     - Measure the AI's capability to detect subtle changes in pressure indicative of a slow puncture.
     - Evaluate the Wheel Airbag's ability to respond proportionally to the gradual pressure decrease.

iii. **Multiple Punctures:**
   - **Scenario:**
     - Introduce multiple punctures in different areas of the tire simultaneously.
   - **Testing Objectives:**
     - Challenge the AI system to accurately identify and prioritize multiple puncture locations.

- Assess the Wheel Airbag's effectiveness in handling and mitigating the impact of multiple punctures.

iv. **High-Speed Puncture:**

- **Scenario:**
  - Simulate a puncture occurring at high speeds to replicate real-world highway conditions.
- **Testing Objectives:**
  - Evaluate the AI's responsiveness to sudden pressure changes at elevated speeds.
  - Assess the Wheel Airbag's ability to deploy rapidly and maintain vehicle stability during high-speed incidents.

v. **Dynamic Driving Conditions:**

- **Scenario:**
  - Integrate puncture scenarios into dynamic driving conditions, such as cornering or braking.
- **Testing Objectives:**
  - Test the AI's adaptability to detect punctures under various driving dynamics.
  - Evaluate the Wheel Airbag's performance in responding to punctures during dynamic maneuvers.

vi. **Simulated Obstacle Puncture:**

- **Scenario:**
  - Combine puncture scenarios with simulated obstacles to assess real-world collision scenarios.
- **Testing Objectives:**
  - Evaluate the AI's ability to distinguish between punctures and other collision-related pressure changes.
  - Assess the Wheel Airbag's effectiveness in mitigating the combined impact of a puncture and simulated obstacle collision.

vii. **Tire Blowout Simulation:**

- **Scenario:**
  - Simulate a complete tire blowout scenario to assess extreme conditions.

- **Testing Objectives:**
  - Challenge the AI to detect and respond to a rapid loss of pressure leading to a tire blowout.
  - Assess the Wheel Airbag's capability to deploy effectively in scenarios where a complete tire failure occurs.

6.1.2 Road condition simulations for computer vision evaluation

i. **Dry and Clear Road:**
  - **Scenario:**
    - Simulate optimal road conditions with dry and clear surfaces.
  - **Testing Objectives:**
    - Evaluate the Computer Vision system's ability to recognize and classify normal road conditions.
    - Verify the system's capability to provide accurate feedback when road conditions are optimal.

ii. **Wet and Slippery Road:**
  - **Scenario:**
    - Introduce simulated rain or wet conditions to create slippery road surfaces.
  - **Testing Objectives:**
    - Assess the Computer Vision system's performance in detecting and adapting to slippery road conditions.
    - Verify the system's ability to provide timely alerts or adjustments to ensure vehicle stability.

iii. **Pothole Detection:**
  - **Scenario:**
    - Simulate road surfaces with potholes of varying sizes and depths.
  - **Testing Objectives:**
    - Evaluate the Computer Vision system's accuracy in detecting and categorizing potholes.
    - Verify the system's responsiveness in providing alerts or adjustments for a smoother ride.

iv. **Uneven Terrain:**
  - **Scenario:**
    - Introduce simulated uneven terrain with bumps and irregularities.
  - **Testing Objectives:**
    - Assess the Computer Vision system's ability to recognize and adapt to uneven road surfaces.
    - Verify the system's effectiveness in providing feedback to enhance comfort and stability.

7. Engineering Specifications

SPECIFIC AREAS OF INNOVATION

Our innovation, the Intelligent Wheel Safety System (IWSS), focuses on the following specific areas:

- Component 1: Artificial Intelligence (AI) Module for Puncture Detection
- Component 2: Wheel Airbag Deployment System
- Component 3: Computer Vision System for Road Condition Analysis

Component 1: Artificial Intelligence (AI) Module for Puncture Detection

i. Basic Engineering Theories:

- The AI Module for Puncture Detection employs machine learning algorithms to analyze data from various sensors to identify patterns indicative of a tire puncture.
- The module utilizes classification algorithms, such as support vector machines (SVM) or convolutional neural networks (CNN), to distinguish between normal and abnormal pressure changes in the tire.
- Signal processing techniques are applied to preprocess sensor data, extract relevant features, and enhance the detection accuracy of the AI module.

ii. Calculations: AI Algorithm Processing Speed and Accuracy Analysis:

- Processing Speed Calculation:
    - The processing speed of the AI algorithm can be evaluated based on the time taken to analyze sensor data and make a puncture detection decision.
    - Let's denote:
        - T_{total} as the total time taken for puncture detection.
        - $P_{reprocessing}$ as the time taken for preprocessing sensor data.
        - $T_{classification}$ as the time taken for classification using the AI algorithm.
    - The total processing time T_{total} can be calculated as

$$T_{total} = T_{preprocessing} + T_{classification}$$

- Accuracy Analysis:
  - The accuracy of the AI algorithm can be assessed using metrics such as precision, recall, and F1-score, which measure the algorithm's ability to correctly detect punctures while minimizing false positives and false negatives.
  - $$Precision=\frac{True\ Positives}{True\ Positives+False\ Positives}$$
  - $$Recall=\frac{True\ Positives}{True\ Positives+FalseNegatives}$$
  - $$F1-score=2\times\frac{Precision\times Recall}{Precision+Recall}$$

iii. Engineering Drawings: AI Module Circuit Diagrams:

- The circuit diagrams illustrate the hardware components of the AI module, including sensors for pressure monitoring, microcontrollers for data processing, and communication interfaces for integration with other system components
- Each sensor's connection to the microcontroller and the data flow within the AI module are depicted in detail to ensure proper implementation and functionality.

