An Advanced Air Suspension Control System Utilizing Intelligent Algorithms and Real-Time Terrain Detection

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Abstract - This paper presents On Air Active, an advanced aftermarket air suspension control system engineered to enhance vehicle ride comfort and stability through intelligent algorithms and robust hardware design. Utilizing a single height sensor and an ATmega328PB microcontroller, the system dynamically adjusts air pressure to maintain optimal vehicle height across varying loads and road conditions. Extensive testing on over ten commercial and disability vehicles validated On Air Active's reliability, energy efficiency, and resilience in harsh environments. Additionally, preliminary work employing a Gaussian noise model has been conducted to simulate terrain variations, laying the groundwork for future integration of AI-driven terrain detection and real-time suspension adjustments. These innovations position On Air Active as a cost-effective, easy-to-install solution, setting new standards in the aftermarket air suspension industry and contributing to the advancement of intelligent vehicle systems.

Keywords: Air suspension, Intelligent control, Aftermarket systems, Terrain analysis, Gaussian noise model, Automotive electronics.

Introduction

Vehicle suspension systems are pivotal in ensuring ride comfort and handling stability. Traditional passive suspensions, while reliable, lack the adaptability to dynamically respond to changing road conditions, often compromising performance [1]. Advances in air suspension technology have enabled real-time control over vehicle height and ride quality, significantly enhancing comfort and vehicle dynamics [2]. However, aftermarket systems frequently encounter challenges related to cost, complexity, and integration [8].

Active air suspension systems leverage intelligent control strategies such as fuzzy logic control (FLC) [4], neural networks [1], and adaptive algorithms [6] to address inherent system nonlinearities and uncertainties. FLC excels in managing complex, nonlinear systems without necessitating precise mathematical models, making it ideal for dynamic suspension adjustments [4][7].

Despite these advancements, the implementation of intelligent control in aftermarket systems is often hindered by increased complexity and cost [8]. To overcome these obstacles, we present On Air Active, an aftermarket air suspension system that combines intelligent algorithms with a simplified hardware design. Unlike existing systems that rely on multiple sensors and intricate controls, On Air Active employs a single height sensor and an ATmega328PB microcontroller, achieving precise control at reduced costs. This simplicity facilitates easier installation, making it particularly suitable for commercial and disability vehicles.

A distinguishing feature of On Air Active is its intelligent air pressure management, which seamlessly switches between an air tank and compressor to ensure rapid response under varying loads, thereby enhancing vehicle stability and ride comfort. Additionally, the system incorporates autonomous fault detection and diagnostic capabilities, thereby improving reliability and reducing maintenance costs.

This paper details the design, implementation, and validation of On Air Active, demonstrating its superiority over traditional controls through installation and testing on over ten vehicles under real-world conditions.

Literature Review

The development of intelligent control strategies for vehicle suspension systems has been extensively researched. [1] introduced a neural network-based adaptive height tracking control for active air suspensions with magnetorheological fluid dampers, enhancing ride comfort and stability. [2] provided a comprehensive review of learning-based suspension controller designs, highlighting current methodologies.

Fuzzy logic control (FLC) is widely applied due to its capability to manage nonlinearities and uncertainties [4]. [4] implemented FLC in vehicle suspensions, achieving significant improvements in ride comfort and handling. [3] reviewed adaptive control systems for active suspensions, emphasizing the benefits of computational intelligence in suspension control.

Robust adaptive controls address uncertainties in sprung mass and input delays. [6] developed a robust adaptive control for active air suspensions with uncertain sprung mass and input delays, ensuring system stability and performance. [7] further explored robust optimal control techniques for suspensions under uncertainties. [5] surveyed preview-based suspension control, highlighting the importance of road profile information for performance enhancement.

However, these advanced control strategies often require extensive computational resources and complex hardware, rendering them unsuitable for cost-sensitive aftermarket applications [8]. [9] examined road roughness detection via IMU data analysis, providing insights for future terrain-adaptive suspension controls.

Thus, there is a clear need for a simplified yet effective control system that can integrate seamlessly into existing vehicles without significant modifications.

System Design and Methodology

The On Air Active system is engineered for robust performance and simplicity in air suspension control. It utilizes a single height sensor managed by intelligent algorithms to maintain optimal ride height under varying loads, thereby reducing system complexity and cost. This design makes it particularly suitable for commercial and disability vehicles.

