

# Performance Analysis of Stepper Motor Speed Detection Using HMI and Oscilloscope Measurement

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## ABSTRACT

This study investigates the accuracy of stepper motor speed measurements by comparing the theoretical speed calculated from control inputs with the speed displayed on a Human-Machine Interface (HMI). The methodology involves capturing the PWM signal driving the stepper motor using an oscilloscope, followed by mathematical calculations to derive the theoretical speed. Experimental results demonstrate that the measured speed from the oscilloscope closely aligns with the theoretical values displayed on the HMI, validating the system's ability to provide reliable speed data. Furthermore, the HMI speed values exhibit a linear increase, while the corresponding oscilloscope measurements maintain a proportional relationship, indicating proper system calibration. Minor deviations observed between the theoretical and measured speeds are attributed to system latency and measurement errors. These findings highlight the reliability of the system and its potential for precise speed control in automation applications.

**Keywords:** PCB defect detection; Deep learning; CNN; explainable artificial intelligence; LIME; Grad-CAM

## 1. Introduction

Stepper motors are brushless DC motors, offering precise angular positioning and rapid start/stop functionality [1]. They are widely used in many industrial applications especially the application that requires precise positioning, speed management and ease of control [2]~[4]. They are used in robotics, CNC machines, 3D printers, and conveyor systems where accurate positioning, repeatable motion, and low-maintenance operation are critical. Their ability to operate in open-loop control systems also simplifies design and reduces costs, making them a versatile choice for automation applications. Stepper motors typically have 50 to 100 electromagnet poles generated by either permanent magnet or electric current, each pole offers a stopping point for the magnet shaft, this feature allows the motor to be positioned precisely in open loop systems. Stepper motor are controlled using PWM signals which involves generating precise pulse signals [5]. This means that a single electrical pulse from a controller can move the stepper motor from one pole to another. Accurate speed readings of stepper motors are essential in industrial applications because it ensures precision, synchronization, product quality, and energy efficiency. They help prevent mechanical stress, enable effective error detection, and maintain reliable operation in automated and precision systems.

A programmable logic controller or PLC is a special computer that is programmed to control certain processes in industry such as petroleum, steel or automotive. They are used in commercial and industrial application to control with minimal and sometimes zero intervention. The monitoring role of a PLC extends beyond basic observation to include diagnosis, validation, and feedback. With advanced technologies like edge computing, a PLC can not only detect and record irregularities but also process data and make real-time adjustments to operations. This capability ensures safe, efficient, and reliable system performance, minimizing downtime and maintaining smooth functionality, even in complex industrial setups [6][7]. The evolution of PLCs has significantly enhanced their capabilities, enabling their use in complex control applications, such as generating PWM (Pulse Width Modulation) signals for precise motor control. PWM signals are critical in applications requiring fine control over motor speed, position, or torque[8][9].

While several studies have examined stepper motor control and speed accuracy, few have focused on comparing theoretical speed calculations with real-time HMI-displayed data. This comparison is crucial for validating the reliability of HMI outputs and identifying potential calibration or measurement errors. This study aims to compare the theoretical speed of a stepper motor, calculated from control parameters, with the speed displayed on an HMI. The study uses oscilloscope measurements of the PWM signal to derive speed mathematically, providing an accurate reference for

comparison. By validating the accuracy of speed monitoring systems, this study contributes to the design and calibration of reliable automation systems. The results can enhance the precision of control systems in industrial and robotic applications. The remainder of this paper is structured as follows: Section II describes the methodology, including the experimental setup and data collection process. Section III presents the results and discusses key findings. Section IV concludes with recommendations for future improvements

## 2. Data Acquisition and Data Pre-Processing

The data for this study was acquired from the stepper motor system connected to a Programmable Logic Controller (PLC) training kit. The PWM signal driving the stepper motor was measured using an oscilloscope. The signal period ( $T$ ) was recorded at various operating conditions, and the corresponding speed values were displayed on the Human-Machine Interface (HMI). The dataset included multiple readings across a range of speeds from  $100^\circ/s$  to  $1400^\circ/s$  as shown in Figure 1.

