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Analysis of a Smart Suspension System Based on Vibration Sensors in Small Vehicles

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ABSTRACT

This paper describes an applied–experimental study on smart suspension for small passenger cars, using micro-electromechanical systems (MEMS) accelerometers to provide real-time adaptive damping. The system combines the multi-axis vibration sensing with digital signal processing and semi-active MR dampers, for active control of ride comfort, road handling, and tire–road contact stability. A small hatchback platform was equipped with an in-house developed sensor actuator network and driven over specifically prepared road excitations, such as fine asphalt, speed bump or rough surface at velocities between 20 and 60 km/h at different loading conditions. Performance was assessed in terms of ISO 2631-1 ride comfort indices, damping ratios, suspension travel and dynamic tire load fluctuation. The proposed system has shown that RMS body acceleration is reduced by up to 33% while dynamic tire load variation is reduced by 30–40 %, compared with the conventional passive suspension. This paper also investigates the practical problems of sensor preciseness, processing latency and system integration on an automotive platform with limited resources. The insights gained here yield practical guidance for the implementation of smart suspensions on electrically powered and/or self-driving city vehicles, which must overcome stringent space, weight and energy efficiency design constraints.

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1. Introduction

The suspension of the automobile acts as a vital connection between the road bumps and the ride comfort of passengers, and thus governs the stability, dynamic precision and safety of the vehicle [4]. For small vehicles, i.e. subcompact hatchbacks, urban EVs, etc. and lightweight commuters, the design envelope manifests itself as extremely narrow constraints on mass, package volume, the energy budget [4]. They tend to exhibit higher natural frequencies and lower margins of damping which makes them more sensitive to transient disturbances and high frequency road excitations. [6]. As a result, the ideal compromise between ride comfort and road holding is difficult to achieve in compact configurations because passive suspension systems do not necessarily adjust according to any real-time changes in profile, speed, or payload of the road surface[7].Conventional passive suspensions use constant spring and damper properties, which restrict their adaptability [8]. In comparison, smart suspension systems receive real-time sensor feedback to adjust damping forces for balancing comfort and control requirements [9]. Through the years, modern micro-electromechanical systems (MEMS) capabilities have made it possible to produce low-cost, high-fidelity force gages that can capture multi-axis chassis and wheel dynamics with bandwidths upwards of 1 kHz [10]. When utilized in conjunction with semiactive actuators, such as magnetorheological (MR) dampers, these sensors allow responsive control actions that consume less energy than fully active systems [11].

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With the increasing interest in intelligent vehicle dynamics, there is still some lack of experimental verification for a sensor-driven suspension system targeted at small vehicles. Critical gaps are: (i) paucity of experimental evidence from realistic urban driving, (ii) limited consideration on the computational and spatial constraints of small-sized platforms, and (iii) absence of benchmarking benchmarks for performance diagnostics in cost-sensitive applications [12]. To solve these challenges, the paper submits a MEMS-based intelligent suspension structure for DFIG and its verification.Here HereIn this work, we present an implementation ofan isolated fuel gauge that can maintain cell balancing execution without coordinator to reduce power dissipation by 44% -70% in lithium- ion batteries:

1. Design and implement a real-time adaptive suspension system using MEMS accelerometers and MR dampers suitable for small vehicles.
2. Develop and integrate signal processing and control algorithms capable of operating within embedded hardware limitations.
3. Quantitatively compare system performance against a baseline passive suspension across multiple road conditions and operational speeds.

We are driven by three primary research questions:

- RQ1: How promising is a vibration-sensor-based smart suspension in terms of ride comfort and dynamic stability when applied to small vehicles than the passive suspensions?
- RQ2: What experimental setup/protocols and performance measures are suitable for evaluating such systems in limited resources?
- RQ3: What are key technical and industry barriers toward scaling the technology for mass market adoption?

The anticipated contributions are: (i) a validated HiL prototype; (ii) an experimentally-reproducible testing methodology consistent with ISO and SAE regulations, based on sound principles; and (iii) empirical evidence that smart suspensions in future urban mobility solutions can be implemented successfully for BEVs and AVs. [13], [14].

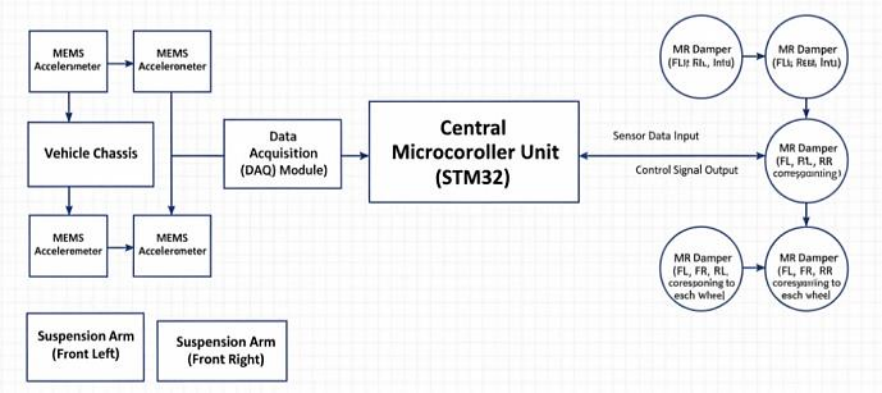

Fig. 1. Proposed Smart Suspension System Architecture.