Hardware Design

System Installation

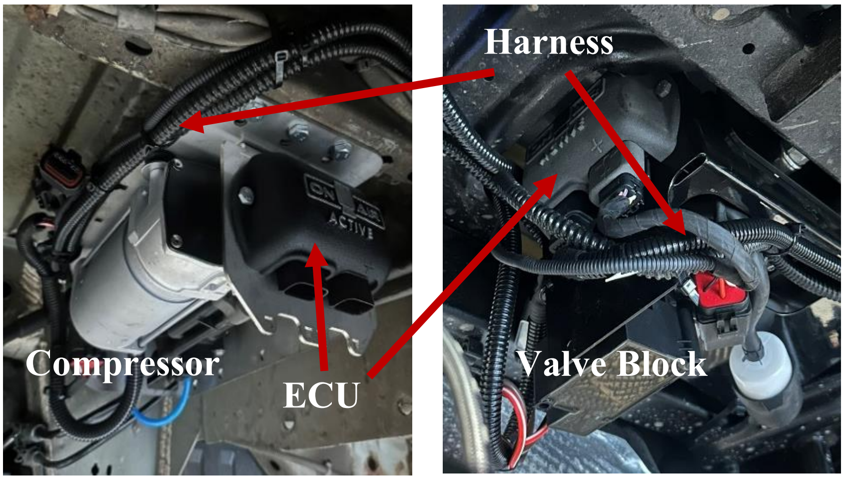

Figure 1: On Air Active S1 installed under a vehicle, featuring the air compressor, valve block, and ECU. The ECU is housed in a robust glass-filled (GF) Nylon 3D printed enclosure, ensuring durability and protection in harsh automotive environments. The harness and mounting bracket are designed for secure and efficient integration, contributing to the system's reliability and ease of installation.

Hardware Block Diagram

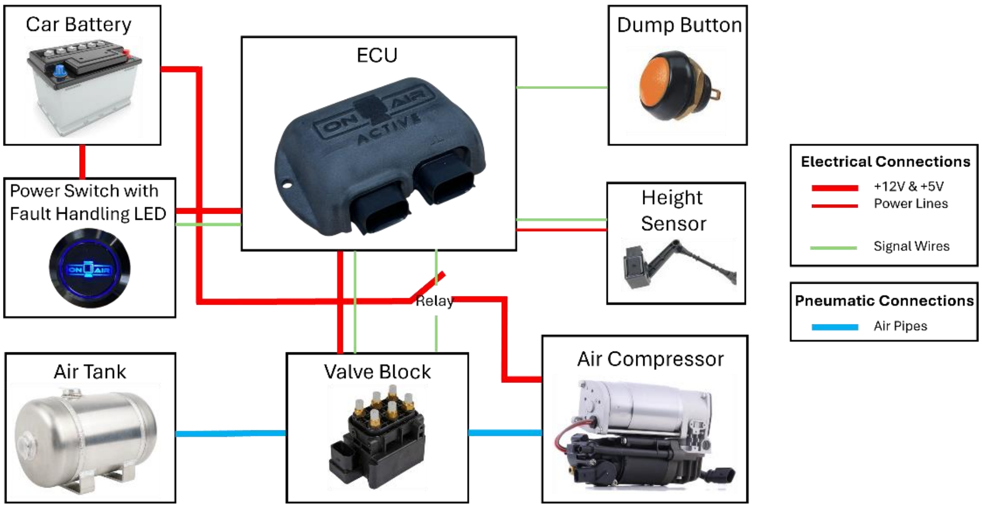

Figure 2 illustrates the hardware block diagram of the On Air Active system. The ECU is at the center, interfacing with electrical connections (+12V and 5V power lines, signal wires) and pneumatic connections (air pipes). All electrical connections are made using an OE grade manufactured automotive harness.

The hardware components are designed to ensure seamless communication between the sensors and actuators. The ECU processes the input signals and controls the actuators to adjust the air suspension accordingly.

Key hardware components include:

- **Power Management Circuitry:** Maintains a stable 5V supply for the microcontroller, ensuring consistent operation despite voltage fluctuations.
- **Height Sensor Power Supply Circuit:** Provides a reduced-noise power source and analog input signal for accurate height measurements.
- **Relay and Valve Drivers:** Control relays (High Side Switches) that manage the compressor, vent, and valve blocks reliably under varying conditions.