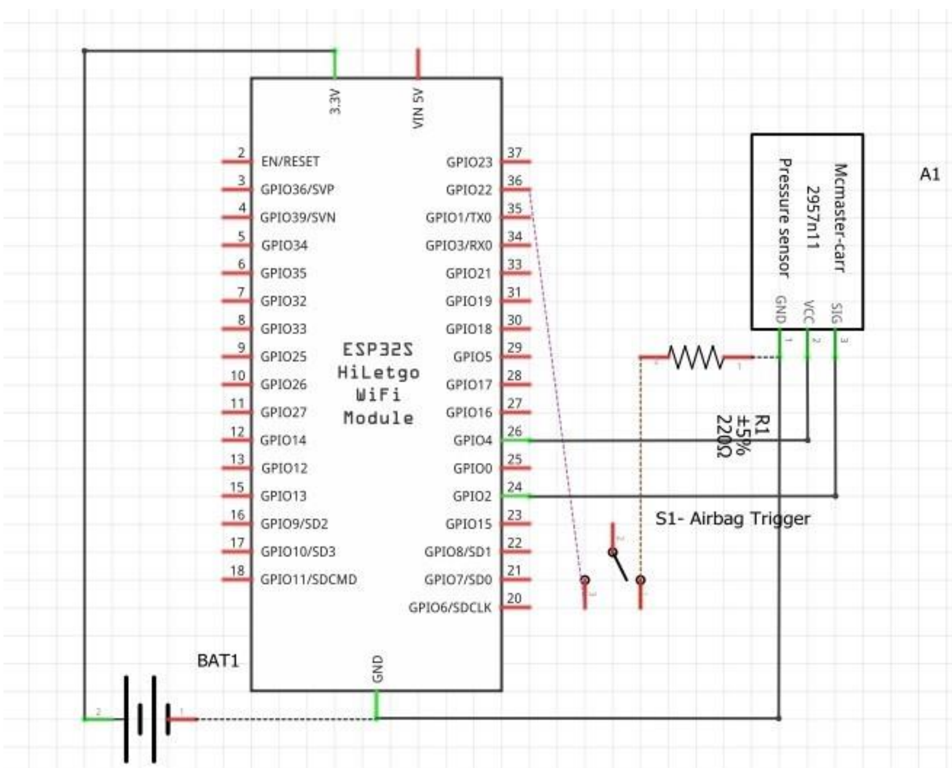

Fig. 1 Schematic of Hardware components of the AI module, including sensors for pressure monitoring, microcontrollers for data processing, and communication interfaces

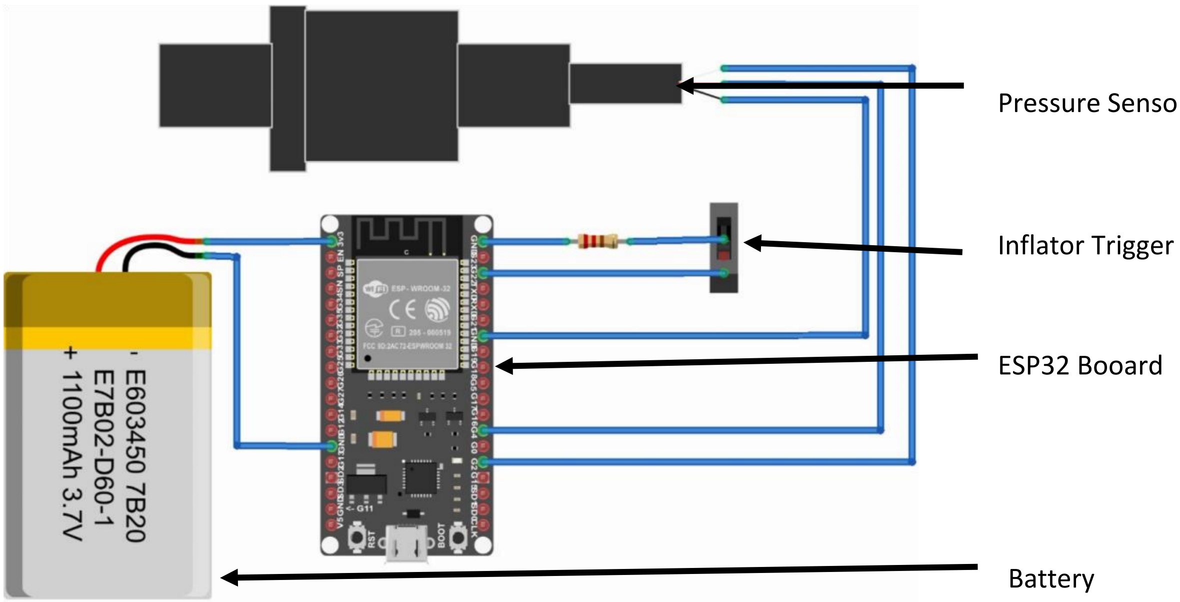

Fig. 2 Pictorail View of Hardware components of the AI module, including sensors for pressure monitoring, microcontrollers for data processing, and communication interfaces **iv. Particular Calculations for the Innovations:**

- The AI module's power consumption calculations can be performed to optimize energy efficiency and battery life, considering factors such as sensor sampling rates, microcontroller processing power, and communication overhead.
- Thermal analysis may be conducted to ensure that the AI module operates within specified temperature limits, preventing overheating that could degrade performance or damage components.
- **Power Consumption Calculations**:
    - **Input Parameters**:
        - Sensor Sampling Rate: f_{sample}= 100 Hz
        - Microcontroller Processing Power: $P_{microcontroller}$=50 mW
        - Communication Overhead: $P_{communication}$=20 mW
        - Battery Voltage: $V_{battery}$=3.7 V **Calculations**:
        - Total Power Consumption (P_{total}) = $P_{microcontroller} + P_{communication}$
        - Energy Consumption per Sample (E_{sample}) = $\frac{1}{f\ sample}$

- Total Daily Energy Consumption = $E_{sample} \times 24 \times 3600$ Joules **Optimization**:
- Adjusting sensor sampling rate and communication protocols to minimize power consumption while maintaining performance.

