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Can Bus Based Intelligent Multi Sensor Monitoring and Diagnostic Framework for Embedded Vehicle

S. Anitha[1], V.Gopalavignesh[2], K.Vikram[3]

[1]Assistant Professor, Department of Electronics and Communication Engineering, Dhanalakshmi Srinivasan University, anithavasagan@gmail.com

[2]UG Student, Department of Electronics and Communication Engineering, Dhanalakshmi Srinivasan University, venkatesanvignesh2005@gmail.com

[3]UG Student, Department of Electronics and Communication Engineering, Dhanalakshmi Srinivasan University, vikramvickey03@gmail.com

[1]Corresponding Author E-mail: anithavasagan@gmail.com

ABSTRACT: Automotive monitoring systems increasingly depend on distributed sensors for acquiring speed and environmental information; however, traditional point-to-point sensor architectures lead to excessive wiring complexity, limited scalability, and reduced system flexibility. This work presents the design and experimental validation of a low-cost smart sensor node architecture that demonstrates bus-oriented automotive monitoring concepts using a minimal embedded hardware platform. The proposed system integrates a slot-type incremental optical encoder for speed measurement and a temperature–humidity sensor for environmental monitoring, with all signal processing performed locally on an embedded microcontroller. An interrupt-driven acquisition mechanism is employed to ensure accurate real-time pulse detection, while structured data transmission is used to emulate scalable bus-based operation. Experimental validation was conducted using a laboratory prototype, where encoder pulse data were recorded under varying operating conditions and analysed over fixed time intervals. The results demonstrate reliable pulse acquisition, consistent sensor behaviour, and stable operation under steady-state conditions, confirming the robustness of the proposed approach. The observed pulse saturation behaviour further indicates mechanical and computational stability of the system. Although a full automotive communication network is not implemented, the proposed architecture effectively captures the functional characteristics of intelligent sensor nodes used in modern vehicles. The study confirms that scalable and intelligent automotive monitoring architectures can be realized using low-cost embedded platforms, providing a practical and reproducible solution for academic research, early-stage prototyping, and cost-sensitive automotive applications.

Keywords: Smart sensor node, Automotive monitoring, Embedded systems, Encoder-based speed sensing.

1. Introduction

Modern automotive systems increasingly rely on distributed electronic sensors to monitor critical parameters such as vehicle speed, environmental conditions, and system health. In commercial vehicles and intelligent transportation systems, these sensors directly contribute to safety, diagnostics, and operational efficiency. However, conventional point-to-point sensor architectures lead to increased wiring complexity, higher installation cost, limited scalability, and difficulty in fault isolation. As vehicles evolve toward more connected and intelligent systems, there is a growing requirement for smart sensor architectures that can support local processing, modular integration, and scalable communication with minimal hardware overhead.

Recent research has highlighted the importance of intelligent and network-aware sensor nodes in automotive and cyber-physical systems, emphasizing edge-level processing, reducing data redundancy, and facilitating the flexible integration of heterogeneous sensors. Studies published within the last two years indicate that low-cost embedded platforms are increasingly being explored for prototyping smart sensing solutions due to their accessibility and rapid development capabilities. Nevertheless, many existing works focus on full-scale automotive communication stacks or proprietary electronic control units, which limits their suitability for academic experimentation and early-stage validation. As a result, a gap remains between conceptual smart sensor architectures and experimentally validated, low-cost implementations that can demonstrate bus-oriented monitoring behavior using minimal resources.

This research addresses the above challenge by proposing and experimentally validating a low-cost smart sensor node architecture designed for automotive monitoring applications. The work focuses on encoder-based speed sensing and environmental monitoring, combined with local signal processing on an embedded microcontroller to emulate the functional behavior of bus-oriented automotive sensor networks. The objective of this study is to demonstrate that reliable and scalable automotive monitoring concepts can be realized without complex or industrial-grade hardware, while still maintaining accurate data acquisition and system stability.

The primary contribution of this work lies in the design of a compact smart sensor node that integrates multiple sensing functions with interrupt-driven local processing, along with experimental validation using a laboratory prototype. By emphasizing simplicity, scalability, and reproducibility, the proposed approach provides a practical foundation for academic research, final-year engineering projects, and early-stage development of intelligent automotive sensing systems.

