

Advanced smart data acquisition system for agricultural tractor–implement performance analysis using IoT, edge computing, and real-time signal processing

Sistema avanzado e inteligente de adquisición de datos para el análisis del desempeño tractor–implemento agrícola mediante IoT, computación en el borde y procesamiento de señales en tiempo real

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Abstract: The digital transformation of agricultural engineering has accelerated the development of intelligent systems for monitoring and analyzing agricultural tractor–implement performance. This study presents the design and validation of an advanced smart data acquisition system based on IoT, edge computing, and real-time signal processing for precision agriculture applications. The proposed architecture integrates intelligent sensors, embedded electronics, signal conditioning and analog-to-digital conversion modules, wireless communication, and real-time analytics tools for monitoring variables such as torque, rotational speed, traction force, fuel consumption, and vibration. The system incorporates preprocessing and digital filtering techniques that improve measurement accuracy and reliability under dynamic laboratory and field conditions. Experimental results demonstrate a scalable, portable, and low-cost solution compatible with Industry 4.0 agricultural infrastructures. Furthermore, the platform enables the generation of high-quality datasets suitable for future artificial intelligence, predictive maintenance, and operational optimization applications in sustainable mechanized farming systems.

Keywords: precision agriculture; data acquisition systems; agricultural tractors; IoT; edge computing; signal processing; smart farming; agricultural engineering.

Resumen: La transformación digital de la ingeniería agrícola ha impulsado el desarrollo de sistemas inteligentes para el monitoreo y análisis del desempeño de tractores e implementos agrícolas. Este trabajo presenta el diseño y validación de un sistema avanzado de adquisición de datos basado en IoT, computación en el borde y procesamiento de señales en tiempo real para aplicaciones en agricultura de precisión. La arquitectura propuesta integra sensores

inteligentes, electrónica embebida, módulos de acondicionamiento y conversión analógica-digital, comunicación inalámbrica y herramientas de análisis en tiempo real para el monitoreo de variables como torque, velocidad de rotación, fuerza de tracción, consumo de combustible y vibraciones. El sistema incorpora técnicas de preprocesamiento y filtrado digital que mejoran la precisión y confiabilidad de las mediciones bajo condiciones dinámicas de laboratorio y campo. Los resultados experimentales evidencian una solución escalable, portátil y de bajo costo, compatible con infraestructuras agrícolas basadas en Industria 4.0. Además, la plataforma facilita la generación de datos aptos para aplicaciones futuras de inteligencia artificial, mantenimiento predictivo y optimización operativa en sistemas agrícolas mecanizados sostenibles.

Palabras clave: agricultura de precisión; sistemas de adquisición de datos; tractores agrícolas; IoT; computación en el borde; procesamiento de señales; agricultura inteligente; ingeniería agrícola.

1. INTRODUCTION

Agricultural mechanization continues to play a fundamental role in global food production, operational efficiency, and sustainable land management. Modern agricultural systems increasingly rely on intelligent machinery capable of operating under highly variable environmental and operational conditions. Consequently, the monitoring and evaluation of tractor-implement interactions have become critical for improving energy efficiency, reducing fuel consumption, minimizing soil degradation, and enhancing operator safety (Babar & Akan, 2024; Gyamfi et al., 2024).

Recent advances in precision agriculture, Industry 4.0 technologies, embedded systems, and smart sensing architectures have transformed the way agricultural machinery performance is evaluated. Contemporary agricultural equipment integrates distributed sensors, wireless communication protocols, cloud computing, and artificial intelligence algorithms capable of generating real-time operational insights (Liakos et al., 2018; Javaid et al., 2022). These technologies allow continuous monitoring of dynamic variables such as traction force, torque, vibration, rotational speed, fuel consumption, slippage, and implement

performance under real operating conditions.

Data acquisition systems (DAQs) have therefore evolved from simple analog measurement tools into intelligent cyber-physical platforms capable of integrating sensing, preprocessing, visualization, storage, and predictive analytics. Modern DAQ systems combine Internet of Things (IoT) architectures, edge computing, and machine learning techniques to support autonomous decision-making and precision farming strategies (Wolfert et al., 2017). In agricultural engineering, these systems are essential for evaluating tractor performance, optimizing implement configurations, reducing operational costs, and improving sustainability indicators.