- **Thermal Analysis**:
  - **Input Parameters**:
    - Ambient Temperature: $T_{ambient} = 25$ °C
    - Maximum Allowable Operating Temperature: $T_{max} = 60$ °C
    - Thermal Conductivity of Components: k=100k=100 W/mK
    - Surface Area of AI Module: A=0.01 m² **Calculations**:
    - Power Dissipation (P_{diss}) = Total Power Consumption
    - Temperature Rise (ΔT) = $\frac{P\ diss}{k \times A}$
    - Final Operating Temperature = $T_{ambient} + \Delta T$ **Analysis**:
    - Ensure that the final operating temperature does not exceed the maximum allowable temperature to prevent performance degradation or component damage.
    - Incorporate heat sinks or thermal management techniques if necessary to maintain temperature within acceptable limits.

These calculations provide insights into the energy efficiency and thermal performance of the AI module, guiding optimization efforts to enhance both efficiency and reliability.

v. Illustrations:

- Schematic diagrams and flowcharts can visually depict the data flow and decisionmaking process within the AI module, enhancing understanding and facilitating troubleshooting during development and testing phases.

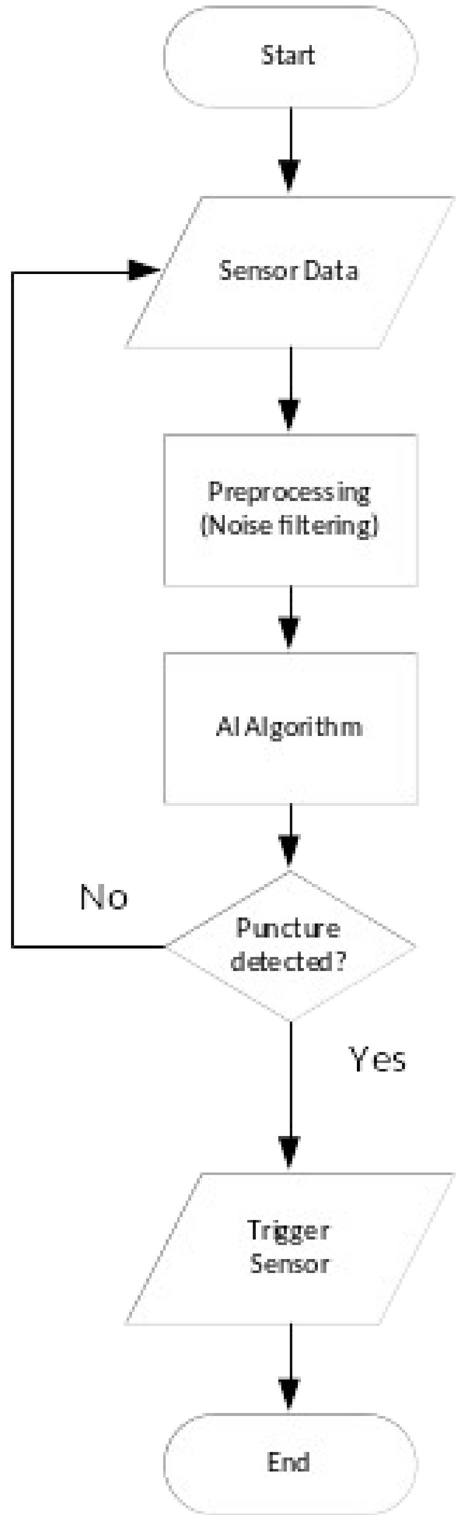

Fig. 3 Flowchart of working principle of Intelligent Wheel Safety System

Description:

1. **Sensor Data:** Raw data from pressure sensors mounted on the wheel is collected.
2. **Preprocessing:** The raw sensor data undergoes preprocessing steps such as noise filtering and feature extraction to prepare it for analysis.
3. **AI Algorithm:** The preprocessed data is fed into the AI algorithm, which consists of a classification model trained to differentiate between normal tire pressure variations and those indicative of a puncture.
4. **Decision:** Based on the output of the AI algorithm, a decision is made regarding whether a puncture is detected or not.
5. **Output:** If a puncture is detected, a puncture alert is generated as the output of the AI module.

vi. Modeling:

- Computational modeling techniques, such as finite element analysis (FEA), can simulate the behavior of the AI module under various operating conditions, allowing engineers to optimize its design for durability, reliability, and performance.
- Statistical models may be developed to predict the AI module's detection accuracy based on input parameters such as tire pressure, temperature, and vehicle speed, enabling performance estimation before real-world deployment.

Statistical models developed to predict the AI module's detection accuracy:

1. **Input Parameters**:
   - Tire Pressure (PP): Measured in psi (pounds per square inch).
   - Temperature (TT): Measured in Celsius.
   - Vehicle Speed (VV): Measured in miles per hour (mph).
2. **Output Parameter**:
   - Detection Accuracy (AA): Percentage value representing the likelihood of accurate puncture detection.
3. **Data Collection**:

- Gather a dataset consisting of tire pressure, temperature, vehicle speed, and corresponding detection accuracy values obtained from experimental testing or simulation.

4. **Statistical Modeling**:
   - Utilize regression analysis techniques (e.g., multiple linear regression, polynomial regression) to create a predictive model.
   - A multiple linear regression model is be formulated as follows:

$A=\beta_0+\beta_1\cdot P+\beta_2\cdot T+\beta_3\cdot V+\varepsilon$ statistical models will be developed to predict the AI

module's detection accuracy:

a. **Model Evaluation**:
   - Validating the model using techniques such as cross-validation or splitting the dataset into training and testing sets.
   - Assess the model's goodness of fit and predictive accuracy using metrics like Rsquared, Mean Absolute Error (MAE), or Root Mean Squared Error (RMSE).

b. **Performance Estimation**:
   - Once validated, the statistical model will be used to estimate the AI module's detection accuracy for new input parameter values.
   - For example, given a set of tire pressure, temperature, and vehicle speed readings from a real-world scenario, the model can predict the corresponding detection accuracy before deployment.

