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A NOVEL APPROACH TO REAL-TIME TORQUE MEASUREMENT THROUGH IOT-INTEGRATED STRAIN GAUGES AND NEURAL NETWORK CALIBRATION

Cosmin Constantin SUCIU, Virgil STOICA, Mariana ILIE, Ioana IONEL

Abstract: *The paper emphasizes the conceptual design and theoretical evaluation of an Internet of Things (IoT)-enabled torque measurement system for vehicular drivetrains. The proposed system integrates cost-efficient components, including a Wemos D1 Mini ESP8266 microcontroller, BF350-3HA-E strain gauges, and an HX711 load cell amplifier, to enable real-time monitoring of rotational forces. Calibration is performed using a dynamometric wrench compliant with ISO 6789:2017 standards, covering a torque range of 5–50 Nm. The system is theoretically expected to achieve ±1.5% accuracy at a cost below 30 euros. The novelty lies in its ability to combine affordability, portability, and precision with IoT-enabled intelligent measuring and control capabilities. This work offers a scalable solution for cost-sensitive automotive applications, with potential for experimental validation and broader adoption.*

Keywords: *Torque measurements, Strain Gauges, Real-Time Monitoring, Portable Torque Sensor, Intelligent measuring and control, Neural Network Calibration*

1. INTRODUCTION

Torque measurement [1] is essential for optimizing drivetrain performance and ensuring vehicle reliability. Traditional systems like dynamometers and rotary torque transducers are highly accurate but expensive, complex to set up, and unsuitable for real-time or mobile applications [2, 3]. This study proposes a low-cost alternative that leverages IoT technology to enable real-time monitoring and data transmission. The incorporation of intelligent measuring and control features further enhances the system's capability to adapt to varying operational conditions and provide actionable insights. The system's intelligence is derived from its ability to process and analyze torque data in real-time, utilizing the computational capabilities of the Wemos D1 Mini ESP8266 microcontroller. This allows for dynamic calibration, adaptive sampling rates based on detected torque variations, and the implementation of custom algorithms for noise reduction and signal processing. Furthermore, the IoT connectivity enables remote monitoring, data logging, and the potential for integration with broader vehicle management systems, facilitating predictive maintenance and performance optimization strategies.

2. LITERATURE REVIEW

2.1 Torque measurement systems as available

Dynamometers [4] are widely used in controlled environments to measure engine output or drivetrain performance. They provide high accuracy (±0.1–0.5%) and require specialized setups and infrastructures [5]. One paper [6] describes an application in wind turbine drivetrains and highlights the prohibitive costs due to large-scale setups.

Rotary transducers measure torque directly on rotating shafts using strain gauges or magnetic sensing principles [7]. Yu et al. (2022) [8] achieved 0.1% full scale (FS) accuracy by employing neural network-based calibration techniques to enhance precision under dynamic conditions [9]. FS represents the maximum measurable value of the sensor or system. When a system specifies an accuracy of 0.1% FS, it means that the measurement error will not exceed 0.1% of the maximum range, regardless of the actual value being measured within that range [8, 10].

Unlike percentage-of-reading accuracy, which varies with the measured value, FS accuracy provides a fixed error margin across the entire measurement range [11]. This level of precision is essential for applications requiring consistent performance over a wide range of operating conditions. Neural network-based calibration techniques are advanced methods used to improve sensor accuracy by addressing nonlinearities, cross-axis coupling effects, and other sources of error that traditional methods often fail to compensate for [8, 12].