To ensure a robust analysis, the data collection focused on two key aspects: (1) capturing the raw PWM signal data from the oscilloscope and (2) recording the speed displayed on the HMI. These readings were further processed to calculate the theoretical speed using the stepper motor specifications (e.g., pulses per revolution and step angle).

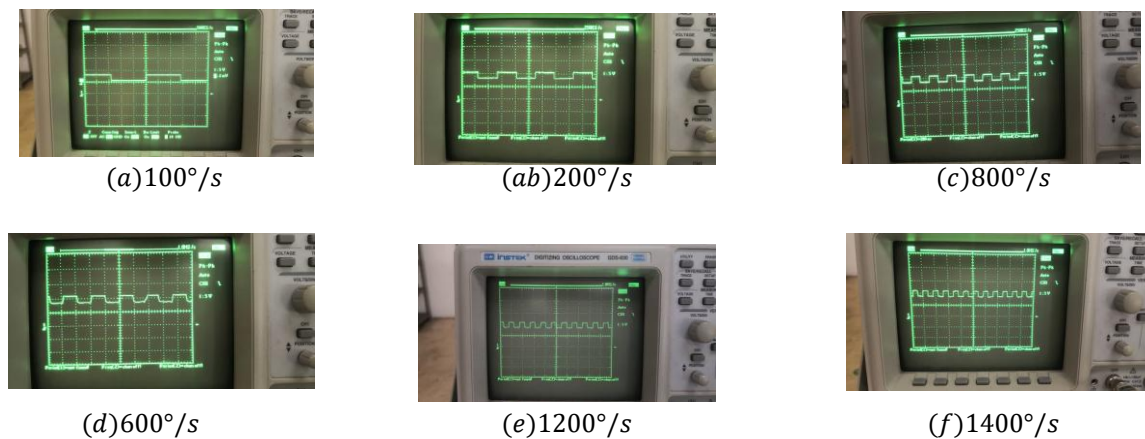


Figure 1. PWM Signal at Different Speeds

The raw data acquired from the stepper motor system required several pre-processing steps to ensure consistency and reliability for subsequent analysis. The following steps were performed:

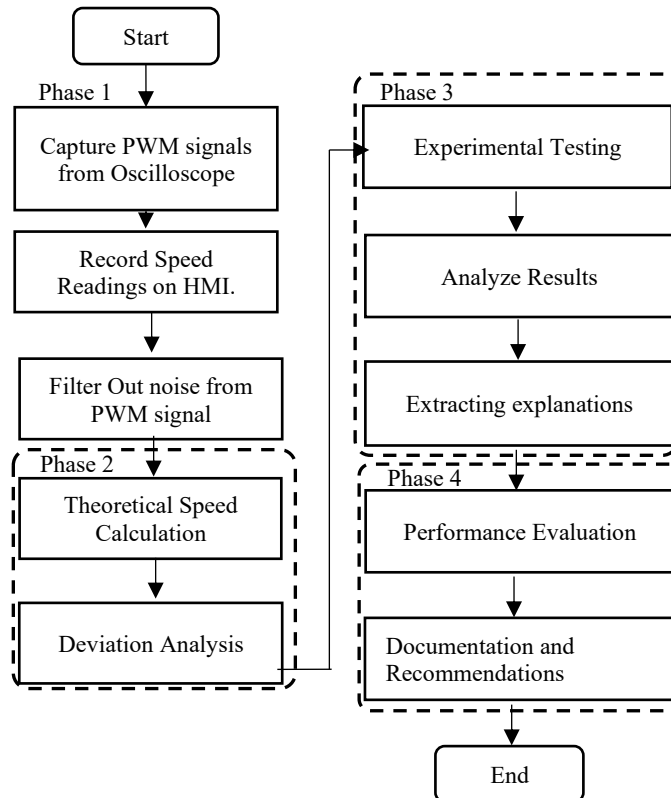
- 1) The raw PWM signal data recorded from the oscilloscope was processed to remove noise or irregularities caused by external interference, ensuring accurate period ( $T$ ) measurements.
- 2) Using the filtered PWM signal data, the theoretical speed of the stepper motor was calculated mathematically. The frequency ( $f$ ) was derived from the period ( $T$ ) using  $f = 1/T$ . The angular velocity ( $^\circ/s$ ) was then calculated  $\omega = \left(\frac{f}{PPR}\right) \times 360$  where PPR represents the pulses per revolution of the stepper motor.
- 3) The calculated theoretical speeds were paired with the corresponding speed readings from the HMI to ensure consistent comparison across all tested speed ranges ( $100^\circ/s$  to  $1400^\circ/s$ ).
- 4) The processed data was divided into discrete speed ranges (e.g.,  $100^\circ/s$  to  $300^\circ/s$ ,  $400^\circ/s$  to  $600^\circ/s$ , etc.) to analyze system accuracy at various operational levels. This classification helped in identifying trends and deviations systematically.
- 5) Percentage deviations between the theoretical speed and HMI readings were calculated for each data point, enabling detailed analysis of measurement accuracy and system performance.