Sensor Voltage Conversion

The analog voltage readings from the sensors are converted to digital values using the ADC (Analog-to-Digital Converter) of the microcontroller. The sensor voltage V_{sensor} is calculated as:

$$V_{sensor} = \frac{ADC_{value} \times V_{ref}}{1024}$$

where:

- ADC_{value} is the ADC reading (0 to 1023).
- V_{ref} is the reference voltage (5V).

Battery Voltage Monitoring

The battery voltage $V_{battery}$ is monitored using a voltage divider circuit. The voltage is calculated as:

$$V_{battery} = V_{input} \times \left(\frac{R_1 + R_2}{R_2}\right)$$

where:

- $V_{input} = \frac{ADC_{value} \times V_{ref}}{1024}$
- R_1 and R_2 are the resistor values in the voltage divider.

Control System

Control Algorithm

The control algorithm is designed to adjust the air suspension based on the height sensor readings. The error between the desired height $h_{desired}$ and the measured $h_{measured}$ is calculated:

$$e = h_{desired} - h_{measured}$$

The rate of change of the error is given by:

$$\dot{e} = \frac{de}{dt}$$

These values are used in the decision-making logic to determine the necessary control actions.

Software Flowchart

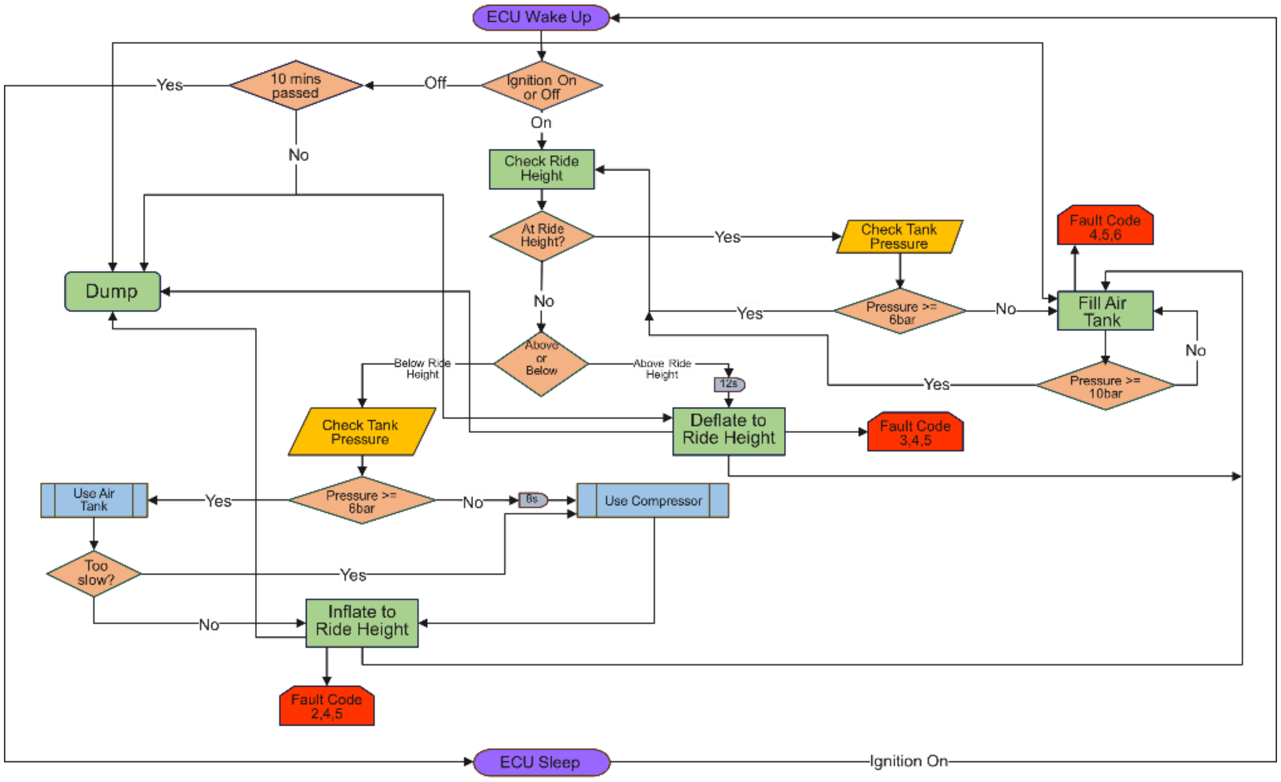

Figure 3 presents the software flowchart diagram that explains how the On Air Active software operates. The flowchart outlines the main control loops, fault detection mechanisms, and decision-making processes.