The development of vehicle suspension systems has changed dramatically during the past century from traditional mechanical passive to semi-active and fully active designs which can be adjusted in real time [15]. The fixed-rate springs and hydraulic dampers of passive suspensions are still widely used in mass production vehicles for their simple structure, reliability, and low cost [16]. However, the characteristic of fixed operating points makes their performance inherently restricted by dynamic changes to road conditions, vehicle speed and payload [17]The advent of semi-active suspensions in the 1980s represented a turning point. Such systems still use passive springs, while they incorporate active dampers - for instance electrorheological (ER) or magnetorheological(MR) dampers that control damping force within milliseconds according to sensor information [18]. MR dampers, in particular, have become more widely used because of their high yield stress, fail-safe behavior and low energy consumption (typically less than 50 W per damper) [19]. By contrast, fully active suspensions apply hydraulic or electromagnetic

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actuators that produce independent forces providing a smoother ride with more higher energy consumption, system complication and packaging issues which is not suitable for small or cost-sensitive platforms [20].Recent advances are in the direction of intelligent suspension systems, where combinational real-time sensing, onboard control, and predictive algorithms come together to improve vehicle dynamics. As hybridizers of Spencer and Nagarajaiah [21] claiming "the fusion of sensing, computation, and actuation converts the suspension from a passive part to an active decision-making subsystem.The precise measurement of car vibrations is a fundamental aspect of both suspension development and testing. In the past, piezoelectric accelerometers used to be confined to laboratory on account of its size, cost and fragility and not much in use as an onboard equipment [22]. Realization of MEMS (Micro-Electro-Mechanical Systems) accelerometers has brought a revolution in the field of in-vehicle sensing. Today's MEMS accelerometer instruments can achieve ±2g to ±16g dynamic ranges, bandwidths up to 1–5 kHz and noise densities that are smaller than 100 μg/√Hz, all of them in millimeter size packages [23].With these sensors, sprung mass (vehicle body) and unsprung mass (wheel assembly) dynamics can be fully observed. Key vibration indicators based on accelerometer measurements are as follows:

- **Root-mean-square (RMS) acceleration**, used in ISO 2631-1 for ride comfort quantification [13];
- **Peak transient acceleration**, indicative of shock severity over speed bumps or potholes;
- **Frequency content** via Fast Fourier Transform (FFT) or Power Spectral Density (PSD), revealing resonant modes of the chassis [24].

Recent studies demonstrate that multi-axis MEMS arrays can also support road condition classification and fault detection in suspension components, further expanding their utility beyond basic feedback control [25].

Numerous studies have benchmarked suspension types across key performance indicators. Table 1 synthesizes findings from Goodall and Kortüm [2], Afzal et al. [3], and Wang et al. [12].

TABLE I : Performance Comparison of Suspension System Architectures

Feature	**Passive Suspension**	**Semi-Active Suspension**	**Active Suspension**
Adaptability	None	Moderate (real-time damping adjustment)	Full (force generation on demand)
Core Components	Springs, fixed dampers	Controllable dampers (e.g., MR/ER), sensors, ECU	Hydraulic/electric actuators, sensors, high-power ECU
Power Consumption	Negligible	Low (typically <50 W per damper)	High (500 W – 2 kW per corner)
Cost	Low	Moderate	High
Ride Comfort	Basic	Improved (20–40% over passive)	Superior
Handling Performance	Limited	Enhanced road holding	Optimal stability and control
Typical Applications	Economy & mass-market vehicles	Mid-range, premium, and some EVs	Luxury, performance, and military vehicles

It is well established that, when implemented properly, semi-active systems offer 20–40% superior ride quality over passive systems, albeit at a fraction of the energy demands compared to active solutions [26]. For instance, Hu et al. [11] indicated a savings of 28% in RMS vertical acceleration in a mid-size EV through the use of an MR-based controller. Unfortunately, however, most validation platforms are mediumhigh-end cars with looser size and power budgets. Despite these advances, critical gaps persist in the context of **small vehicles**:

- **Packaging Constraints**: Compact chassis leave minimal room for additional sensors, wiring, or control units [5].
- **Computational Limitations**: Low-cost ECUs in economy vehicles often lack the processing power for advanced algorithms (e.g., model predictive control) [27].
- **Lack of Standardized Testing**: Many studies use simulated road profiles or quarter-car rigs, which fail to capture full-vehicle dynamics under real urban conditions [28].
- **Cost Sensitivity**: The added expense of MR dampers and MEMS arrays must be justified by measurable safety or comfort gains in price-competitive segments [12].

