Plant Archives Vol. 26, Supplement 1, 2026 pp. 986-992 e-ISSN:2581-6063 (online), ISSN:0972-5210

Plant Archives

Journal homepage: http://www.plantarchives.org
DOI Url : https://doi.org/10.51470/PLANTARCHIVES.2026.v26.supplement-1.131

A WIRELESS INSTRUMENTATION SYSTEM FOR REAL-TIME MONITORING OF TRACTOR POWER TAKE-OFF (PTO) SPEED

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(Date of Receiving : 09-10-2025; Date of Acceptance : 18-12-2025)

ABSTRACT

The current research concentrated on creating, developing, and validating a Real Time Wireless Speed Measuring Unit to monitor the Power Take-Off (PTO) speed of tractors. Precise PTO speed measurement is crucial in agricultural machinery because it affects power output, fuel efficiency, and overall performance. Traditional methods, like analog meters or relying on the operator's judgment, often lack accuracy and reliability. To address these issues, a cost-effective and portable wireless system was devised using an ESP32 microcontroller with the ESP-NOW communication protocol, paired with an inductive proximity sensor to detect the rotation of the PTO shaft. The detected pulses were processed and sent wirelessly to a receiver module, where real-time RPM values were shown on an I2C LCD. The system's accuracy was tested against two standard reference devices: a handheld tachometer (TM-4005) and a PTO torque sensor with a wireless data logger. Tests were conducted at nine different PTO speeds, and the results were compared using statistical accuracy indicators. The Root Mean Square Error (RMSE) was 8.8 RPM and 8.4 RPM when compared with the torque sensor and handheld tachometer, respectively. The Mean Absolute Percentage Error (MAPE) was 2.66% and 2.06%, and the Maximum Absolute Variation (MAV) was 16 RPM in both cases.
Keywords **:** ESP microcontroller, Proximity sensor, I2C Lcd display, PCB, PTO speed, RPM, Accuracy, Speed Measurement, Validation.

Introduction

Agriculture is among the most challenging professions and serves as the primary source of food supply globally. Investing in agricultural machinery and equipment is substantial, as these tools have made farming more manageable and have streamlined tasks within the agricultural setting by boosting productivity. The efficiency of rotational power output is vital, as it greatly influences overall expenses. Effective rotational power affects every stage of agricultural activities, from planting to harvesting.

Modern technology has advanced all crucial areas, particularly agriculture, by making many important operational processes easier, more straightforward, and less time-consuming. For instance, smart automation in irrigation allows for precise control over the start and end times of irrigation periods, likewise another essential tool in agriculture is the Tachometer, which measures rotational power by determining rotational speed in revolutions per minute (rpm).

Conventional tractor tachometers are typically mechanical or require a handheld device, either through direct contact with the PTO shaft or by using reflector tape for non-contact measurement. In both cases, the operator must position the tachometer close to the rotating shaft, which poses a considerable safety risk during operation. The proposed Real-Time Wireless Speed Measuring Unit overcomes these limitations by incorporating a non-contact inductive proximity sensor paired with wireless ESP-NOW communication, enabling continuous and accurate PTO speed monitoring without physical proximity. The measured RPM is transmitted wirelessly and displayed on an LCD mounted on the tractor dashboard, allowing the operator to monitor PTO speed effortlessly and safely in real time.

An ESP system is another recent application of modern technology. It includes a programming language that can be used in various applications and can be easily modified and customized to create new modules for measuring systems, sensors, and databases to work with different electrical devices (Maier *et al.,* 2017). ESP is an open-source platform that facilitates data reception and transmission, specifically designed to simplify the development of concepts and projects related to automatic control systems using the Arduino programming language (Arduino C, which is based on the C programming language). Therefore, a study was conducted to develop a wireless instrumentation system to measure the real-time PTO speed.