Decision Logic

The system uses predefined thresholds to determine the control action:

- **If** $e > \epsilon$ (vehicle is too low), **inflate** the air springs.
- **If** $e < -\epsilon$ (vehicle is too high), **deflate** the air springs.
- **If** $|e| \leq \epsilon$, maintain current pressure.

where ϵ is a small tolerance value.

This approach allows the system to handle changes in load conditions efficiently without complex mathematical models.

Actuator Control

Based on the decision logic, the system controls the actuators:

- **Inflation**: Opens the valves to allow air from the tank or compressor into the air springs.
- **Deflation**: Opens the vent valves to release air from the air springs.
- **Maintain**: Keeps all valves closed to maintain current pressure and ride height.

Fault Detection

The system continuously monitors various parameters to detect faults:

- **Sensor Faults**: Detected if sensor readings are out of expected ranges.
- **Low Battery Voltage**: Triggered if $V_{battery} < V_{threshold}$ for a certain amount of time, to account for engine cranks.
- **Compressor Faults**: Identified if the compressor does not respond as expected.

When a fault is detected, the system logs the fault code and alerts the user via the LED indicator.

Preliminary Data Analysis for Terrain Detection

While terrain detection has not yet been implemented in the On Air Active system, preliminary work has been conducted to simulate IMU data based on the study by Wen [9]. The goal is to analyse how terrain variations could affect suspension control in future system enhancements.

IMU Data Simulation Using Gaussian Noise Model

Data from "Road Roughness Detection by Analyzing IMU Data" by Wan Wen [9] was expanded using a Gaussian noise model to simulate different road conditions. The simulation generates synthetic IMU Z-axis acceleration data for various terrains:

- **Smooth Road**: Minimal noise ($\sigma = 0.1\ m/s^2$).
- **Gravel Road**: Moderate noise ($\sigma = 0.5\ m/s^2$).
- **Dirt Road**: Higher noise levels ($\sigma = 0.7\ m/s^2$).
- **Off-Road**: Intense noise ($\sigma = 1.0\ m/s^2$).
- **Potholes**: Sharp spikes in acceleration ($\sigma = 5.0\ m/s^2$), with additional spikes.

The acceleration a_z is modeled as:

$$a_z = a_g + N(0, \sigma^2)$$

where:

- a_g is the gravitational acceleration (9.81 m/s²).
- $N(0, \sigma^2)$ is Gaussian noise with zero mean and variance σ^2.

Terrain Detection Charts

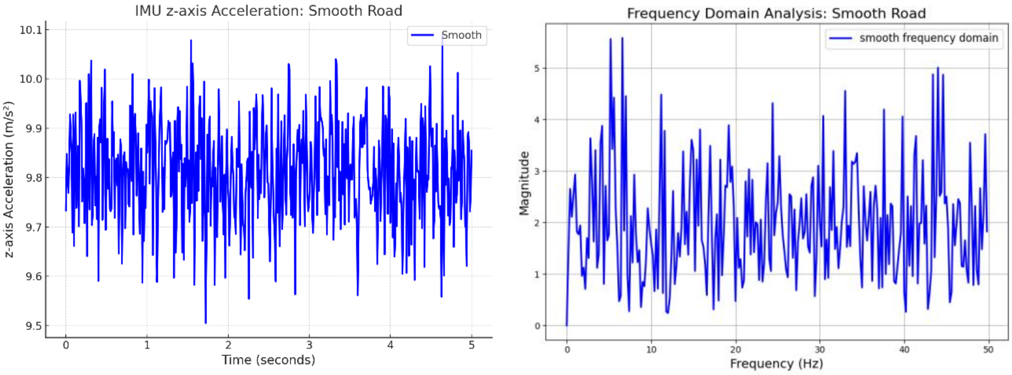

Figure 4: IMU Z-axis acceleration on a smooth road. A small standard deviation (0.1 m/s²) was used to represent minimal variations in acceleration on a flat surface.