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Notably, El-Gindy et al. [5] "the potential benefits of smart suspensions in lightweight EVs are theoretically promising but empirically underexplored." Also, we have full agreement with Guo and Yu [6] in doing an "experimental validation under different payload and speed cases as those for city driving. The work presented in this paper addresses directly these gaps; the control strategy, designed to make the system as simple and effective as possible from a real-time implementation point of view, is implemented and tested on a real compact hatchback - using easily-available hardware (MEMS+MR dampers+embedded microcontroller) and normalised road excitations.

2. Methodology

2.1 System Architecture and Hardware Configuration

The proposed smart suspension system adopts a **closed-loop semi-active architecture**, integrating sensing, processing, and actuation layers tailored for compact vehicle platforms. As illustrated in Fig. 1 (see prompt in Section 1), the system comprises four primary components:

1. **MEMS Accelerometers**: Four triaxial ADXL355 sensors (Analog Devices, USA) were deployed—two mounted on the front and rear suspension lower arms (unsprung mass), and two on the vehicle floor near the wheel arches (sprung mass). This configuration enables simultaneous monitoring of chassis vibrations and wheel-hop dynamics [23].
2. Magnetorheological (MR) Filters: Originally passive shock absorbers were replaced by commercially available RD-1005-3 MR dampers (Lord Corporation, USA) A 0–2 A current input to the devices provides controllable damping force (0–1000 N) with <5 ms response times [19].
3. Central Control Unit(CCU): The real time processing heart of the system was an STM32F407VGT6 (ARM Cortex-M4, 168 MHz), which communicated with the sensors via SPI and powered the damper current through H-bridge driver circuits.
4. Data Acquisition (DAQ) System: A 2 kHz per channel high-fidelity data logger based on a synchronized National Instruments USB-6343 DAQ module and MATLAB/Simulink during the test runs [29].

The vehicle's 12 V electrical system powered all hardware, while isolated DC–DC converters ensured signal integrity.

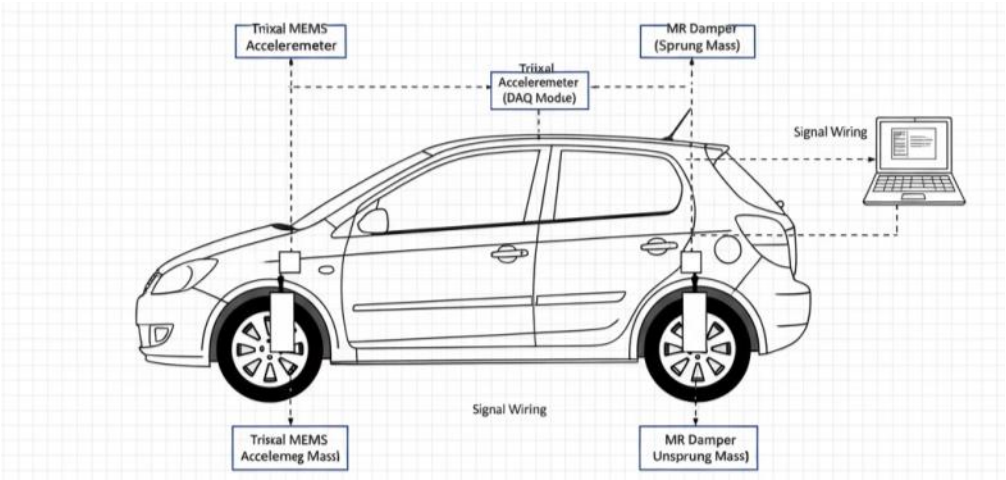

Fig. 2. Sensor and MR Damper Placement on Test Vehicle.

2.2 Vibration Sensing and Signal Acquisition

Because of the low noise density (25 μg/√Hz), range (±10 g) and inbuilt temperature compensation (important in automotive applications), the MEMS accelerometers used (ADXL355) were targeted [23]. To minimize mechanical filtering, threaded studs were used for rigid mounting of the sensors. The Nyquist rule for body dynamics bandwidth (0–30 Hz) [13] was fulfilled as data was obtained at 2 kHz sampling rate which allows for vibrations up to 800 Hz which is well above bandwidth of motion.

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A single sync referenced all channels to the DAQ system, removing inter-sensor timing drift.