Tachometer Background

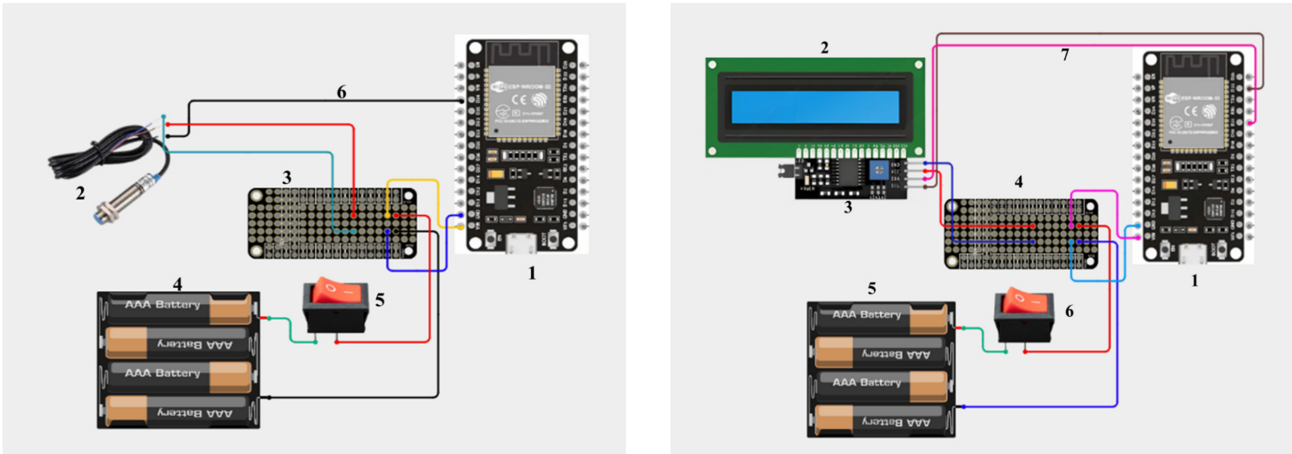
A tachometer is an instrument designed to gauge the rotational speed of machine. Typically, this device presents the speed in revolutions per minute (RPM) on a digital screen, though it has traditionally been shown on an analog display. The term tachometer is derived from the Greek words Ταχος (tachos), meaning speed, and metron, meaning to measure (Tisaj, 2014).

In the past, tachometers were entirely mechanical, but they have significantly evolved with technological progress. The first mechanical tachometer, created by German engineer Dietrich Uhlhorn in 1817, operated on the principle of a centrifugal governor and was primarily used to gauge machinery speed. Over time, tachometers were utilized in locomotives, cars, tractors, trucks, and aircraft. The initial electronic models relied on the monostable multivibrator circuit, which has one stable and one quasi-stable state. In this setup, no output was produced until a triggering current pulse from the ignition system was received, causing the circuit to enter the quasi-stable state for a set period before returning to stability. Each ignition pulse generated a consistent output pulse of fixed length, and the frequency of these pulses per second determined the tachometer's reading. Although monostable multivibrators are still used in some designs, modern tachometers increasingly employ voltage pulses instead of current pulses, as routing ignition coil current through the tachometer proved inefficient. The evolution of tachometer design was often driven by cost reduction rather than accuracy improvement. In the late 1960s, when Integrated Circuits (ICs) were first introduced, their application in tachometers was limited due to high costs and concerns about reliability in automotive settings (Dwivedi *et al*., 2019).