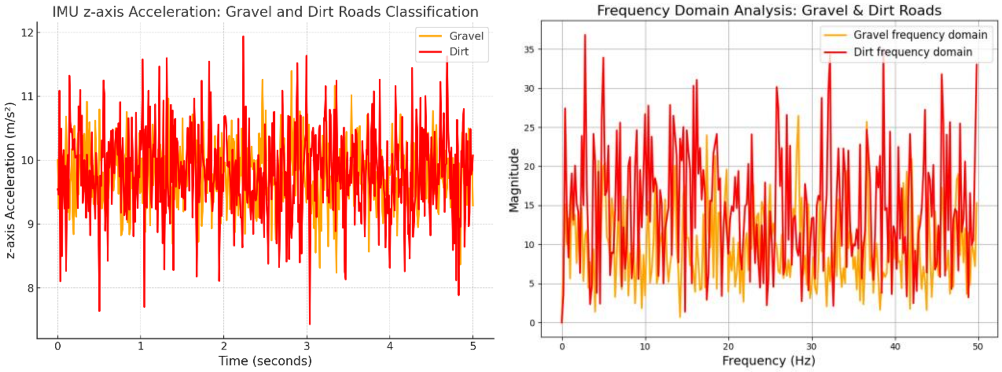

Figure 5: IMU Z-axis acceleration on a gravel & dirt road. Moderate standard deviations (0.5 and 0.7 m/s²) were applied to simulate the unevenness and roughness of these terrains.

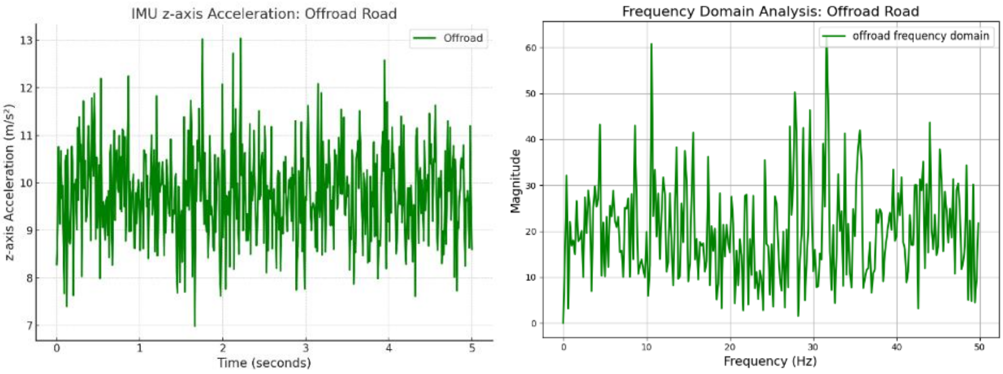

Figure 6: IMU Z-axis acceleration off-road. A higher standard deviation (1.0 m/s²) was applied to capture the larger and more unpredictable fluctuations in acceleration typical of off-road environments.

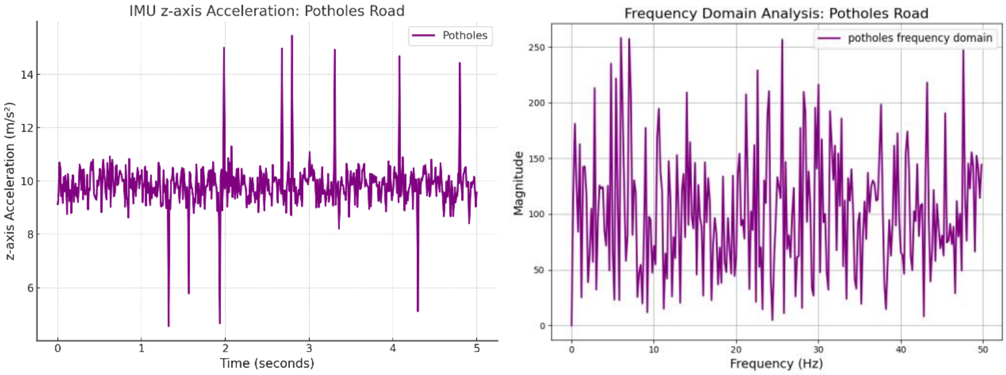

Figure 7: IMU Z-axis acceleration encountering potholes. To simulate the sharp impacts of potholes, large and abrupt changes were introduced by adding occasional spikes (±5 m/s^2) to the otherwise fluctuating acceleration data, with a reduced frequency to reflect real-world pothole encounters.