These techniques work by training machine learning models on datasets collected from sensors under controlled conditions. The raw outputs from sensors are paired with reference values obtained from calibrated standards, such as torque wrenches. The neural network learns to map these raw outputs to accurate values by identifying and compensating for systematic errors and nonlinear behaviors in the sensor data [7]. Neural networks offer several advantages over traditional calibration methods. They can model complex relationships between input and output variables, which are often nonlinear and challenging to address using polynomial fitting or linear regression techniques [8]. Additionally, they adapt to dynamic changes in sensor behavior caused by environmental factors such as temperature variations or vibrations [9]. These networks are also effective in mitigating cross-axis coupling effects, where forces or torques along one axis influence measurements on another axis [13]. In torque measurement applications, neural networks have been successfully used to achieve high precision by compensating for errors introduced by additional torques in complex systems such as robotic arms [8, 12].

For instance, radial basis function (RBF) neural networks combined with optimization algorithms like Levenberg–Marquardt have been shown to significantly reduce calibration errors, achieving accuracies as high as 0.1% FS after training [8, 14]. By combining neural network-based calibration techniques with high-precision sensors capable of achieving 0.1% FS accuracy, significant advancements in torque measurement technology have been realized. Neural networks effectively address limitations of traditional calibration methods by compensating for nonlinearities and environmental influences while maintaining consistent precision across the full measurement range [8, 12]. These innovations enable more reliable and accurate torque measurements in dynamic and complex applications such as robotics and automotive systems [9].

IoT is a system involving interconnected physical devices embedded with sensors, software, and advanced technologies. These devices are capable of collecting and exchanging data over the internet independently, without the need for human interaction [11, 12]. IoT devices incorporate devices from simple household items up to sophisticated industrial tools, enabling seamless communication between people, processes, and machines [2]. In automotive applications, IoT facilitates real-time data acquisition from sensors embedded in vehicles or their components, enhancing safety, efficiency, and predictive maintenance [9, 15].

This paper focuses on developing an IoT-enabled torque measurement system that integrates strain gauges with wireless communication technology to address the limitations of traditional methods.

IoT-enabled systems emerge as cost-effective alternatives by integrating wireless communication for real-time monitoring [15]. Xia et al. [15] introduced an optoelectronic system achieving 0.92% error using SAPSO-RBF neural network calibration methods [16]. The optoelectronic torque measurement system [16] uses photoelectric sensors to detect deformations caused by torque and processes these signals using a hybrid Simulated Annealing and Particle Swarm Optimization to optimize the parameters of a Radial Basis Function neural network (SAPSO-RBF) neural network calibration algorithm. This algorithm combines SAPSO-RBF neural network, effectively handling nonlinearities and minimizing calibration errors. The system achieves a low error rate of 0.92%, making it highly precise and suitable for dynamic applications like robotics and automotive systems. Its design eliminates common issues found in strain gauge-based systems, such as adhesion inaccuracies and environmental sensitivity.

2.2 Limitations of the available systems

Current torque measurement systems face three main limitations: high costs, complexity in setup and calibration, and lack of portability. These challenges restrict their adoption, particularly in small-scale or dynamic applications.

The high costs result from the torque measurement systems. They are expensive due to advanced designs, such as brushless or slip-ring configurations, which increase manufacturing complexity [2]. While strain gauge-based sensors are more affordable than magnetic or optical systems, their cost remains prohibitive for small-scale applications, limiting accessibility for research facilities or industries with constrained budgets [7]. Contributing factors include the need for precise calibration processes, robust materials to withstand mechanical stress, and integration with data acquisition tools [11, 12].

These systems require intricate setups to ensure accuracy. Calibration involves addressing variables like force application, angular alignment, and parasitic forces such as bending moments [8]. Environmental factors such as temperature fluctuations further complicate the process [17]. Specialized equipment like dynamometers or hydraulic torque wrenches is often required, demanding skilled operators and controlled environments [7, 12]. Additionally, torque sensors are prone to errors caused by vibrations or electromagnetic interference, which may necessitate compensation algorithms that add further complexity [14, 18].