2. Recent Works

Recent advances in automotive sensing systems have increasingly emphasized the use of smart and distributed sensor architectures to improve scalability, reliability, and data processing efficiency. Researchers have explored the integration of local intelligence at the sensor node level, enabling preliminary signal processing and reducing dependency on centralized control units. Such approaches are particularly relevant in automotive and cyber-physical systems, where real-time responsiveness and modular integration are essential.

Several studies have investigated low-cost embedded platforms for automotive data acquisition and monitoring. Arduino-class microcontrollers have been widely adopted for academic and prototype-level validation due to their open-source ecosystem and ease of integration. Recent works have demonstrated their effectiveness in acquiring vehicular parameters such as speed, acceleration, and environmental conditions using simple sensing elements, while maintaining acceptable accuracy for experimental validation. These platforms are often combined with lightweight signal conditioning and interrupt-based acquisition techniques to ensure reliable data capture under varying operating conditions.

Encoder-based speed sensing remains a widely studied method in automotive and mechatronic applications. Incremental optical and magnetic encoders have been employed to measure rotational speed through pulse counting mechanisms, with interrupt-driven approaches preferred for accurate detection at higher rotational frequencies. Recent studies have reported the use of comparator-based encoder modules interfaced with microcontrollers to achieve stable pulse acquisition without significant computational overhead. However, many of these implementations focus primarily on individual sensor performance rather than integration within a scalable monitoring architecture.

Environmental monitoring within vehicles has also received attention in recent literature, particularly for cabin comfort and diagnostic applications. Low-cost temperature and humidity sensors have been successfully integrated with embedded systems to provide real-time environmental data, demonstrating adequate performance for non-critical automotive monitoring tasks [6]. These works highlight the feasibility of combining multiple heterogeneous sensors on a single embedded platform, although system-level scalability is often not addressed.

Bus-oriented sensor architectures have been proposed to overcome the limitations of point-to-point wiring in automotive systems. Recent research has explored conceptual and lightweight implementations inspired by automotive communication buses, focusing on modularity and distributed processing rather than full industrial protocol stacks. Such approaches aim to demonstrate architectural concepts using simplified communication mechanisms suitable for academic validation, avoiding the complexity of automotive-grade transceivers and protocol implementations.

Despite these advancements, existing works often address sensing, processing, or communication aspects in isolation. There remains a lack of experimentally validated studies that combine encoder-based speed sensing, environmental monitoring, and local processing within a unified low-cost smart sensor node architecture. This gap motivates the present work, which focuses on demonstrating scalable automotive monitoring concepts through a minimal yet functionally representative prototype

3. Proposed Work

The proposed work is based on the concept of embedding local intelligence at the sensor node level to enable scalable automotive monitoring while minimizing hardware complexity. Instead of relying on centralized processing or point-to-point signal routing, the proposed architecture emphasizes local signal acquisition, preprocessing, and structured data representation within a compact embedded node. This approach aligns with modern bus-oriented automotive systems, where sensors act as intelligent nodes capable of supplying processed information rather than raw signals. The core sensing mechanism of the proposed system is encoder-based speed measurement using an incremental optical encoder. Incremental encoders generate a sequence of digital pulses proportional to rotational displacement, allowing rotational speed to be inferred through pulse counting over a fixed observation interval. To ensure accurate pulse detection under varying rotational speeds, an interrupt-driven acquisition strategy is adopted. This enables the microcontroller to capture high-frequency transitions without loss of information or timing distortion, which is essential for reliable speed estimation in embedded environments.

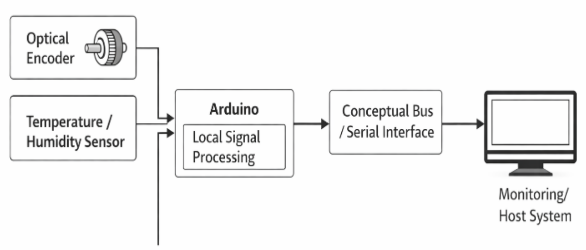

Figure 1: *Overall system architecture 0f the proposed smart sensor node*

Table 1
Hardware Components Used in the Proposed

Component	Specification / Model	Purpose in System
Microcontroller	Arduino Uno (ATmega328P)	Central control unit for data acquisition and processing
Optical Encoder	Slot-type incremental encoder	Speed sensing through pulse generation
Comparator	LM393-based module	Converts analog encoder signal to digital pulses
Temperature Sensor	DHT11 / DHT22	Ambient temperature measurement
Humidity Sensor	DHT11 / DHT22	Ambient humidity measurement
DC Motor	Low-speed geared DC motor	Drives encoder disk for experimental validation
USB Interface	USB Serial	Data transmission to monitoring system