Materials and Methods

System configuration

This study concentrated on creating and deploying a real time speed-measuring unit for non-contact measurement of rotational speed of PTO shaft of a tractor. The system consisted of two units: sensing unit and display unit. Conceptual circuit diagram of these two units are shown in Fig. 1. The sensing unit utilized inductive proximity sensing principles to identify the rotational movement of a metallic target and used ESP-NOW wireless communication to send the collected data to a remote display unit. The system's design separated the sensing and processing unit from the display unit, thereby improving flexibility and usability across different operational settings. The system utilized two ESP32-WROOM modules as its main processing part for sensing and display unit, respectively. With built-in Wi-Fi and Bluetooth, particularly the ESP-NOW protocol, these modules enabled smooth wireless communication between the sensor and display units. An LJ12A3-4-Z/AY inductive proximity sensor was utilized to identify the movement of a metal target. This device functioned based on electromagnetic induction, creating a fluctuating magnetic field. When a metal object came within the sensor's 4 mm detection range, it disturbed the magnetic field, leading to a shift in the sensor's output state. With an operating voltage range of 6 to 36 VDC and an IP65 safety rating, the sensor was well suited for a variety of industrial and experimental settings. The sensor's output was set up to deliver a digital pulse for each revolution detected. An I2C LCD display, featuring a 16x2-character layout and managed through an I2C interface with the address 0x27, was employed to show RPM measurements in the display unit. The I2C interface streamlined the wiring process by utilizing just two data lines, SDA and SCL, for communication. The display's backlight and white characters ensured excellent visibility under different lighting conditions. The LCD was set up and programmed to present the RPM information in an easily understandable format for users. A variety of jumper wires was utilized to create stable electrical connections between the ESP32 microcontroller and other system components. Female-to-male jumper wires were used to link the ESP32 with the inductive proximity sensor, ensuring the sensor's output and power lines were effectively connected to the ESP32's GPIO, VIN, and GND pins. For the I2C LCD display, female-to-female jumper wires connected the VIN, GND, SDA, and SCL lines from the display to the corresponding I2C pins on the ESP32. These jumper wires offered a flexible and modular wiring solution ideal for prototyping and experimentation. Two Printed Circuit Board (PCB) were used for the two units respectively, to handle the system's power connections and distribution. These boards enabled organized and secure wiring among the ESP32 microcontroller, sensor, display, and power supply, ensuring consistent electrical performance and minimizing the risk of loose or shorted connections during field operations. The power supply was provided using a battery holder containing four 1.5 V cells, delivering a combined output of 6V. This arrangement offered a compact and dependable energy source for the system. The use of separate 1.5 V batteries made replacement simple and ensured consistent performance of the ESP32 microcontroller with the inductive proximity sensor, and I2C LCD display during operation.



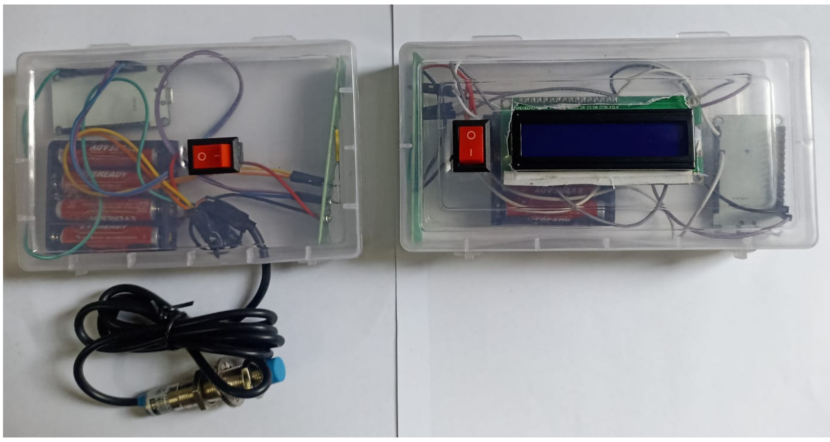
(a) 1. ESP32-WROOM module; 2. LJ12A3-4-Z/AY inductive proximity sensor; 3. PCB; 4. Battery; 5. Switch; 6. Jumper wires

(b) 1. ESP32-WROOM module; 2. 16×2 LCD display module; 3. I2C module; 4. PCB; 5. Battery; 6. Switch; 7. Jumper wires

Fig. 1: Conceptual circuit diagram of the (a) Sensing unit and (b) Display unit of the proposed system

Connections of Hardware

All electronic parts were housed in plastic enclosure for each of sensing unit and display unit. Fig. 2 shows the real time wireless speed measuring unit setup. Pin connections of Sensor and LCD display with Microcontroller is shown in Table 1.