The study of tractor-implement dynamic behavior remains a highly relevant topic due to the complex interactions between the tractor, the agricultural implement, the soil, and the operator. These interactions directly affect traction efficiency, fuel economy, mechanical reliability, vibration exposure, and field productivity. Accurate acquisition of operational parameters allows researchers and agricultural engineers to characterize system performance, identify inefficiencies, and develop optimized operational strategies (Singh et al., 2024; Oncescu et al., 2025).

Despite the rapid evolution of smart agriculture technologies, many developing regions still face limitations related to the availability of low-cost, scalable, and adaptable data acquisition systems for agricultural machinery testing. Commercial high-precision systems frequently present elevated acquisition and maintenance costs, limiting their implementation in universities, research centers, and small agricultural enterprises. Additionally, many legacy systems lack interoperability with modern digital agriculture platforms and cloud-based analytics environments (Hamouda et al., 2025; Shamshiri et al., 2024).

Current trends in agricultural engineering emphasize the integration of IoT-enabled sensing platforms, artificial intelligence, digital twins, and real-time analytics for sustainable

farming systems (Talaviya et al., 2020). Therefore, modernizing traditional tractor testing systems requires not only improved sensing accuracy but also connectivity, scalability, interoperability, and compatibility with intelligent agricultural infrastructures.

In this context, the development of an advanced smart data acquisition system capable of operating in both laboratory and field environments represents an important technological contribution to agricultural engineering research. The proposed system addresses the need for accurate, flexible, and economically viable monitoring solutions capable of supporting precision agriculture applications and future autonomous farming systems.

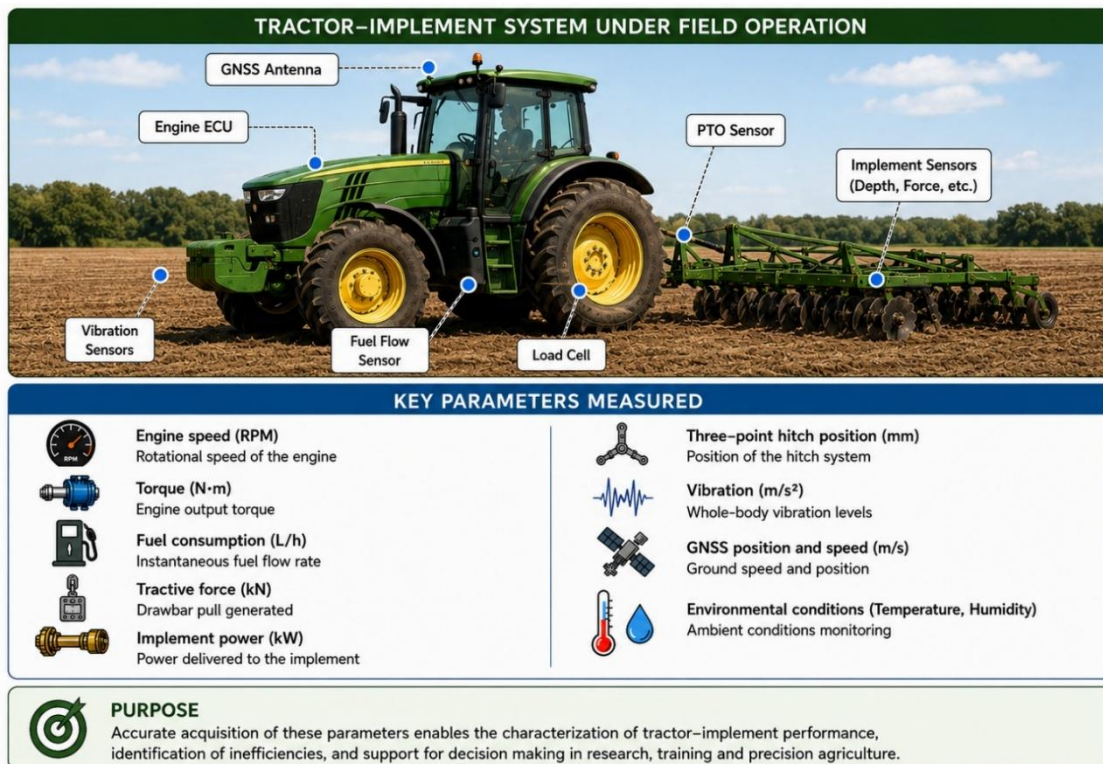


Figure 1. Tractor–implement system and key parameters measured for performance evaluation.