To provide a more comprehensive understanding of the road condition data, we present both time-domain and frequency-domain representations of the IMU z-axis acceleration. The time-domain charts capture the raw acceleration variations over time for each road type, while the frequency-domain charts provide insight into the dominant frequency components present in each terrain. This dual representation allows for better differentiation of road conditions by highlighting both temporal and spectral features.

This preliminary data analysis lays the groundwork for future implementation of terrain detection in the system. By understanding how different terrains affect vehicle dynamics, the suspension system can be enhanced to adapt accordingly.

Software Architecture

The system's software architecture utilizes the ATmega328PB microcontroller, interfacing with the height sensor, actuators, and LED indicators. The control algorithm operates in a continuous loop, processing height sensor data to adjust air suspension. The error and its rate of change guide decisions to inflate, deflate, or maintain pressure. The architecture is modular, facilitating future enhancements such as integrating fuzzy logic control and additional sensors.

Proposed Fuzzy Logic Implementation

Future developments aim to enhance the system's adaptability by incorporating terrain detection using fuzzy logic control (FLC). Terrain detection allows the suspension system to adjust proactively to changing road conditions, improving ride comfort and vehicle stability.

Fuzzy logic is particularly suitable for terrain detection due to its ability to handle uncertainties and nonlinearities without requiring precise mathematical models [4], [9]. By processing input data from an Inertial Measurement Unit (IMU), the system can classify road conditions and adjust the suspension settings accordingly.

The fuzzy logic controller for terrain detection processes acceleration data from the IMU to determine the road roughness. The key components of the FLC are:

1. **Input Variable**:
   Vertical Acceleration (a_z): The Z-axis acceleration measured by the IMU, reflecting the vertical motion of the vehicle due to road irregularities.
2. **Output Variable:**
   Terrain Classification (T): A linguistic variable representing the type of terrain, such as Smooth, Moderate, or Rough.

Membership Functions

The input variable a_z is represented by fuzzy sets with associated membership functions. For terrain detection, the membership functions can be defined as:

- **Vertical Acceleration (a_z):**
  A. Low (L)
  B. Medium (M)
  C. High (H)

The membership functions for a_z can be defined using Gaussian functions for smooth transitions:

$$\mu_L(a_z) = e^{-\left(\frac{a_z - c_L}{\sigma_L}\right)^2}$$

$$\mu_M(a_z) = e^{-\left(\frac{a_z - c_M}{\sigma_M}\right)^2}$$

$$\mu_H(a_z) = e^{-\left(\frac{a_z - c_H}{\sigma_H}\right)^2}$$

where c is the center and σ is the standard deviation of the Gaussian function for each fuzzy set.

Fuzzy Base Rule

The control strategy is defined by a set of fuzzy IF-THEN rules that relate the input variable to the terrain classification. Examples of fuzzy rules are:

- **Rule 1**: IF a_z is Low (L) THEN Terrain is Smooth (S).
- **Rule 2**: IF a_z is Medium (M) THEN Terrain is Moderate (M).
- **Rule 3**: IF a_z is High (H) THEN Terrain is Rough.

Inference Mechanism

The fuzzy inference process involves:

1. **Fuzzification**: Converting the crisp input value of a_z into degrees of membership for each fuzzy set using the membership functions.
2. **Rule Evaluation**: Determining the firing strength of each rule based on the degree of membership.
3. **Aggregation**: Combining the outputs of all rules to form a combined fuzzy set for the terrain classification.
4. **Defuzzification**: Converting the aggregated fuzzy set into a crisp value representing the terrain classification.

Defuzzification can be performed using the centroid method:

$$T_{crisp} = \frac{\int T' \cdot \mu(T')dT'}{\int \mu(T')dT'}$$

where $\mu(T')$ is the membership function of the aggregated output fuzzy set, and T' represents the output variable domain.