Traditional systems are bulky and unsuitable for mobile applications due to their physical size and infrastructure requirements [9]. Rotary transducers often require direct mechanical connections to the shaft being measured, leading to downtime for installation or driveline modifications [15]. Emerging IoT-enabled devices provide a promising alternative by integrating wireless connectivity into compact designs, eliminating physical connections while maintaining accuracy through advanced signal processing techniques [16, 19]. In summary, the high costs, complex calibration requirements, and lack of portability in current systems limit their usability in dynamic or small-scale applications. However, advancements in IoT technology and sensor miniaturization offer solutions by addressing these challenges while maintaining accuracy and reliability [8, 12].

3. PROPOSED SYSTEM AND DATA MANAGEMENT

The proposed system introduces a conceptual design for an IoT-enabled torque measurement solution aimed at vehicular drivetrains. It integrates strain-based sensing, signal processing, and wireless communication into a compact assembly mounted on a rotating shaft. This system is designed to address challenges such as cost, portability, and real-time monitoring, offering a scalable alternative to traditional torque sensors. The modularity of the design allows for flexibility in adapting the system to different applications. For example, the sensing subsystem can accommodate various types of strain gauges depending on the required sensitivity and environmental conditions. Similarly, the signal processing subsystem can be customized to include additional filtering or error compensation techniques if needed for specific use cases. Another significant advance of the system is its ability to achieve real-time monitoring and wireless data transmission, eliminating the need for physical connections like slip rings. Figure 1 provides a general schematic representation of the system's architecture. It highlights the integration of three primary subsystems: sensing, signal processing, and wireless communication. The sensing subsystem includes strain gauges mounted on a rotating shaft to detect torsional strain caused by applied torque. The signal processing subsystem amplifies and digitizes these measurements, while the wireless communication subsystem transmits data to cloud-based platforms for real-time monitoring.

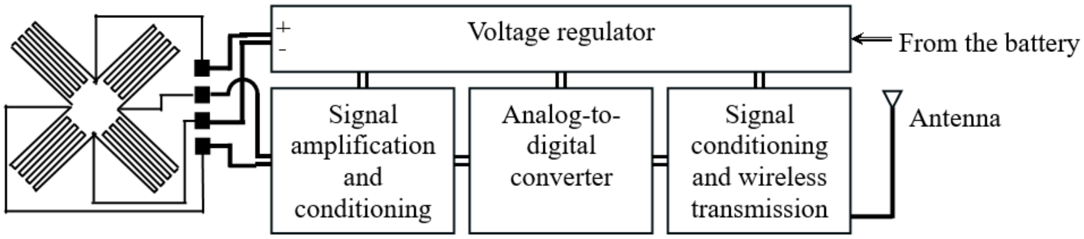


Fig. 1. Rotating torque measurement assembly schematic.

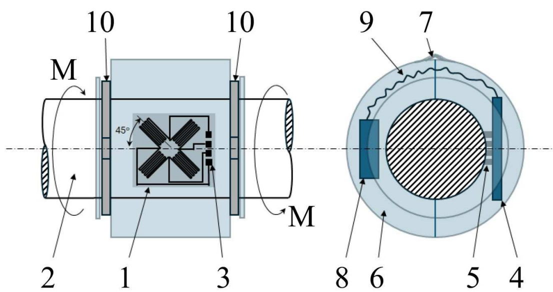
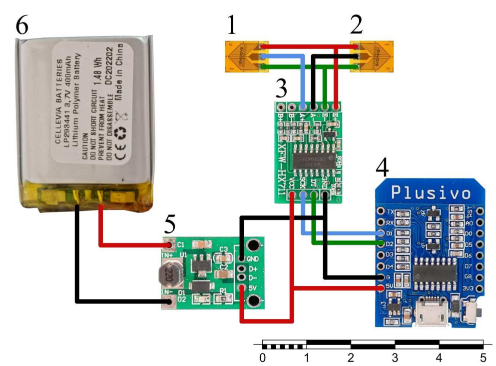


Fig. 2. Side view and sectional view of the proposed system.