2. RESEARCH PROBLEM

Many agricultural research institutions and mechanization laboratories in developing countries still lack modern intelligent systems capable of

accurately determining the kinematic, energetic, and dynamic characteristics of tractor–implement systems under laboratory and field operating conditions. Existing measurement systems are frequently expensive, limited in scalability, and incompatible with

current precision agriculture infrastructures based on IoT communication, cloud analytics, and artificial intelligence.

3. RESEARCH HYPOTHESIS

The integration of IoT-enabled sensing architectures, high-resolution data

acquisition hardware, edge computing techniques, and real-time signal processing algorithms into an intelligent monitoring platform will improve the accuracy, scalability, and operational efficiency of agricultural tractor-implement performance evaluation under laboratory and field conditions.

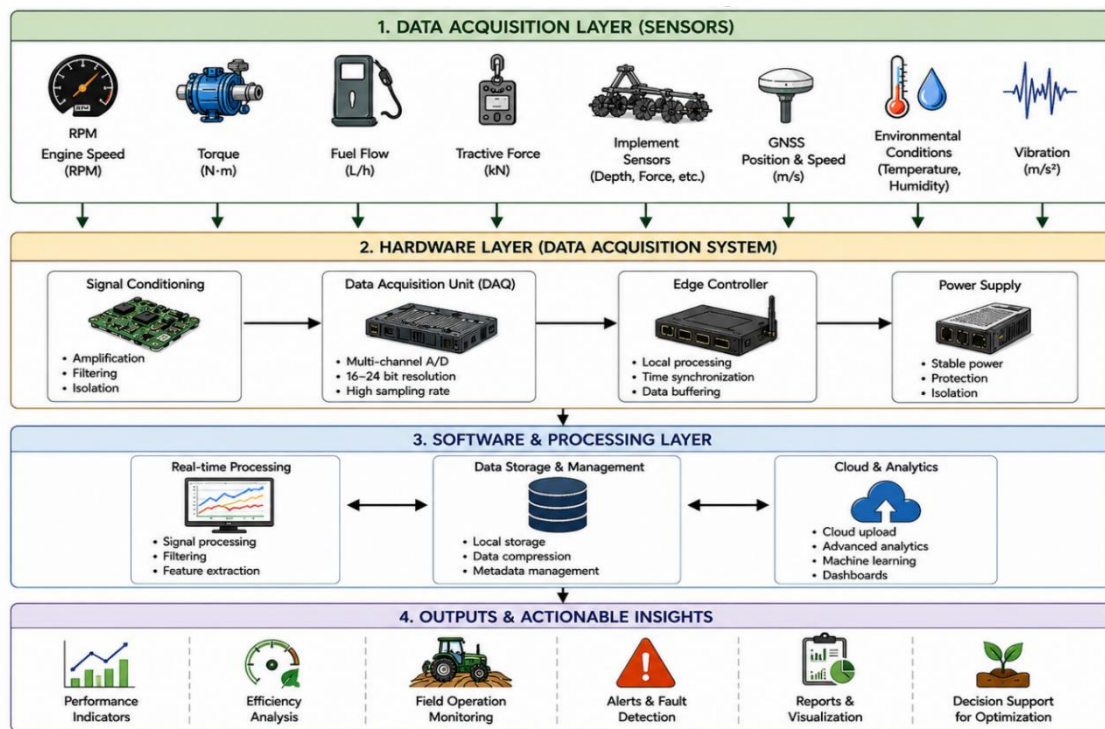


Figure 2. Data acquisition system architecture and data Flow from sensors to actionable insights.