(i) Sensing unit **(ii) Display unit**

Fig. 2 : Real time wireless speed measuring unit setup

Table 1: Pin connections of Sensor and LCD display with Microcontroller

Component Pin	ESP32 Pin	Function
Proximity Sensor		
VCC	VIN	Power supply
GND	GND	Ground connection
Signal	D34	Data sensor output pin

I2C LCD Display		
SDA	GPIO 21	I2C Data line
SCL	GPIO 22	I2C Clock line
VCC	VIN	Power supply
GND	GND	Ground connection

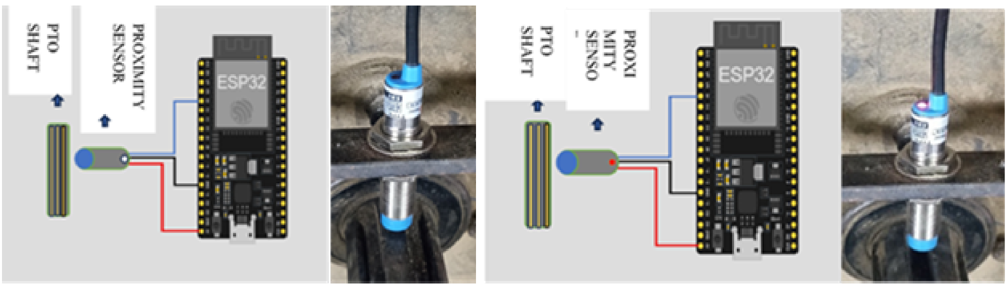
Software Implementation

The ESP32 microcontrollers were configured using the Arduino IDE, which is an intuitive integrated development environment. To utilize the ESP32's hardware peripherals and features, the ESP32 Arduino core library was employed. For wireless communication, the ESP-NOW library was utilized. The LiquidCrystal_I2C library (liquidcrystal.h) facilitated the connection with the I2C LCD. The installed libraries were ESP32_NOW.h, WiFi.h, esp_mac.h, ESP32_NOW.h, Wire.h, LiquidCrystal_ I2C.h.

Inductive Sensing and Signal Acquisition

The inductive proximity sensor was meticulously placed above the Power Take-Off (PTO) shaft to guarantee consistent and dependable detection of the rotating metal splines. The sensor's detection range was precisely adjusted using the mounting nuts on the sensor body. This fine-tuning was essential to reduce false triggers and ensure accurate readings by maintaining optimal alignment with the PTO shaft.

The proximity sensor's output was linked to GPIO pin 34 on the first ESP32 microcontroller (transmitter), which was set up as an interrupt input. Interrupts were used to detect the rising edge of the sensor's digital signal, indicating the presence of a metallic target. Each time a spline of the PTO shaft entered the detection range, the sensor output switched to "HIGH" state, producing a digital pulse that was captured by the ESP32. As the spline departed the detection range, the sensor returned to its "LOW" state. In summary, whenever a PTO spline passed near the sensor, it triggered HIGH condition, and once it moved away, the sensor turned LOW, which is shown in Fig. 3. These transitions between HIGH and LOW states indicated the passage of individual splines, allowing for accurate measurement of rotational speed.



(i) HIGH condition (ii) LOW condition

Fig. 3 : Proximity switch HIGH-LOW condition

Data Processing and RPM calculation

The sensor mounted ESP32 microcontroller was tasked with determining the rotational speed of the PTO shaft by timing the intervals between successive pulses produced by the inductive proximity sensor. Each pulse was generated when a metallic spline passed beneath the sensor, with several pulses occurring per revolution, as specified by PULSES_PER_REV. To maintain precision, the ESP32 employed its high-resolution timer to capture the microsecond-level timing of each interrupt event. These events were initiated by the rising edge of the sensor output whenever a spline was detected. The microcontroller recorded the cumulative time intervals (intervalSum) and tallied the number of pulses (pulseCounter) within a set time frame of one second.