Figure 2 provides a more detailed visualization of the system's physical layout. The side view illustrates the external arrangement of components, including the strain gauges (1), shaft (2), Wheatstone bridge circuit (3), protective housing (6), and holding clips (10). The sectional view complements this by showing the internal configuration, such as the placement of electronic components (4), electrical connections (5), antenna (7), battery (8), and wiring (9). Together, these views offer insight into how the subsystems are integrated into a compact assembly designed for drivetrain applications. The system's architecture emphasizes modularity and efficiency. The sensing subsystem measures torsional strain through changes in resistance detected by strain gauges bonded to the shaft at ±45° angles. The signal processing subsystem ensures accurate amplification and digitization of these signals, while the wireless communication subsystem eliminates the need for physical connections between the rotating assembly and external monitoring systems. The conceptual design prioritizes scalability, affordability, and portability. All components are enclosed within a protective housing that shields them from environmental factors such as dust, moisture, and vibrations. Power is supplied by a portable energy source regulated by an efficient power management module. The schematic represents a theoretical assembly designed for conceptual validation rather than physical implementation at this stage. By addressing key challenges in torque measurement systems, it demonstrates potential for future experimental validation and broader adoption in automotive engineering.



1. strain gauges
2. strain gauges
3. load cell amplifier
4. microcontroller
5. DC-DC converter
6. battery

Fig. 3. System components.

The BF350-3HA-E strain gauges (Fig. 3: components 1, 2) are foil-type resistance strain gauges widely used for their high accuracy, stability, and temperature compensation capabilities [2, 11]. These gauges are made with constantan alloy as the gate material and a modified phenolic resin backing, providing excellent flexibility and durability under varying environmental conditions. Configured in a Wheatstone bridge, they are bonded to the shaft at ±45° angles to measure torsional strain [12]. This arrangement enhances sensitivity by quadrupling the output signal compared to quarter-bridge setups, offers thermal compensation by balancing temperature effects across the bridge, and ensures linear output for simplified calibration [12].

The strain gauges operate within a temperature range of -30°C to +80°C and have a fatigue life exceeding 10 million cycles, making them suitable for dynamic applications [12]. Their resistance tolerance is within ±0.1%, ensuring consistent performance under mechanical stress.

The HX711 load cell amplifier (Fig. 3: component 3) is a high-resolution 24-bit analog-to-digital converter (ADC) designed for precision measurements in weighing and force applications. It amplifies the small voltage signals from the strain gauges with selectable gain options of 32x, 64x, and 128x to accommodate different signal levels. This module supports dual differential input channels and integrates an on-chip low-noise programmable gain amplifier (PGA), ensuring stable readings even under dynamic conditions [7]. Operating with a low current consumption (<1.5mA) and a voltage range of 2.7V–5.5V, the HX711 is ideal for battery-powered systems3. Its ability to reject simultaneous 50Hz/60Hz noise further enhances measurement accuracy in industrial environments.

The Wemos D1 Mini ESP8266 microcontroller (Fig. 3: component 4) facilitates wireless data transmission using IEEE 802.11 b/g/n Wi-Fi standards. This compact development board features an ESP8266EX microcontroller with an operating frequency of up to 80MHz, flash memory of 4MB, and support for multiple GPIO pins for versatile connectivity. The microcontroller processes amplified signals from the HX711 and transmits real-time data wirelessly to monitoring systems or cloud platforms [12]. Its compatibility with Arduino IDE simplifies programming, while its low power consumption makes it suitable for IoT applications requiring extended operation times. The Wemos D1 Mini also supports integration with various shields for expanded functionality.

The system's power management relies on a portable Li-Po battery (ACCU-LP293441/CL) with a capacity of 400mAh (Fig. 3: component 6). This lightweight battery delivers consistent energy for approximately 12 hours of continuous operation. A DC-DC converter (Fig. 3: component 5) regulates the power supply with an efficiency of ~93%, minimizing energy losses during operation [13]. Li-Po batteries are chosen for their high energy density, compact size, and ability to operate efficiently across a wide temperature range [11]. These characteristics make them ideal for portable IoT systems that demand reliability in diverse environments.