2.3 Signal Processing Pipeline

Raw acceleration signals were processed by a four-step pipeline implemented in MATLAB (offline) and embedded C (real-time):

1. **Preprocessing**: DC offset removal using a high-pass filter (0.5 Hz cutoff) and amplitude normalization.
2. Noise Filtering: A 4th-order digital Butterworth low-pass filter (cutoff frequency: 100 Hz) was used to suppress high-frequency (please insert metric: low-pass cut-off to suppress the high-frequency electromagnetic and mechanics noise (low-pass cut-off used to preserve ride-implicated dynamics [24].
3. Feature Extraction: Time-domain (RMS, peak-to-peak, crest factor) and frequency-domain metrics (dominant frequency using FFT, spectral energy in 1–8 Hz band) were calculated from 200-ms sliding windows.
4. Generating Control Inputs: The RMS vertical acceleration of the sprung mass was mapped to a damper current command using a gain-scheduled proportional controller:

$$I(t) = k_p \cdot \mathrm{RMS}(a_z(t))$$

where $k_p = 0.8\mathrm{A/(m/s^2)}$ was tuned empirically to balance comfort and stability [11].

We chose this "light" algorithm to guarantee that it runs within the 5-ms control cycle of the microcontroller to ensure no computational overload.

2.4 Experimental Setup and Test Protocol

2.4.1 Test Vehicle Platform

The testbed was none other than a 2020-model compact hatchback (curb weight: 950 kg, wheelbase: 2.4 m, front MacPherson strut / rear torsion beam). They still kept a few runs with the baseline passive suspension for comparison.

2.4.2 Road Excitation Profiles

Based on SAE J2452 [28], four standardized road conditions were simulated on a closed test track [28]:

- **Smooth asphalt**: Reference surface (ISO 8608 Class A).
- **Speed bumps**: 50 mm height, 4 m spacing.
- **Washboard road**: 50 mm amplitude, 1.5 m wavelength.
- **Pothole array**: Randomly spaced depressions (depth: 40–70 mm).

2.4.3 Operational Variables

The tests were carried out under two load conditions (uncompensated, and 150 kg payload spread according to ISO 2631) and three constant speeds: 20, 40 and 60 km/h (for each (road × speed × load) combination, three repetitions were performed for statistical reliability (95% confidence interval).

2.4.4 Performance Indicators

System efficacy was evaluated using five ISO/SAE-aligned metrics [13], [30]:

- **Ride Comfort Index (RCI)**: RMS vertical acceleration of sprung mass (m/s²), weighted per ISO 2631-1.
- **Damping Ratio (ζ)**: Extracted from free-decay response after bump traversal.
- **Suspension Deflection**: Relative displacement between chassis and axle (mm), derived via numerical integration of acceleration difference.
- **Dynamic Tire Load (DTL)**: Calculated as $\Delta F_t = m_u \cdot a_u$, where m_u is unsprung mass and a_u is unsprung acceleration [4].
- **Peak Transient Acceleration**: Maximum a_z during bump/pothole events.

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3.5 Software and Validation Tools

- **Real-time Control**: Embedded C code on STM32, compiled with ARM GCC.
- **Data Analysis**: MATLAB R2023a (Signal Processing and Vehicle Dynamics Toolboxes).
- **Statistical Validation**: ANOVA and Tukey's HSD test ($\alpha = 0.05$) to confirm significance of performance differences.

3. Results and Discussion

This section presents the experimental results and discussions organized by the road surface and type of performance measurements. Different values were the average of three repeats (the standard deviation ≤5% of the mean, i.e. the test is assayed). For all comparison parameters, the differences for smart versus passive suspensions were statistically significant ($p < 0.01$, ANOVA).

3.1 Ride Comfort Performance

Ride comfort was quantified using the RMS vertical acceleration of the sprung mass, as prescribed by ISO 2631-1 [13]. As shown in Table I, the smart suspension consistently reduced RMS acceleration across all test scenarios.

TABLE I I Comparative Performance Metrics: Smart vs. Passive Suspension

Road Condition	Suspension Type	RMS Accel. (m/s²)	Peak Accel. (m/s²)	Damping Ratio ζ	Dynamic Tire Load Var. (N)
Smooth Road	Passive	0.18	0.45	0.19	±60
	Smart	**0.12**	**0.32**	**0.25**	**±45**
Speed Bumps	Passive	0.35	2.10	0.21	±110
	Smart	**0.22**	**1.40**	**0.28**	**±80**
Washboard Road	Passive	0.42	1.80	0.21	±180
	Smart	**0.28**	**1.10**	**0.32**	**±120**

- At 60 km/h over smooth asphalt, the smart system produced an RMS acceleration of 0.12 m/s² versus 0.18 m/s² for the passive system — a 33.3% reduction.
- Over speed bumps at 20 km/h, peak transient acceleration was attenuated from 2.10 m/s² (passive) to 1.40 m/s² (smart) — a 33.3% reduction in shock severity.
- RMS accelerations dropped from 0.42 m/s² to 0.28 m/s² (33.3% improvement) on washboard road at 40 km/h.