Data Display

The second ESP32 microcontroller, acting as the receiver, obtained RPM data packets sent through the ESP-NOW protocol from the transmitter module. Once received, the RPM value was extracted, formatted, and shown on a 16x2 character I2C LCD. The LiquidCrystal_I2C library was employed to manage communication and control of the LCD module, simplifying initialization and data writing via the I2C protocol.

Validation of the sensor

To ensure the precision of the real-time wireless speed measurement device, its readings were compared against two standard instruments: the TM-4005 microprocessor-based handheld tachometer (Fig. 4 (a)) and a torque sensor system (Fig. 4 (b)) equipped with a wireless data logger. These instruments offered reference RPM values, allowing for the cross-verification of the sensor's performance in real-world conditions.

(a) (b)

Fig. 4 : Test Setup for Validation of Real Time Wireless Speed Measuring Unit with **(a)** Handheld Tachometer and **(b)** Torque Sensor

Accuracy Evaluation Using Statistical Error Metrics

To ensure the precision and dependability of the Real time speed measuring unit, three commonly recognized statistical measures namely Root Mean Square Error (RMSE), Mean Absolute Percentage Error (MAPE) and maximum absolute variation (MAV) were utilized.

The RMSE offers a comprehensive measure of the extent of deviation between predicted and actual values, with a focus on larger discrepancies. It is determined using the following equation 1 (Hensh *et al.*, 2021).

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P-A)^2} \quad (1)$$

Where, P = Real time speed measuring unit Reading

A = Standard reading

N = Total count of observations

The MAPE was employed to evaluate the mean absolute percentage difference between the Real time speed measuring unit measurements and the standard values, offering a standardized and clear insight into accuracy. It is determined using the following equation 2 (Hensh *et al.*, 2021).

$$MAPE = \frac{100}{n}\sum_{i=1}^{n}\left|\frac{A-P}{A}\right| \quad (2)$$

MAPE quantifies the error as a percentage of the actual values, making it particularly effective for assessing relative performance across various RPM levels.

The Maximum Absolute Variation (MAV) represents the greatest discrepancy between the output of the developed system and the readings from a reference device. It is crucial for evaluating the maximum potential error in real-time RPM measurements. MAV plays a vital role in confirming the system's peak performance variation across various conditions. It is determined using the following equation 3 (Hensh *et al.*, 2021).

$$MAV = \frac{A-P}{A} \times 100 \quad (3)$$

Results and Discussion

Installation of the developed wireless speed measuring unit

The developed wireless speed-measuring unit was installed in the tractor. The sensing unit was placed on the PTO shaft and the display unit was placed in front of the driver on the dashboard. The installed devices are shown in Fig. 5.

Fig. 5: Installation of Real time speed measuring unit on Tractor

Comparison of the sensor reading with standard instruments

Validation involved comparing RPM readings from the new unit with those from two benchmark devices: a handheld tachometer (TM-4005) shown in Fig. 4 (a) and a PTO torque sensor (Fig. 4(b)) system. To assess accuracy and reliability, three statistical performance metrics were used: Root Mean Square Error (RMSE), Mean Absolute Percentage Error (MAPE), and Maximum Absolute Variation (MAV). The findings are presented in both tables and graphs, accompanied by analyses that highlight the precision, consistency, and reliability of the system under test conditions.

The collected RPM data of real time speed measuring unit, torque sensor and tachometer are shown in Table 2 and graphically represented for a comparative study in Fig. 6. The graph indicated that the RPM values obtained from the Real Time Wireless Speed Measuring Unit were in close agreement with those recorded by the reference devices.