Calibration ensures accurate torque measurements by correlating sensor outputs with known torque values. The process involves bonding four strain gauges to the rotating shaft at ±45° angles to optimize sensitivity and thermal compensation11. Incremental torques ranging from 5–50 Nm are applied using an ISO-compliant dynamometric wrench. The raw ADC outputs from the HX711 amplifier are recorded, and a calibration curve is generated to establish a linear relationship between sensor readings and reference torque values [8, 19].

To improve accuracy further, best practices such as preloading the torque transducer three times before calibration and conducting measurements at multiple mounting positions (e.g., rotated through 120°) are recommended [11, 20]. These steps help account for repeatability errors and ensure robust performance across varying operating conditions.

By integrating advanced components such as BF350-3HA-E strain gauges, an HX711 amplifier, and a Wemos D1 Mini ESP8266 microcontroller, this system delivers precise torque measurements in real-time applications while addressing challenges related to cost, complexity, portability, and environmental factors [7, 12]. The use of high-performance strain gauges ensures reliable sensing under mechanical stress, while the HX711 amplifier provides accurate signal processing. Additionally, the Wemos D1 Mini enables seamless wireless communication for remote monitoring.

The neural network-based calibration process leverages neural network techniques inspired by Xia et al. [15], who employed a hybrid Simulated Annealing and Particle Swarm Optimization (SAPSO)-Radial Basis Function (RBF) neural network. Raw ADC values from the HX711 amplifier serve as inputs, while reference torque values from the ISO-compliant dynamometric wrench provide labeled training data.

The network architecture comprises an input layer (ADC readings), a hidden RBF layer for nonlinear mapping, and an output layer (calibrated torque values). Training is conducted in MATLAB using the Levenberg-Marquardt algorithm to minimize mean squared error, similar to Yu et al. [8]. Post-training, the model is deployed on the Wemos D1 Mini to convert raw sensor data into calibrated torque measurements in real-time.

This conceptual design is particularly suited for applications requiring lightweight designs, extended operational periods, and high measurement precision, such as IoT-enabled industrial monitoring or automotive testing environments [2, 7, 12] and will be materialized to validate its practical applicability.

4. COMPARISON WITH COMMERCIAL SYSTEMS

Table 1

Comparison of the proposed system with commercial systems.

Feature	Commercial Systems	Proposed System
Cost	High (e.g. dynamometers)	Under 30€
Accuracy	±0.1–0.5% FS	±1.5% FS
Portability	Limited	Compact and portable
Real-Time Monitoring	Available	Wireless via Wi-Fi
Calibration Complexity	Requires specialized setups	Simplified using ISO standards

Table 1 highlights that while commercial systems excel in accuracy and established reliability, they are costly, complex to set up, and lack portability for dynamic applications. In contrast, the proposed system offers a cost-effective, portable alternative with real-time monitoring capabilities and simplified calibration processes, making it suitable for small-scale or mobile applications without sacrificing significant.

5. APPLICATIONS

The proposed system has broad applications in automotive engineering. One of the applications includes drivetrain optimization through real-time torque profiling. It can also identify abnormal torque patterns signaling predictive maintenance and serve as a tool for quality control in various vehicle manufacturing processes. Torque measurements from wheels can additionally be utilized for electronic stability program (ESP) systems, enhancing vehicle stability and safety. These measurements are valuable for controlling both thermal and electric motors in closed-loop systems, enabling precise performance adjustments. They can also help determine characteristics of the running surface, which directly aids braking systems by improving their efficiency and responsiveness.