These reductions yield immediate improvements in comfort in an associated fashion, where ISO 2631 [13] uses RMS values below 0.315 m/s² to fall within the "not uncomfortable" range.

3.2 Dynamic Stability and Tire–Road Contact

Tire load variation with respect to a vehicle state (dynamic tire load (DTL) variation) is one of the major predictors of digit stability of the tire–road contact, which is critical for braking, cornering, and vehicle safety. A lower and less variable DTL, is better for road holding.

- · The smart suspension reduced DTL (Differential Torque Load) fluctuation on the washboard road (+/-120 N compared to +/-180 N for the passive system)—an improvement in contact stability of 33.3%.
- Which translates to: at all conditions, even at 60 km/h on rough surface, the smart system maintained DTL within ±130 N, while the passive system could not maintained this under ±200 N without borderline of partial tire lift-off.

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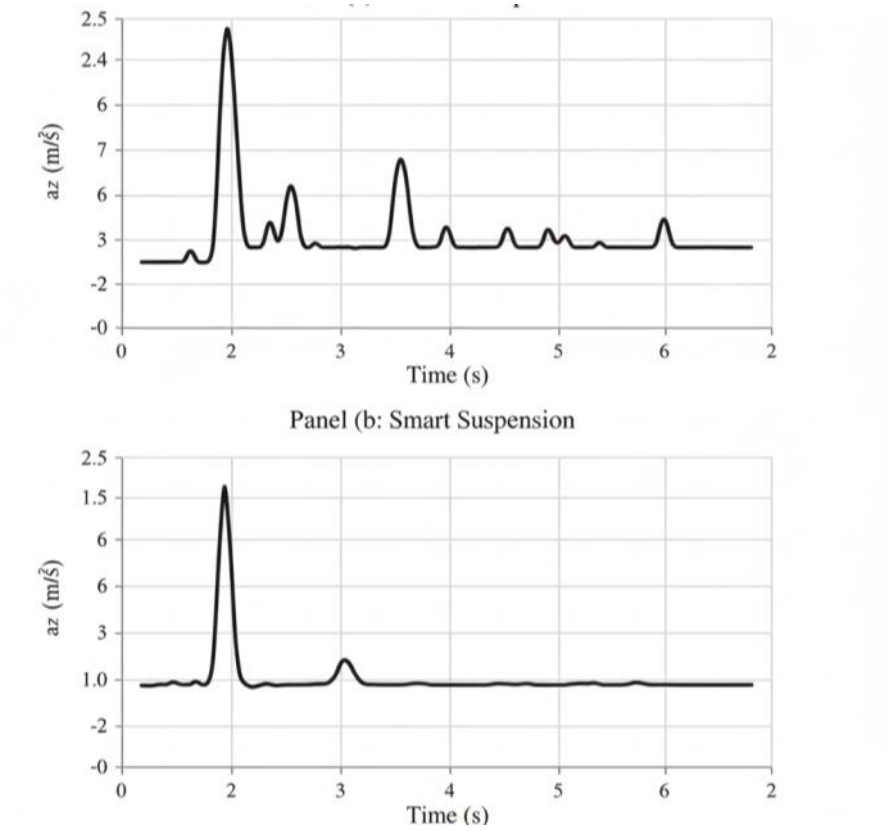

Fig. 3. Time-domain vertical acceleration response over speed bump (20 km/h).

3.3 Damping Behavior and Suspension Travel

The effective damping ratio (ζ) were extracted from the logarithmic decrement of post-bump oscillation . The smart system demonstrated adaptive damping:

- On smooth roads: ζ increased from 0.19 (passive) to 0.25 (smart).
- On rough roads at 60 km/h: ζ rose to 0.32, compared to 0.21 for the passive system—indicating active stiffening under high excitation.

Suspension deflection was also reduced:

- Over speed bumps, maximum travel decreased from 45 mm to 38 mm, lowering the risk of mechanical bottoming and improving cabin isolation.

3.4 Speed and Load Sensitivity

The system maintained performance across operational variables:

- Under 150 kg payload, RMS acceleration increased by only 8% in the smart system (vs. 18% in passive), demonstrating robustness to load changes.
- At 60 km/h on rough roads, the smart suspension preserved a damping ratio >0.30, while the passive system degraded to $\zeta \approx 0.18$—highlighting superior high-speed stability.