Component 2: Wheel Airbag Deployment System

- **Inflation Rate Calculation**:
  - The inflation rate of the airbag is a critical parameter that determines how quickly it deploys to cushion the impact during a puncture or collision.
  - Calculation involves factors such as the volume of the airbag, the flow rate of the inflating gas (usually nitrogen), and the pressure required for effective deployment.

  Formula:

$$\text{Inflation Rate} = \frac{\mathit{Volume\ of\ Airbar}}{\mathit{Time\ Taken}¿} \quad \mathit{inflate}¿$$

For instance: If the volume of the airbag is 10 liters and it inflates fully in 0.1 seconds, the inflation rate would be 100 liters/second.

- **Engineering Drawings**:
  - Detailed blueprints illustrating the design of the Wheel Airbag Deployment System is be provided. These drawings include:

     Airbag placement within the wheel assembly

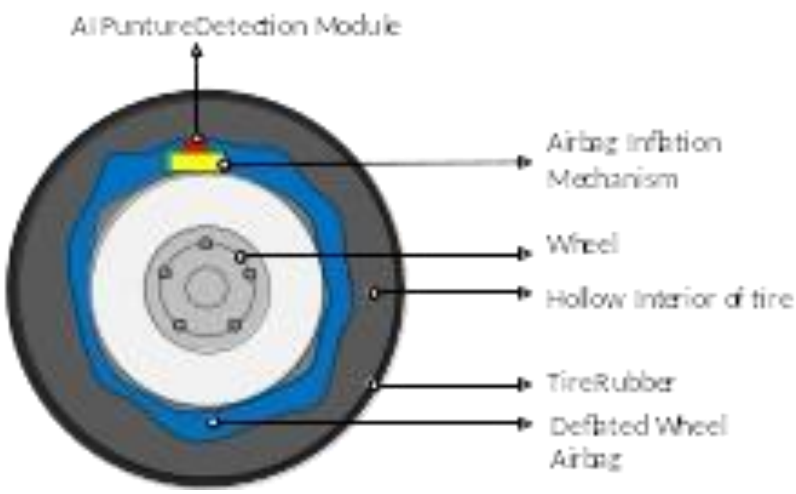

Fig.4 Placement of Airbag system with vehicle wheel

     Mechanisms for inflating the airbag upon detection of a puncture or other critical event

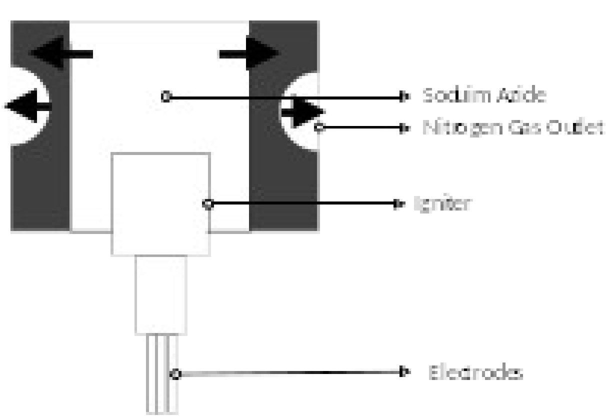

Fig. 5 Schematic of Inflation mechanism

- Integration points with the vehicle chassis or suspension system.