Beyond automotive applications, the system offers a wide range of uses. If designed to be cost-effective, it could be integrated into industrial machines for monitoring and controlling various processing operations. As mentioned earlier in the introduction, its functionality can also be extended to robotics, where it can play a critical role in control systems and operational precision. This versatility highlights the potential of the system across multiple fields beyond traditional vehicle engineering.

6. CONCLUSIONS AND FUTURE WORK

This paper demonstrates the feasibility of an IoT-enabled torque measurement system for vehicular applications that combines affordability with real-time monitoring capabilities while maintaining acceptable accuracy levels (±1.5%). While experimental validation is yet to be conducted, preliminary theoretical analysis suggests strong potential for practical deployment. By leveraging standardized calibration methods and modular components, this work introduces a novel approach to torque sensing by integrating cost-effective, off-the-shelf components with IoT technology, enabling wireless data transmission and real-time analysis at a significantly reduced cost compared to commercial solutions. This innovation provides a scalable solution for drivetrain optimization, predictive maintenance, and quality control in automotive systems. It also requires further experimental validation before full-scale implementation can be claimed. The system's ability to achieve comparable accuracy to commercial sensors while reducing complexity and cost highlights its unique contribution to the field of automotive engineering. The integration of intelligent measuring and control functionalities positions this system as a versatile tool for advanced automotive engineering applications, offering potential for improved efficiency and performance in vehicle drivetrain systems. Future iterations could adopt integrated MEMS-based designs inspired by tire pressure monitoring systems (TPMS), combining wireless telemetry, energy harvesting, and miniaturized strain sensing into a single package. Future work will focus on experimental validation of the proposed system under real-world conditions, including long-term durability and recalibration requirements. The sensor housing will be designed to meet IP68 protection standards, ensuring resistance to environmental factors like dust, water, and vibrations. To improve accessibility, alternative calibration methods using tools like suspended scales will be explored. Scalability will also be investigated by adapting the system for various shaft sizes and deformation ranges, enabling broader applications in automotive and industrial contexts.

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O abordare inovatoare pentru măsurarea în timp real a cuplului utilizând tensometre integrate IoT și calibrare prin rețele neuronale

Lucrarea prezinta proiectarea conceptuală și evaluarea teoretică a unui sistem de măsurare a cuplului bazat pe tehnologia Internet of Things (IoT), destinat transmisiei vehiculelor. Sistemul propus integrează componente rentabile, inclusiv un microcontroler Wemos D1 Mini ESP8266, tensometre BF350-3HA-E și un amplificator HX711, pentru monitorizarea în timp real a momentului de torsiune din arborele roții. Calibrarea este realizată utilizând o cheie dinamometrică conformă cu standardele ISO 6789:2017, acoperind un interval de cuplu de 5–50 Nm. Sistemul este estimat teoretic să atingă o precizie de ±1,5%, la un cost sub 30 de euro. Noutatea constă în capacitatea sa de a combina accesibilitatea, portabilitatea și precizia cu funcționalități inteligente de măsurare și control bazate pe IoT. Această lucrare oferă o soluție scalabilă pentru aplicații auto sensibile la costuri, cu potențial pentru validare experimentală și adoptare extinsă.

Cuvinte cheie: *măsurători de cuplu, tensiometre, monitorizare în timp real, senzor de cuplu portabil, măsurare și control inteligent, calibrare rețea neuronală*

Cosmin Constantin SUCIU, PhD student, Politehnica University Timisoara, Faculty of Mechanical Engineering, cosmin.suciu@student.upt.ro.

Virgil STOICA, PhD, Assoc. Professor, Politehnica University Timisoara, Faculty of Mechanical Engineering, virgil.stoica@upt.ro. (correspondent author)

Mariana ILIE, PhD, Assoc. Professor, Politehnica University Timisoara, Faculty of Mechanical Engineering mariana.ilie@upt.ro.

Ioana IONEL, PhD, Professor, Politehnica University Timisoara, Faculty of Mechanical Engineering, ioana.ionel@upt.ro.