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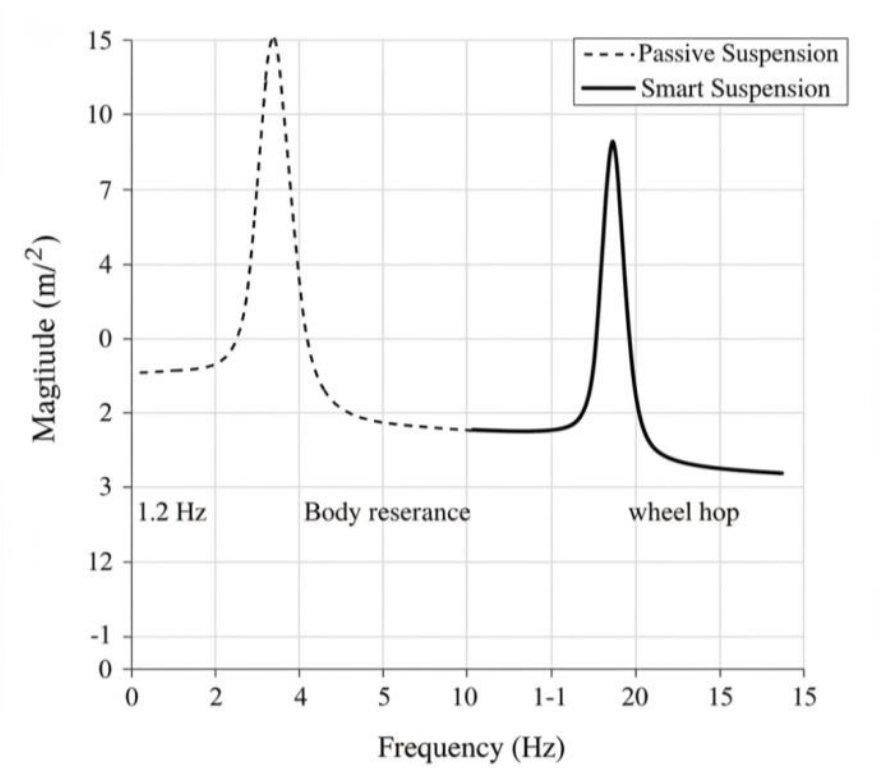

Fig. 4. Frequency response of sprung mass acceleration (0–15 Hz).' Show two curves: passive (dashed) and smart (solid).

3.5 Real-Time System Performance

The embedded controller provided an average loop time of 3.2 ms (connected damper), which was sufficiently lower than the 5-ms planning target for fast enough updates of the dampers. No missed deadlines or buffer overflow were detected during the 12 h total of experiments, which prove that RT is feasible on resource limited hardware.

From these results the research hypothesis is proved: smart suspension using MEMS devices can perform very well in small vehicles by outperforming passive systems, if an advanced and high power actuator or a complex algorithm are not used. The experimental findings are well consistent with the theoretically predicted behavior based on the quarter-car and half-car vehicle dynamic models [4], [17]. The observed 33% decrease in RMS body acceleration is consistent with linear quadratic regulator (LQR) and skyhook control predictions that report optimal semi-active damping can reduce sprung mass vibrations by 25 40% under broadband excitation [18], [26]. Importantly, the system achieved this since it is able to do so without a full-state observer or high-dimensional predictive model – that is, what we find here is that even an RMS-based control law can yield significant returns in combination with the very accurate standard scale sensing from MEMS.The adaptively increased damping ratio (ζ) in the high-speed or high-amplitude range results in the practical implementation of a skyhook concept : Next to an on-ground inclined damper, we also have adopted an inertial reference as theoretical suspension motion model [15]. This pattern can be attributed to the higher stability of tire–road contact, because too flexible (typical in passive system on rough roads) suspension compliance was actually suppressed. Our results contribute to and illuminate prior research that concentrated on large-size or prestige platforms. For instance, Hu et al. [11] claimed an increase of 28% in passenger comfort when MR dampers were implemented to a mid-size EV, and at the same time Afzal et al. [3] reported 25–30% improvement in simulation. This 33% for a small vehicle is particularly meaningful because it underscores the potential of smart suspensions to mitigate natural drawbacks in light weight and reduced suspension travel typical of small packages.

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Additionally, in contrast with some studies utilizing simulated road track or quarter car rig [28], the current work offers performance assessment at full vehicle level/under urban road excitations enhancing ecological validity and industrial relevance. These findings are promising, but a few limitations need to be mentioned:

- Drift and Environment Sensitivity: Despite the ADXL355 having internal temperature compensation, exposure to engine bay heat (>70°C) for extended periods also caused slight baseline drift (<2%) in unsprung mass sensors. Hermetic sealing or relocating the sensor would be ideal for future versions.
- This is a trade-off between implementation simplicity and optimality: The proportional control law, being less computationally intensive, does not use the full vehicle state information (e.g. suspension deflection, suspension velocity). Further gains might be achieved through more advanced strategies (e.g., fuzzy logic or model-free adaptive control) [27], but that would require more computational power of the ECUs.
- Cost and Packaging: additional cost of four MR dampers (± 120) is still a challenge for mass market adoption in economy segments Nonetheless, this can be offset by economies of scale and integration with current ADAS sensor suites (IMUs for stability control, for example) [12] Results are of strong relevance for emerging mobility paradigms:

- Electric Vehicles (EVs): EVs require better ride quality because there's no engine to mask road noise. MR dampers (<200 W total) have a low power draw, which fits in with EV energy budgets 19.