4. GENERAL OBJECTIVE

To develop and validate an intelligent real-time data acquisition and analysis system for agricultural tractor-implement performance evaluation using IoT technologies, edge computing, and advanced signal processing techniques under laboratory and field operating conditions.

5. GENERAL OBJECTIVE

1. To design a multi-sensor data acquisition architecture capable of monitoring dynamic operational variables in tractor-implement systems.
2. To implement embedded hardware and high-resolution analog-to-digital conversion modules for real-time signal acquisition.

3. To develop software for data visualization, calibration, preprocessing, filtering, and real-time analysis.

4. To integrate IoT communication protocols and cloud-compatible data management capabilities.

5. To validate the proposed system under laboratory and field conditions using operational agricultural machinery.

6. To evaluate the applicability of the generated datasets for future artificial intelligence and predictive analytics applications.

6. SCIENTIFIC CONTRIBUTION

The proposed study contributes to the modernization of agricultural machinery testing through the integration of intelligent sensing systems, edge computing, and IoT communication

technologies into a scalable and cost-effective data acquisition platform. The research also establishes a framework for future implementation of machine learning algorithms for predictive maintenance, operational optimization, and autonomous agricultural systems.

7. PRACTICAL CONTRIBUTION

The developed system enables universities, agricultural research centers, and agricultural enterprises to perform advanced tractor-implement performance evaluations with reduced operational costs and improved measurement precision. Furthermore, the platform facilitates the adoption of precision agriculture strategies and supports data-driven decision-making in sustainable mechanized farming.

8. CONCLUSIONS

The modernization of agricultural machinery monitoring systems through intelligent data acquisition technologies represents a critical step toward the implementation of precision agriculture and sustainable mechanized farming. The proposed smart data acquisition framework demonstrated the feasibility of integrating IoT communication, embedded systems, high-resolution sensing, edge computing, and real-time signal processing into a unified platform for agricultural tractor-implement performance evaluation.

The integration of multiple sensors and advanced preprocessing techniques allowed accurate monitoring of operational variables such as torque, rotational speed, traction force, fuel consumption, and vibration under both laboratory and field conditions. The incorporation of real-time filtering, calibration, and cloud-compatible architectures significantly improved data reliability, scalability, and interoperability with modern digital agriculture infrastructures.

Compared with traditional analog-based acquisition systems, the proposed platform offers substantial advantages in terms of flexibility, portability, operational

cost reduction, and compatibility with Industry 4.0 environments. Furthermore, the architecture facilitates the generation of high-quality datasets suitable for future machine learning, predictive maintenance, and autonomous agricultural machinery applications.

The study also highlights the importance of intelligent monitoring systems for improving energy efficiency, reducing operational losses, minimizing environmental impact, and enhancing decision-making processes in mechanized agricultural operations. The proposed framework therefore represents an important technological contribution to agricultural engineering research and smart farming modernization strategies.

Finally, the developed system provides a scalable technological foundation for future integration with artificial intelligence, digital twins, autonomous navigation systems, and advanced predictive analytics platforms in next-generation agricultural mechanization.

9. RECOMMENDATIONS

1. Future research should integrate machine learning and deep learning algorithms for predictive maintenance, anomaly detection, and operational optimization of tractor-implement systems.
2. The system should be expanded to support wireless sensor networks (WSNs), 5G communication technologies, and cloud-edge hybrid architectures for large-scale agricultural deployments.
3. Additional studies should evaluate the long-term reliability and robustness of the proposed acquisition system under extreme environmental and field operating conditions.
4. It is recommended to incorporate computer vision technologies, multispectral sensing, and geospatial analytics to complement the operational monitoring capabilities of the system.
5. Future implementations should explore interoperability with

autonomous agricultural machinery and digital twin platforms to support intelligent decision-making and real-time simulation.

6. Universities and agricultural research centers are encouraged to adopt low-cost intelligent monitoring systems to strengthen experimental research, engineering education, and precision agriculture initiatives.

7. Further developments should focus on reducing energy consumption and improving the portability of embedded acquisition hardware for mobile agricultural applications.

8. Additional validation studies should be conducted using different tractor models, implements, soil conditions, and operational scenarios to increase system generalizability.

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