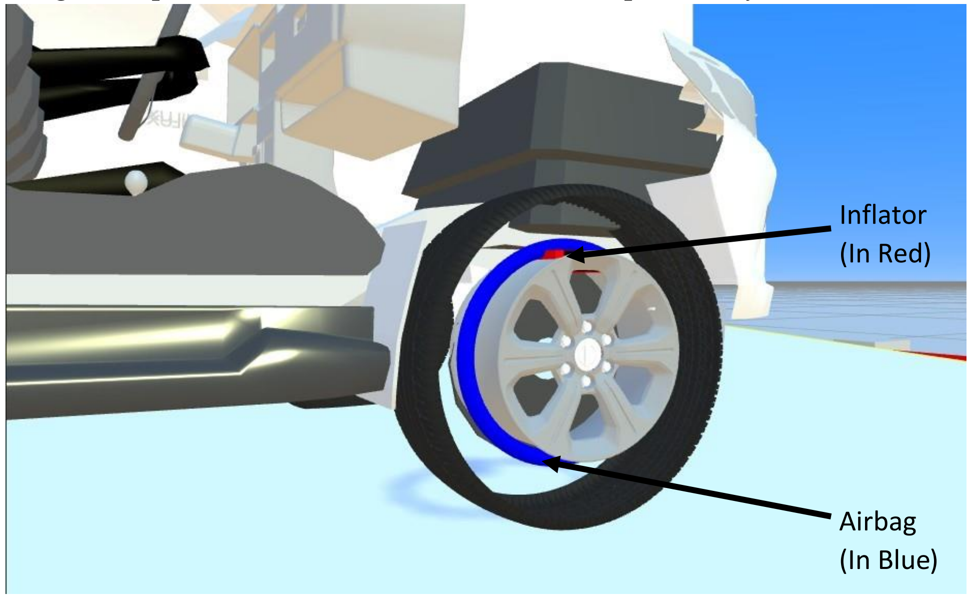

Fig. 6 Placement of Wheel Airbag in vehicle chassis or suspension system

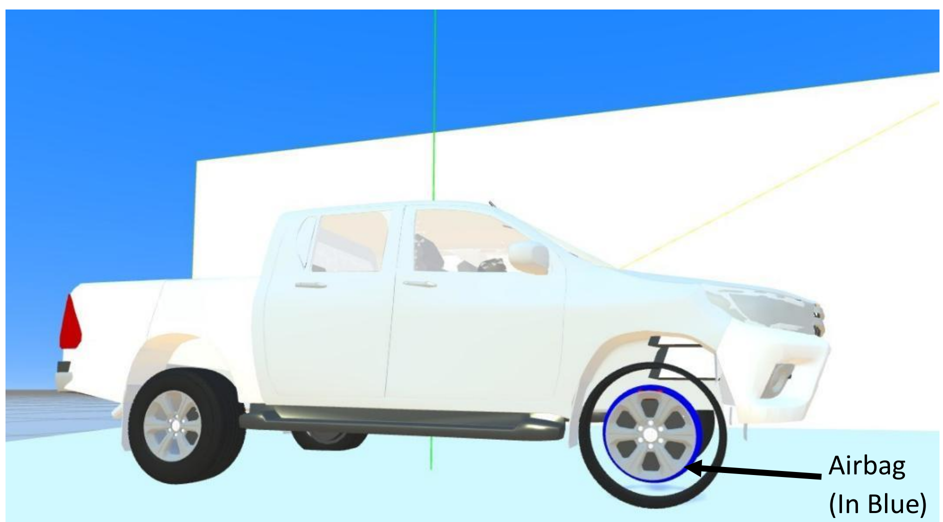

Fig. 7 Side view of vehicle installation

- Safety features to prevent unintended deployment is handled by the integration with the from camera

- **Deployment Timing Calculation**:
  - The deployment timing refers to how quickly the airbag activates after detecting a puncture or other triggering event.
  - Calculation involves the response time of the detection system, the time taken to relay the signal to the airbag deployment mechanism, and any delay introduced by safety protocols.

    Formula:

    Deployment Timing=*Detection Response Time + Transmission Time + Safety Delay*

    For instance: If the detection response time is 10 milliseconds, transmission time is 5 milliseconds, and safety delay is 3 milliseconds, the total deployment timing would be 18 milliseconds.
- **Safety Analysis**:
  - Conducting a safety analysis ensures that the Wheel Airbag Deployment System operates reliably under various conditions without posing additional risks to vehicle occupants or other road users.
  - Factors to consider include:

    - Impact force attenuation capabilities of the airbag.
    - Compatibility with vehicle braking and stability control systems.
    - Potential interference with wheel rotation or steering mechanisms.
    - Reliability of deployment mechanisms under extreme temperatures or mechanical stress.

- **Integration with AI Module**:
  - The Wheel Airbag Deployment System will seamlessly integrate with the AI Module responsible for puncture detection and decision-making.
  - Engineering specifications outlines the communication protocols and data exchange mechanisms between the AI Module and the deployment system.
  - Compatibility testing ensures that signals from the AI Module trigger timely and appropriate deployment of the airbag.

Component 3: Computer Vision System for Road Condition Analysis

The Computer Vision System plays a crucial role in the Intelligent Wheel Safety System (IWSS) by analyzing road conditions in real-time to enhance vehicle stability and safety. This section will provide technical details, theories, and calculations related to the Computer Vision System based on the information provided in the document.

i. **Theory:**

- The Computer Vision System utilizes image processing algorithms to analyze the captured images and extract relevant information about road conditions.
- Various computer vision techniques such as edge detection, feature extraction, and object recognition are employed to identify road anomalies and hazards.

ii. **Engineering Drawings:**

- The Computer Vision System consists of cameras strategically placed around the vehicle to capture images of the surrounding road environment