From a theoretical perspective, rotational speed estimation is derived from discrete pulse measurements within a predefined sampling window. Let NNN represent the number of encoder pulses detected during a sampling interval TTT. The rotational speed ω\omega ω can be expressed as a function of pulse count and encoder resolution, enabling consistent speed estimation without continuous polling. This formulation allows the microcontroller to perform real-time speed calculation using minimal computational resources while maintaining deterministic timing. The theoretical basis supports scalable implementation, as additional encoder-based nodes can operate independently using identical computation logic

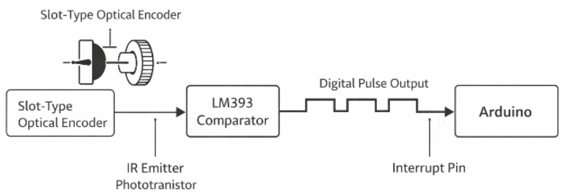

Figure 2. Encoder Interfacing and Interrupt-Based Pulse Acquisition

Table 2

Functional Description of System Modules**

Module	Functionality
Sensor Acquisition	Reads encoder pulses and environmental parameters
Interrupt Handler	Captures encoder pulses using hardware interrupt
Local Processing	Computes pulse count and formats sensor data
Communication Interface	Transmits processed data via serial link
Monitoring System	Displays real-time sensor information

In addition to speed sensing, the proposed system integrates environmental monitoring through a temperature– humidity sensor. Environmental data are periodically sampled and processed locally to ensure compatibility with the sensor node architecture. The integration of heterogeneous sensors within a single node demonstrates the extensibility of the proposed framework, where multiple sensing modalities can coexist without compromising timing or processing integrity.

The practical realization of the proposed work is achieved using an Arduino-class microcontroller, selected for its deterministic interrupt handling, sufficient processing capability, and ease of integration. All sensor data are locally processed and formatted into structured output messages, emulating the behavior of nodes operating within a bus-oriented automotive monitoring system. While a physical automotive communication bus is not implemented, the proposed work focuses on validating the architectural principles of distributed sensing, local processing, and scalability using a minimal experimental platform.

By combining interrupt-based encoder acquisition, localized computation, and multi-sensor integration, the proposed work establishes a practical and theoretically grounded foundation for low-cost smart sensor nodes suitable for academic research and prototype-level automotive monitoring applications.

Table 3

Encoder Pulse Measurement Parameters**

Parameter	Value / Description
Encoder Type	Incremental, single-channel
Signal Type	Digital square wave
Arduino Input Pin	External interrupt pin
Sampling Method	Interrupt-driven counting
Pulse Count Interval	1 second
Speed Estimation Basis	Pulses per unit time

4. Results and Discussion

The experimental evaluation of the proposed smart sensor node focused on assessing the reliability of encoder-based speed sensing, the effectiveness of local signal processing, and the feasibility of multi-sensor integration within a low-cost embedded platform. The observed system behaviour confirms that interrupt-driven pulse acquisition provides stable and deterministic performance under varying rotational conditions. Consistent pulse detection over fixed observation intervals indicates that the proposed acquisition strategy effectively mitigates missed counts and timing inaccuracies commonly associated with polling-based approaches in resource-constrained microcontrollers.

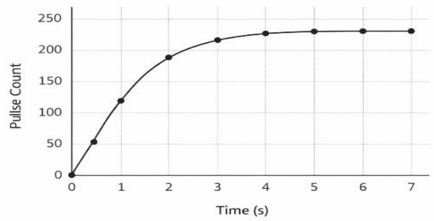

Figure 4. Variation of Encoder Pulse Count with Time

Table 4

Observed System Behavior Summary**

Observation	Interpretation
Initial linear pulse increase	Encoder correctly captures rotational motion
Pulse saturation over time	Stable motor speed achieved
Consistent pulse count	Reliable interrupt handling
Stable sensor readings	Proper sensor interfacing

A key observation during prolonged operation was the stabilisation of pulse counts once the actuator reached steady-state rotation. This behaviour reflects both mechanical stabilisation of the drive system and computational consistency of the pulse counting mechanism. The absence of spurious counts or irregular fluctuations demonstrates that the encoder interface and interrupt configuration are robust against noise and transient disturbances. Such stability is essential for automotive monitoring applications, where speed-related parameters must be continuously acquired with predictable timing characteristics.