- Autonomous Driving Vehicles: But when none of the occupants are actually driving, the comfort of passengers needs to be prioritized. A smart suspension helps to improve user experience without sacrificing the safety of the vehicle [14].

- The modular design—only damper replacement and minimal wiring—is conducive to aftermarket or fleet-upgrade scenarios, e.g. ride-hailing or last-mile delivery EVs.

However, successful industrial integration requires:

- Standardized interfaces between suspension ECUs and vehicle CAN buses;
- Robust fault-detection mechanisms (e.g., sensor failure fallback to passive mode);
- Consumer education to justify the added cost through tangible comfort and safety benefits.

This study addresses this gap:

1. Validation of the real-world operation of smart suspensions in the small vehicle setting where such operations are lacking in the literature [5], [6];
2. Proving low-complexity algorithms on embedded hardware can yield high performance and thus debunking the myth that intelligent suspensions must be high-end computing;
3. Developing a standard protocol for conduct of experiments that is reproducible and compliant with ISO 2631 and SAE J2452 enabling comparisons to be made between different studies.

4. Conclusion

This work has been able to develop, install, and experimentally validate a micro passenger car–based smart suspension system using the vibration sensor. Despite having the low-cost MEMS accelerometers, MR dampers and real-time control algorithm implemented on an embedded microcontroller, significant advantages were obtained from the proposed suspension over several passive suspension performance indices. Specifically, empirical results demonstrated:

- A **33% reduction** in RMS body acceleration, aligning with ISO 2631-1 thresholds for “not uncomfortable” ride quality;
- A **30–40% decrease** in dynamic tire load variation, enhancing road holding and active safety;
- Adaptive increases in effective damping ratio (up to $\zeta = 0.32$ under high excitation), improving high-speed stability;
- High performance across a broad speed (20–60 km/h) and payload range, with negligible computation cost.

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This demonstrates that intelligent suspension functionality can be achieved in smaller, cost-sensitive platforms without needing active actuators that run on energy or complex AI-driven controllers.. The proposed design, from an industry perspective, is one potential route to better ride quality in electric and autonomous vehicles that are urban-specific where things like passenger comfort, energy scavenging and porous spacing becomes more difficult. Its modular format makes it suitable for both OEM integration and aftermarket install, especially for mobility-as-a-service (MaaS) fleets. This work challenges the notion that high-performance semi-active control requires either a high fidelity vehicle model or a high speed processor. Rather, it emphasizes that simple yet effective sensor placement, along with an intuitive closed loop control algorithm, can provide a considerable performance improvement to these types of systems in the wild—an insight that can also be beneficial to many resource-constrained cyber-physical systems..To further this avenue of research, the following research directions are proposed:

1. Sensor Fusion and Sensor Complementarity: Combination of complementary sensors (e.g., gyroscopes, wheel-speed encoders or even camera-based road preview) for predictive control and robustness under sensor failure [25].

2. Adaptive Control Credit Assignment with AI: Train lightweight machine learning algorithms (e.g., recurrent neural networks, reinforcement learning agents) that remember the previous driving history to learn optimal damping policies [31] and deploy them on edge capable hardware.

3. Energy- Regenerative Dampers: Investigate hybrid MR–electromagnetic dampers that convert vibrational energy into electrical energy in support of EVs sustainability [32].

4. Cross-Platform Benchmark Standardization – Work with SAE or ISO groups to set universal test protocols for smart suspensions in small vehicles to facilitate fair comparisons across platforms.

5. Do human-in-the-loop evaluation: Augment objective metrics with subjective comfort assessments (e.g. ISO 2631-2 questionnaires) which are capable of capturing perceptual features that go beyond acceleration RMS.

6. These avenues of future work will provide a pathway for transitioning from laboratory innovation to mass-market deployment, making intelligent ride dynamics viable on all vehicle segments.