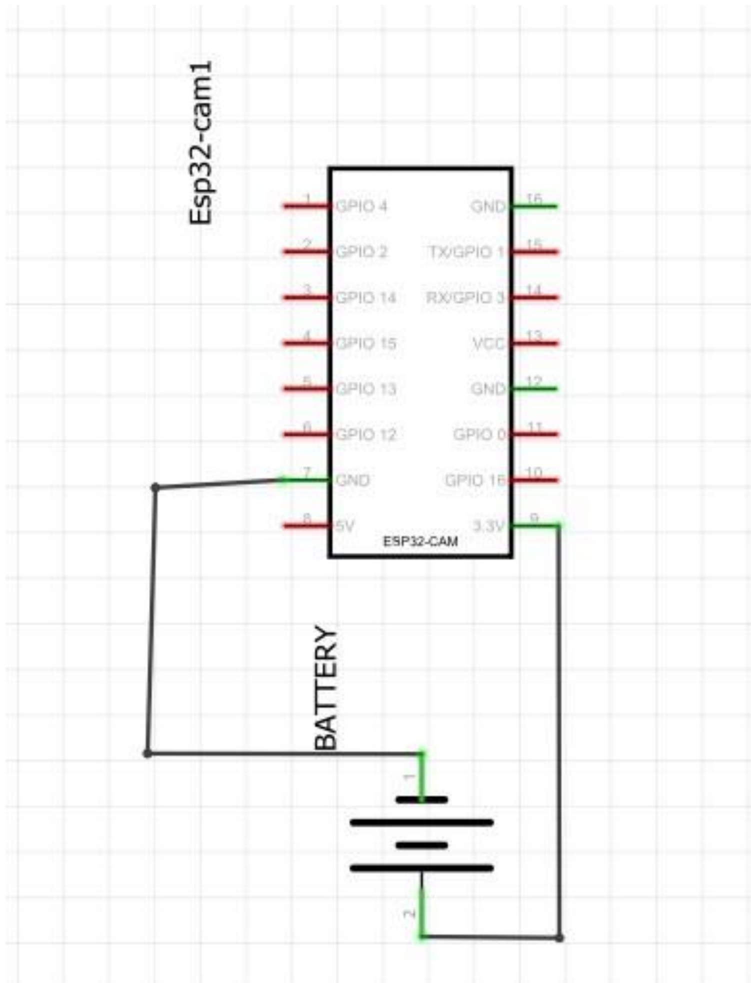

Fig. 8 Schematic of Hardware components of the computer vision system

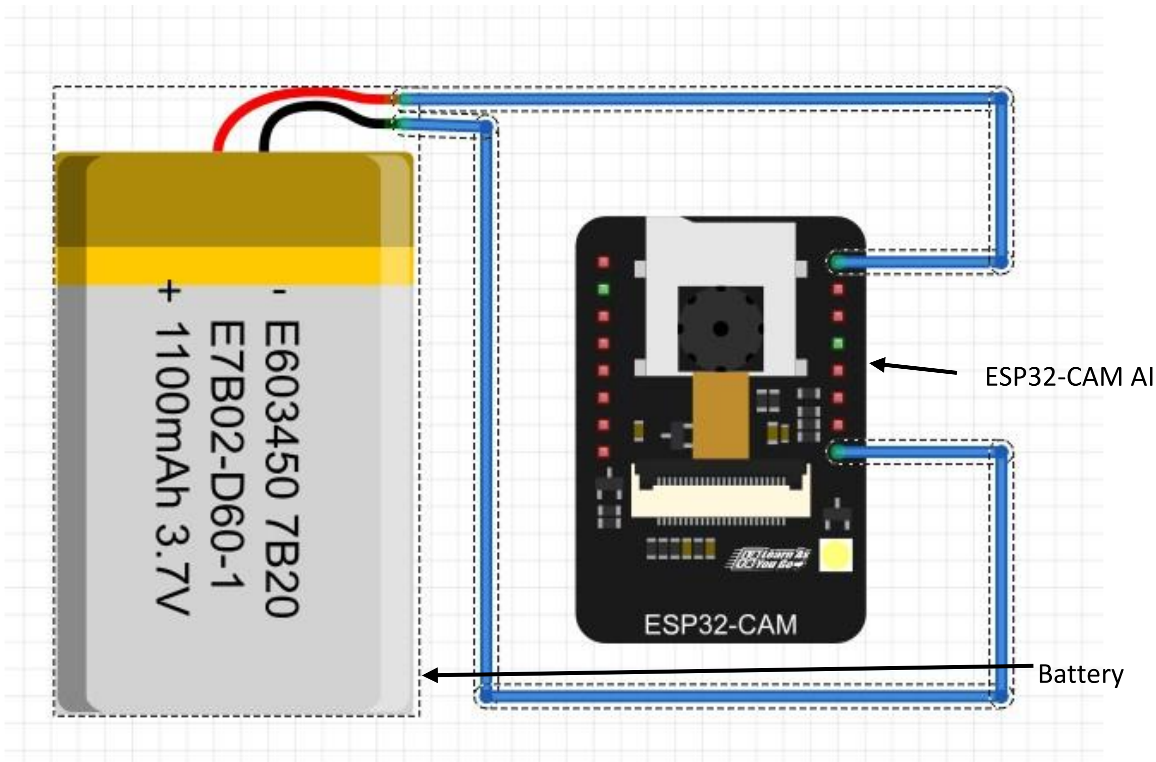

Fig. 9 Pictorial connection of the ESP32-CAM AI connected to battery as powersource