Table 2 : Comparison of RPM Readings between Real Time Wireless Speed Measuring Unit, Torque Sensor, and Handheld Tachometer

Sl. No.	Real time speed measuring unit reading	Torque sensor reading	Hand tachometer reading
1	157	152	152.3
2	206	190	201
3	250	247	249
4	297	285	289
5	364	361	355
6	406	399	399
7	470	475	468
8	500	513	512
9	566	570	582

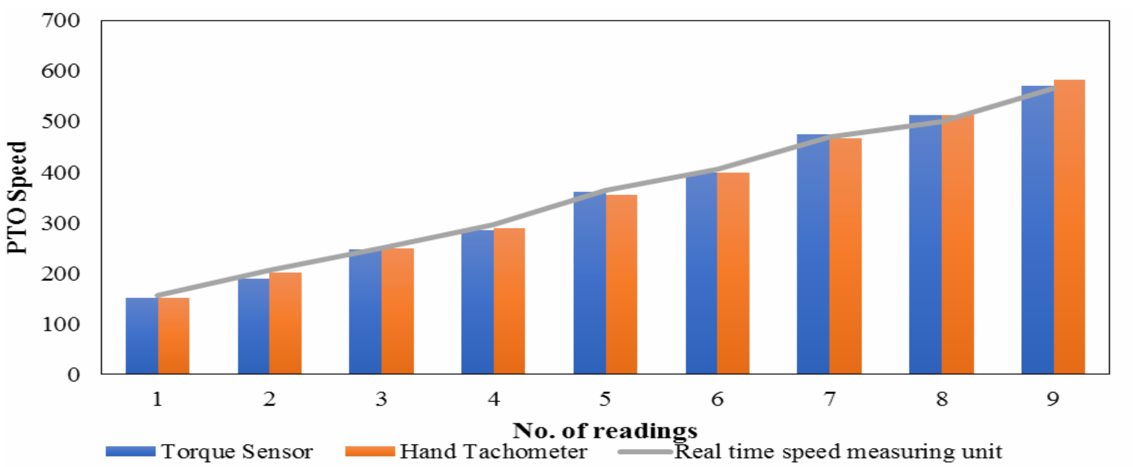


Fig. 6: Comparative Graph of RPM Readings from Real Time Wireless Speed Measuring Unit, Torque Sensor, and Handheld Tachometer

Statistical Accuracy Evaluation of the Real Time Wireless Speed Measuring Unit

To evaluate the system's precision and dependability, three well-established statistical evaluation metrics were utilized: Root Mean Square Error (RMSE), Mean Absolute Percentage Error (MAPE), and Maximum Absolute Variation (MAV). The RMSE for the torque sensor paired with the Real Time Wireless Speed Measuring Unit was calculated at 8.8 RPM, while for the handheld tachometer combined with the same unit, it was 8.4 RPM, showing minimal discrepancy between the measured and reference values. The MAPE was found to be 2.66% for the torque sensor combination and 2.06% for the handheld tachometer combination, indicating that the percentage deviation was well within acceptable accuracy limits for agricultural applications in the field. Furthermore, the MAV, which indicates the maximum absolute difference from reference readings, was recorded at 16 RPM in both scenarios,

Conclusion

This study concentrated on creating, developing, and validating a Real Time Wireless Speed Measuring Unit designed to monitor the Power Take-Off (PTO) speed of tractors. The low value of RMSE, MAPE and MAV showed that the developed sensor performed closer to the standard instruments. The impetus for this work stemmed from the necessity for precise PTO speed monitoring in agricultural tasks, as fluctuations in power delivery can significantly impact efficiency, performance, and safety. Underscoring the need for a cost-effective, wireless, and reliable alternative. The results showed that the Real Time Wireless Speed Measuring Unit could serve as a reliable tool for monitoring agricultural machinery. Its portability, wireless functionality, and precision have the potential to reduce operator reliance on subjective judgment, improve operational efficiency, and enable better control of tractor–implement interactions.

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