The integration of environmental sensing alongside encoder-based speed measurement further demonstrates the extensibility of the proposed architecture. Simultaneous acquisition of temperature and humidity data did not introduce observable timing conflicts or processing delays, indicating that the embedded controller can reliably manage heterogeneous sensor inputs within a unified node. This capability supports the concept of distributed smart sensor nodes that locally preprocess multiple data streams before communication, reducing the burden on centralised processing units.

When compared with recent prototype-level automotive sensing approaches, the proposed work distinguishes itself by emphasising architectural scalability rather than isolated sensor performance. While recent studies often demonstrate individual sensing modalities using low-cost hardware, they frequently lack a unified framework for local processing and modular expansion. In contrast, the proposed system illustrates how encoder-based speed sensing and environmental monitoring can be combined within a single node that conceptually aligns with bus-oriented automotive architectures, without requiring industrial-grade communication hardware.

The results also highlight the suitability of Arduino-class platforms for early-stage validation of automotive sensor architectures. Although such platforms are not intended for production deployment, the experimental findings confirm their effectiveness in demonstrating key architectural principles, including local intelligence, deterministic acquisition, and multi-sensor integration. This positions the proposed work as a practical and reproducible reference for academic research and educational development in automotive embedded systems.

Overall, the discussion of experimental behaviour confirms that the proposed low-cost smart sensor node achieves reliable operation and architectural coherence, addressing current challenges in scalable automotive monitoring while maintaining simplicity and reproducibility.

Table 5

Comparison with Existing Prototype-Level Approaches**

Aspect	**Existing Works**	**Proposed System**
Hardware Cost	Medium to High	Low
Processing Location	Centralized	Local (Sensor Node)
Encoder Handling	Polling-based	Interrupt-based
Bus Concept	Industrial CAN	Conceptual serial bus
Experimental Complexity	High	Minimal

5. Conclusion

This research presented a low-cost smart sensor node architecture aimed at prototype-level automotive monitoring applications, emphasising encoder-based speed sensing and environmental parameter acquisition using an Arduino-class microcontroller. The proposed approach demonstrates that meaningful sensing and local data processing can be achieved using minimal hardware resources while maintaining a modular and scalable architectural structure. By employing interrupt-driven pulse acquisition for incremental optical encoders, the system enables reliable rotational speed measurement without dependence on complex or industrial automotive communication frameworks. The inclusion of local signal processing at the sensor node level highlights the potential of distributed intelligence in reducing centralised processing overhead and improving system extensibility.

The developed prototype validates the feasibility of integrating multiple sensing modalities within a unified embedded platform, supporting structured data acquisition and transmission through a conceptual bus-oriented interface. This design approach is particularly relevant for academic research, educational environments, and early-stage automotive system exploration, where simplicity, reproducibility, and cost efficiency are essential. The architectural clarity and experimental transparency of the proposed system establish it as a practical foundation for studying smart sensor concepts in automotive and related embedded domains.

While the system successfully demonstrates core sensing and processing capabilities, it is subject to certain limitations inherent to low-cost prototyping platforms. The communication mechanism remains conceptual and does not reflect automotive-grade protocols, and the sensing accuracy is constrained by the characteristics of inexpensive components and controlled laboratory conditions. Additionally, the current implementation does not address robustness, fault handling, or real-time synchronization requirements typically expected in production-level automotive systems. These constraints, however, are consistent with the academic scope of the work and do not detract from its research value.

Future work may extend this architecture by incorporating standardized communication protocols, multi-node scalability, and enhanced signal processing techniques to improve measurement reliability. The proposed smart sensor node framework thus provides a valuable baseline for further investigation into low-cost, distributed sensing architectures for automotive monitoring applications.

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