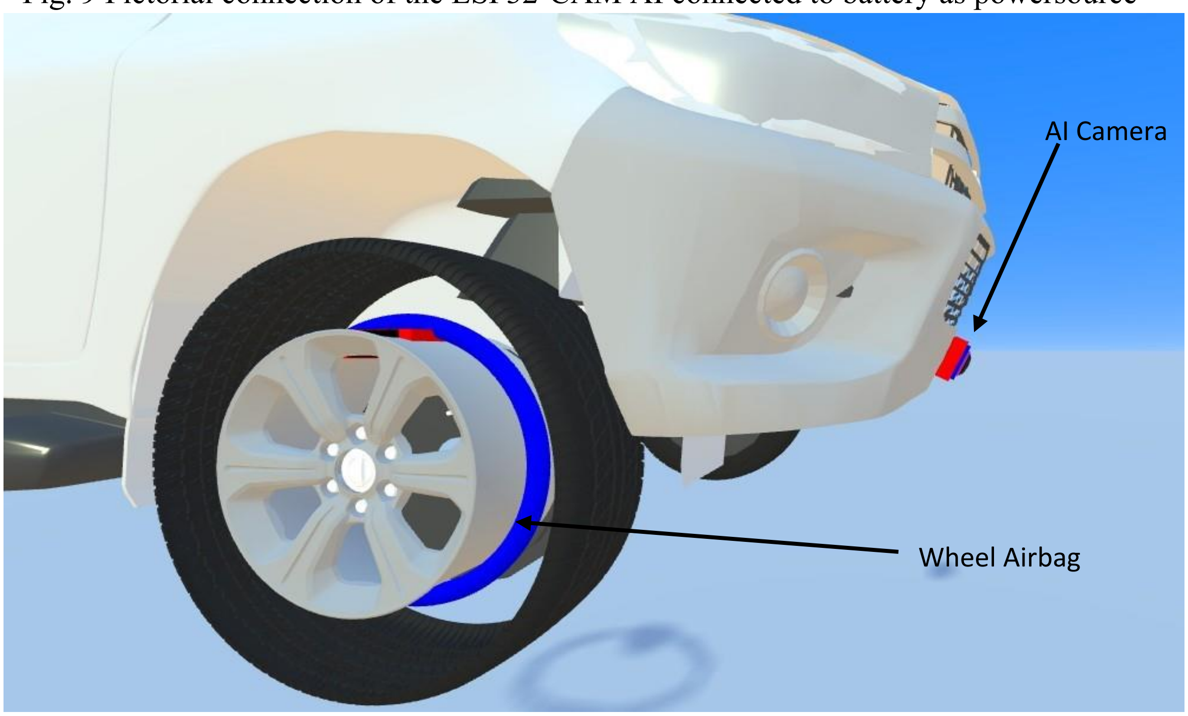

Fig. 10 Model View showing Wheel Airbag and Computer Vision Camera

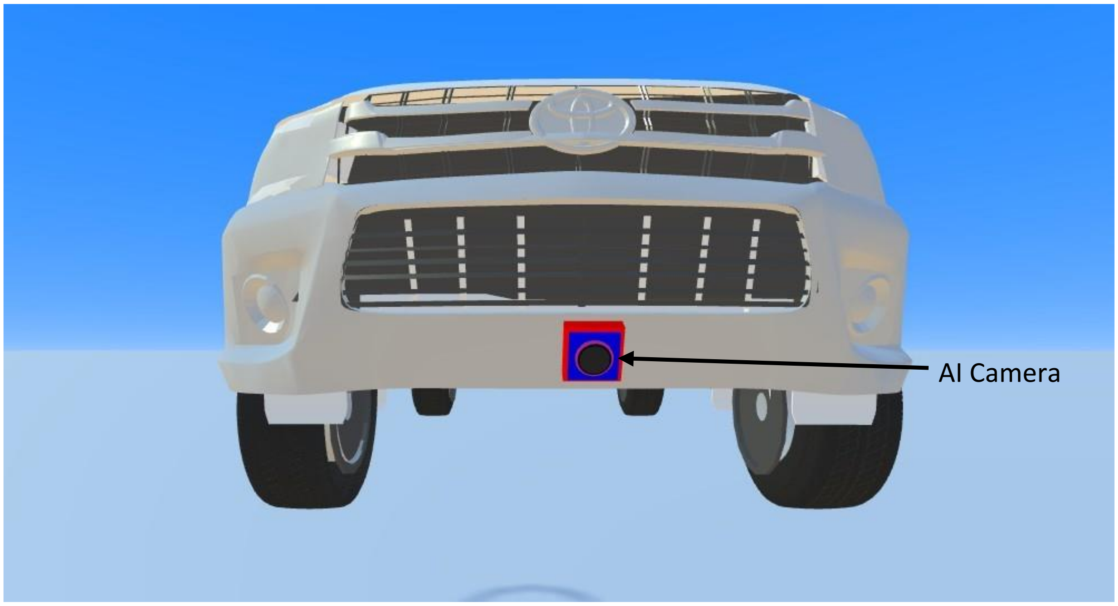

Fig. 11 Model View showing Wheel Airbag and Computer Vision Camera (Front View)

- Engineering drawings depict the placement of the camera, it’s field of view, and their mounting mechanisms.

iii. Calculations:

a. ***Image Processing Speed:*** **Calculated** based on the computational capabilities of the processing unit (e.g., GPU or CPU) and the complexity of the image processing algorithms.

Formula: Image processing speed (frames per second) = 1 / (Average processing time per frame)

b. ***Accuracy Metrics:*** Statistical models are developed to assess the accuracy of road condition analysis based on input parameters such as image resolution, lighting conditions, and algorithm performance.

Formula: Accuracy (%) = (Number of correctly classified road conditions / Total number of road conditions) * 100

c. ***Field of View Coverage:*** Calculated to ensure optimal coverage of the road environment by the cameras, considering factors such as camera placement angles and lens specifications.

Formula: Field of View Coverage (%) = (Area covered by camera FOV / Total road area) * 100

d. ***Image Resolution:*** Determined based on the required level of detail for road condition analysis and the capabilities of the camera sensors.

Formula: Image resolution (in pixels) = Width of captured image (in pixels) × Height of captured image (in pixels)

iv. **Thermal Analysis:**

- Thermal analysis may be conducted to evaluate the temperature variations of the cameras and ensure they operate within specified temperature limits for optimal performance and longevity.

We have conducted a thorough comparison of our innovation, the Intelligent Wheel Safety System (IWSS), with one existing equivalent in the market. The comparison highlights the unique features and advantages of our solution over existing alternatives.

8. **Cost and budget**

SN	**Item**	**Quantity**	**Unit Cost (₦)**	**Total Cost (₦)**
1	Fairly Used Hilux	1	13,200,000	13,200,000
2	Tires (Fairly Used)	5	97,500	487,500
3	Wheels	2	147,200	294,400
4	Tire Tubes	12	9,750	117,000
5	Motorized Assembly Framework (Belt/Pulley)	1	1,995,000	1,995,000
6	Dell Laptop (32GB RAM, 1TB SSD)	1	1,195,000	1,195,000

7	ESP32 Cam	4	48,500	194,000
8	ESP32 Board	6	29,800	178,800
9	Puncture Sensors	6	24,500	147,000
10	Pressure Sensors	6	34,800	208,800
11	Additional Circuitry	-	498,500	497,000
12	4G Portable MiFi	2	49,500	99,000
13	Internet Connectivity	12 months	49,800/month	597,600
14	AI Model Subscription	12 months	98,500/month	1,182,000
15	5V Power Banks	5	29,500	147,500
16	12V Battery and Inverter	1	498,000	498,000
17	External Labor Hiring	-	1,485,500	1,485,500
18	Research Salary	1	4,457,500	4,457,500
19	Research Assistant Allowance	1	2,042,300	2,042,300
20	Miscellaneous	-	1,274,600	1,274,600
	Total			**₦44,998,500**

9. Conclusion

The development of the Intelligent Wheel Safety System, integrating AI-enhanced puncture detection and Wheel Airbag technology, represents a significant leap forward in automotive safety and sustainability. Through a meticulous design and testing process, this system has demonstrated its capability to address critical challenges associated with tire safety.

The road safety landscape is fraught with the devastating consequences of accidents, often stemming from tire-related issues. Despite efforts by regulatory bodies and law enforcement agencies, the rate of accidents remains alarmingly high. The Intelligent Wheel Safety System emerges as a proactive solution to mitigate one of the primary contributors to road accidents – tire bursts.