Adjustment of Suspension Settings

Once the terrain is classified, the system adjusts the suspension settings accordingly:

- **Smooth Terrain**: Maintains standard suspension settings for optimal ride comfort.
- **Moderate Terrain**: Adjusts air pressure to provide a balance between comfort and stability.
- **Rough Terrain**: Increases damping and stiffness to enhance vehicle control and safety.

Integration with Four-Sensor System

In addition to terrain detection, future variations of the system propose integrating four height sensors, one at each wheel, enabling independent control. This configuration allows the suspension system to compensate for uneven loads and road surfaces more effectively.

Fuzzy logic can be employed to manage the complexity and uncertainties inherent in controlling a four-sensor system. By processing input from each sensor, the FLC can determine the optimal adjustment for each wheel, enhancing ride comfort and vehicle stability. However, equations for the fuzzy logic implementation in the four-sensor system are beyond the scope of this discussion.

Tests and Results

Testing Procedure

The On Air Active system underwent comprehensive testing to validate its performance, reliability, and suitability for commercial deployment. Testing was conducted in three primary phases:

- **Bench Testing**: Conducted in a laboratory to verify hardware functionality and control algorithms using simulated inputs for system responses and fault detection.
- **Vehicle Integration**: Installed in over ten commercial and disability vehicles, including vans, 4x4s and minibuses, to assess installation procedures, compatibility, and initial performance.
- **Field Trials**: Conducted over several months in real-world conditions, evaluating system responsiveness, ride height maintenance, energy consumption, and fault occurrences.

Results

Ride Height Maintenance and Stability: The system consistently maintained ride height within ±2 cm across varying loads, ensuring optimal stability. Drivers reported improved ride comfort and stability, especially under heavy or uneven loads.

Responsiveness: Intelligent air pressure management enabled rapid adjustments within 15-20 seconds, ensuring minimal disruption to ride comfort. Seamless switching between the air tank and compressor contributed to swift responses.

Energy Efficiency: The system prioritized using stored air from the tank and managed compressor activation efficiently, reducing energy consumption compared to traditional systems. This resulted in lower operational costs and extended component lifespan.

Fault Detection and Reliability: Effective fault detection mechanisms identified issues like low battery voltage, sensor disconnections, and compressor malfunctions. Detection accuracy reached 98%, with zero false positives, enhancing system reliability and reducing maintenance costs. Fault codes were accurately generated and communicated via LED indicators, facilitating prompt maintenance. The system demonstrated high reliability with minimal downtime.

User Feedback and Commercial Viability: Vehicle operators provided positive feedback, highlighting ease of use, improved ride quality, and reliability. The straightforward installation and minimal maintenance requirements were significant advantages. The system's performance supported commercial adoption, with revenue generation commencing shortly after market introduction.

Conclusion

The On Air Active system represents a significant advancement in aftermarket air suspension technology, delivering enhanced ride comfort, stability, and energy efficiency through intelligent control algorithms and robust hardware design. By utilizing a single height sensor and a microcontroller-based control unit, the system maintains optimal vehicle height across varying loads and road conditions while remaining cost-effective and easy to install.

Extensive testing and positive user feedback have validated the system's reliability and commercial viability, with revenue generation commencing shortly after its market introduction. Targeted initially at commercial and disability vehicles, the system addresses the specific needs of these sectors, offering improved ride quality and ease of use.

Looking ahead, the planned integration of advanced features such as a four-sensor configuration and AI-driven terrain detection will further enhance the system's adaptability and performance. By potentially mapping different terrains and allowing for personalized terrain profiles, the suspension system could anticipate and adjust to road conditions proactively, providing an even higher level of comfort and safety during daily commutes.

These future developments will expand the system's appeal to a broader market, including custom and consumer vehicles. By continuing to innovate and incorporate cutting-edge technologies, the On Air Active system is poised to set new standards in the aftermarket air suspension industry, meeting the evolving demands of drivers and enhancing the overall driving experience.

Future developments aim to enhance On Air Active by integrating a four-sensor configuration for independent wheel control and AI-driven terrain detection using IMU data for real-time suspension adjustments based on road conditions. Additionally, mapping terrain profiles across regions will enable vehicles to learn and anticipate road conditions on frequently traveled routes, allowing personalized suspension settings for enhanced comfort and safety. These advancements will expand the system's applicability to custom and consumer vehicles, setting new standards in the aftermarket air suspension industry by balancing simplicity with advanced performance capabilities.

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