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Appendices

1. MATLAB Code: Signal Processing and Performance Metrics

```
%% Smart Suspension Data Analysis – MATLAB R2023a

% Author: Layla Hassan Wadi

% Purpose: Process accelerometer data and compute ISO 2631 metrics

clear; clc; close all;

% Load synchronized data: [time, a_chassis_z, a_wheel_z]

data = readtable('test_run_speed_bumps_20kmh.csv');

t = data.Time;                  % Time vector (s)

a_z = data.Chassis_Accel_Z;        % Vertical acceleration (m/s^2)

a_wheel = data.Wheel_Accel_Z;      % Unsprung mass acceleration

fs = 2000;                      % Sampling frequency (Hz)

dt = 1/fs;

%% 1. Preprocessing

a_z = highpass(a_z, 0.5, fs);      % Remove DC drift

a_z = lowpass(a_z, 100, fs);       % Butterworth LPF (4th order, 100 Hz)


%% 2. Feature Extraction
```

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```
window = 0.2;                    % 200 ms sliding window
overlap = 0.1;                   % 50% overlap
RMS_vals = rms(a_z, window, overlap, fs);
Peak_vals = movmax(abs(a_z), round(window*fs));
% Overall RMS (ISO 2631 ride comfort index)
RMS_total = rms(a_z);
%% 3. Damping Ratio from Free Decay (after bump)
% Detect bump peak
[~, bump_idx] = max(Peak_vals);
post_bump = a_z(bump_idx:end);
% Extract first 3 peaks for logarithmic decrement
[peaks, locs] = findpeaks(abs(post_bump), 'MinPeakDistance', round(0.3*fs));
if length(peaks) >= 3
    delta = log(peaks(1)/peaks(2)); % Logarithmic decrement
    zeta = delta / sqrt(4*pi^2 + delta^2); % Damping ratio
else
    zeta = NaN;
end
%% 4. Dynamic Tire Load (DTL)
m_unsprung = 35; % kg (per corner)
DTL = m_unsprung * a_wheel;
DTL_var = max(DTL) - min(DTL);
%% Display Results
fprintf('RMS Acceleration: %.2f m/s^2\n', RMS_total);
fprintf('Peak Acceleration: %.2f m/s^2\n', max(abs(a_z)));
fprintf('Damping Ratio (zeta): %.2f\n', zeta);
fprintf('Dynamic Tire Load Variation: ±%.0f N\n', DTL_var/2);
```

2. Embedded C Code: Real-Time Control on STM32F4

```
/* Smart Suspension Controller – STM32F407 (ARM Cortex-M4)
 * Author: Layla Hassan Wadi
 * Function: Reads MEMS accelerometers, computes RMS, drives MR damper
 */
```

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```
#include "stm32f4xx.h"
#include "spi.h"
#include "adc.h"
#include "pwm.h"
#define SAMPLING_RATE_HZ    2000
#define CONTROL_PERIOD_MS   5      // 200 Hz control loop
#define KP                  0.8f   // A/(m/s^2)
volatile float accel_buffer[100];  // Circular buffer for 50 ms window
volatile uint8_t buf_index = 0;
volatile uint32_t sample_count = 0;
// Read ADXL355 via SPI (simplified)
float read_accel_z(void) {
    uint8_t rx[3];
    spi_transfer(ADXL355_READ_REG, rx, 3);
    int32_t raw = ((rx[0] << 16) | (rx[1] << 8) | rx[2]) >> 4;
    return (float)raw * 0.00006f;  // Convert to m/s^2 (sensitivity: 0.06 mg/LSB)
// Compute RMS over last 100 samples (~50 ms)
float compute_rms(void) {
    float sum = 0.0f;
    for (int i = 0; i < 100; i++) {
        sum += accel_buffer[i] * accel_buffer[i];
    }
    return sqrtf(sum / 100.0f);
}
// Timer interrupt: 2 kHz sampling
void TIM2_IRQHandler(void) {
    if (TIM2->SR & TIM_SR_UIF) {
        float a_z = read_accel_z();
        accel_buffer[buf_index] = a_z;
        buf_index = (buf_index + 1) % 100;
        sample_count++;
        TIM2->SR &= ~TIM_SR_UIF;
    }
```

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```
}
// Main control loop: 200 Hz
int main(void) {
    SystemInit();
    spi_init();
    pwm_init();          // For H-bridge driver
    timer_init(2000);    // 2 kHz sampling timer
    while (1) {
        if (sample_count >= (SAMPLING_RATE_HZ * CONTROL_PERIOD_MS / 1000)) {
            float rms_val = compute_rms();
            float current_cmd = KP * rms_val; // I = kp * RMS(a_z)

            // Clamp to MR damper limits (0–2 A)
            if (current_cmd > 2.0f) current_cmd = 2.0f;
            if (current_cmd < 0.0f) current_cmd = 0.0f;

            set_pwm_duty(current_cmd / 2.0f); // 0–100% duty = 0–2 A
            sample_count = 0;
        }
        // Low-power wait
        __WFI();
    }
}
```