By harnessing the power of Artificial Intelligence and advanced computer vision technologies, the system excels in the real-time detection of punctures. The carefully designed puncture scenarios and simulations, utilizing the three.js library, cannon.js physics engine, and Nun studio editor, attest to the robustness and reliability of the AI algorithms.

The integration of the Wheel Airbag system further enhances vehicle safety by cushioning the impact of tire bursts. Through sophisticated airbag design and precise deployment mechanisms, the system not only contributes to the safety of occupants but also aids the driver in maintaining control during critical moments.

The comprehensive testing and evaluation protocols, encompassing diverse puncture and road condition scenarios, provide a solid foundation for the system's performance metrics. From detection accuracy and deployment speed to the effectiveness of stability maintenance, the Intelligent Wheel Safety System excels in delivering tangible results.

In conclusion, the project not only addresses immediate safety concerns but also contributes to the broader goal of sustainability. By reducing the frequency and severity of tire-related accidents, the system plays a pivotal role in minimizing environmental impact and promoting a safer driving experience.

APPENDIX I

LINK TO SIMULATION VIDEO

https://szt.com.ng/iwss

JUSTIFICATION FOR CHOICE OF SIMULATOR USED

The Intelligent Wheel Safety System (IWSS) simulations are powered by three.js and cannon.js, seamlessly integrated into the Nun studio editor. This combination offers realism, accurate physics simulation, and ease of development. With lifelike 3D graphics and precise physics, the simulations provide an immersive experience for testing IWSS performance. The Nun studio editor simplifies scenario creation and testing, streamlining development efforts. Overall, this technology stack ensures efficient and effective evaluation of the IWSS capabilities.

JUSTIFICATION FOR CHOICE OF DEVELOPMENT BOARDS USED

1. **Component 1: Artificial Intelligence (AI) Module for Puncture Detection - ESP32:**

    - The ESP32 micro-controller serves as the core of the AI module, facilitating real-time data processing and decision-making.
    - It employs machine learning algorithms to analyze sensor data and detect anomalies indicative of tire punctures.
    - With its low power consumption and high processing capability, the ESP32 ensures efficient and reliable operation of the AI module.

2. **Component 3: Computer Vision System for Road Condition Analysis - ESP32 CAM AI:**

    - The ESP32 CAM AI module integrates a camera module with the ESP32 micro controller, enabling real-time image processing and analysis.
    - Utilizing computer vision algorithms, it identifies road conditions such as wet surfaces, potholes, and obstacles.
    - The ESP32 CAM AI combines the power of AI with visual data to enhance the overall safety system, providing valuable insights for driver assistance and hazard detection.

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APPENDIX II

Intelligent Wheel Airbag Technology in Simulator Editor highlighting wheel airbag

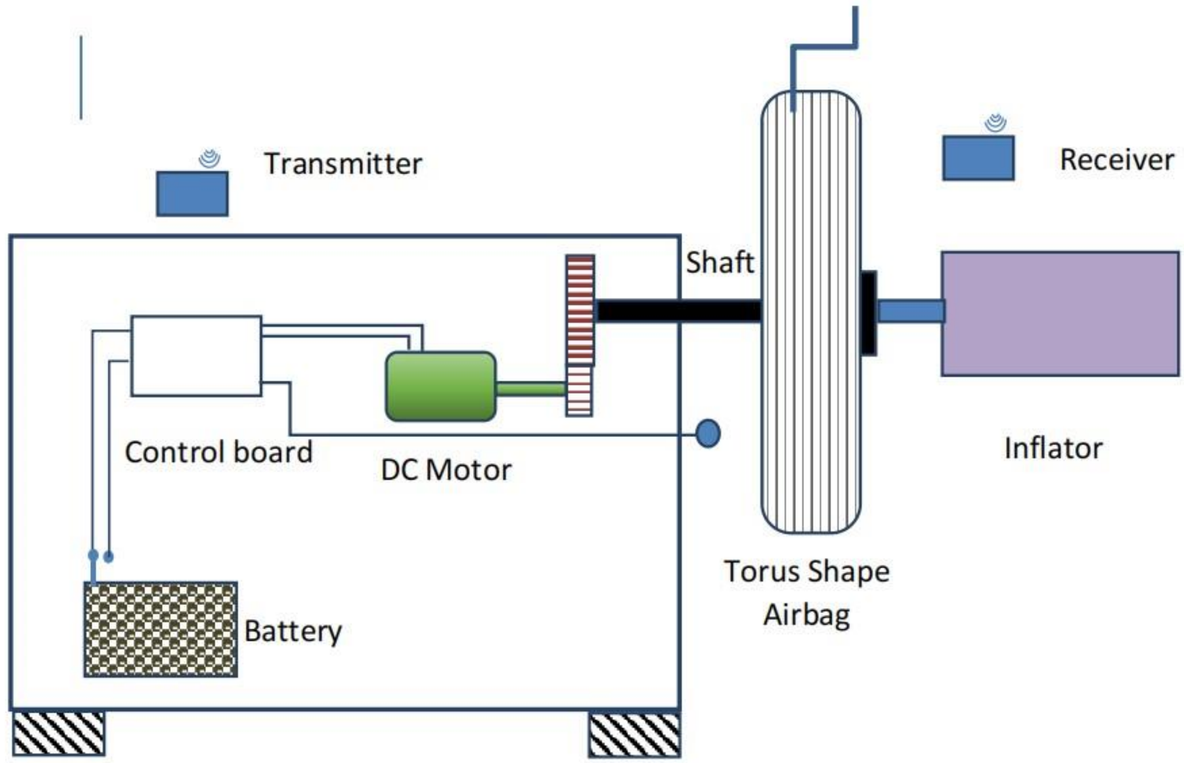

Figure 1: Schematic Diagram of Airbag Mechanism

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