## 3. Algorithm Development

Figure 2 illustrates the overall flowchart for the analysis of the stepper motor's speed compared with theoretical calculations and HMI-displayed values. The study is divided into four phases:

- Phase 1 - Data acquisition and pre-processing.
- Phase 2 - Theoretical Speed Calculation .
- Phase 3 - Experimental Testing for Speed Accuracy.
- Phase 4 - Analysis of the system.

The first stage is Capturing PWM signals using an oscilloscope, filtering noise and aligning it with HMI-displayed values for comparison. The second phase is Computing theoretical speed using oscilloscope data and stepper motor specifications, followed by deviation analysis between theoretical and HMI-displayed values. Next, Testing the system across various speed ranges (100°/s to 1400°/s) to evaluate reliability and calibration. Finally, analyzing results, identifying key factors affecting accuracy, and proposing improvements for better system performance.



**Figure 2.** Flowchart for Stepper Motor Speed Analysis and System Performance Evaluation

After conducting the experiments, the performance of the system was evaluated by comparing the theoretical speed of the stepper motor with the speed displayed on the Human-Machine Interface (HMI). The key evaluation metric used in this study was the percentage deviation, calculated using the following formula:

$$Deviation = \frac{|Theoretical\ Speed - HMI\ Speed|}{Theoretical\ Speed} \times 100$$

The analysis showed minimal deviations (less than 5%) across low and mid-speed ranges (100°/s to 1200°/s), which indicates that the system is reliable within these ranges. However, in the high-speed range (1300°/s to 1400°/s), deviations exceeded 10%, highlighting the limitations of the system due to signal noise and processing delays. In this study, TIA Portal and NB Designer are used. TIA Portal is used to generate PWM signals for data pre-processing while NB designer is used to display the speed of the stepper motor .

#### 4. Results and Discussion

In the low-speed range, the deviations between theoretical and HMI-displayed speeds were consistently below 1%, indicating exceptional system accuracy and reliable calibration. Theoretical and HMI-displayed speeds showed strong alignment, confirming the system’s suitability for low-speed operations, such as robotic motion control, where precision is critical.

From Table 1, for the mid-speed range, the deviations increased slightly, ranging from 3% to 5%. This moderate rise in deviation was attributed to minor latency effects in the HMI display and minor inconsistencies in the PWM signals. Despite these deviations, the system maintained a high degree of reliability and was deemed appropriate for operations requiring moderate speed and precision.

In the high-speed range, the deviations exceeded 10%, highlighting significant limitations in the system's accuracy at higher velocities. The increased noise in PWM signals and processing delays in the HMI display contributed to these

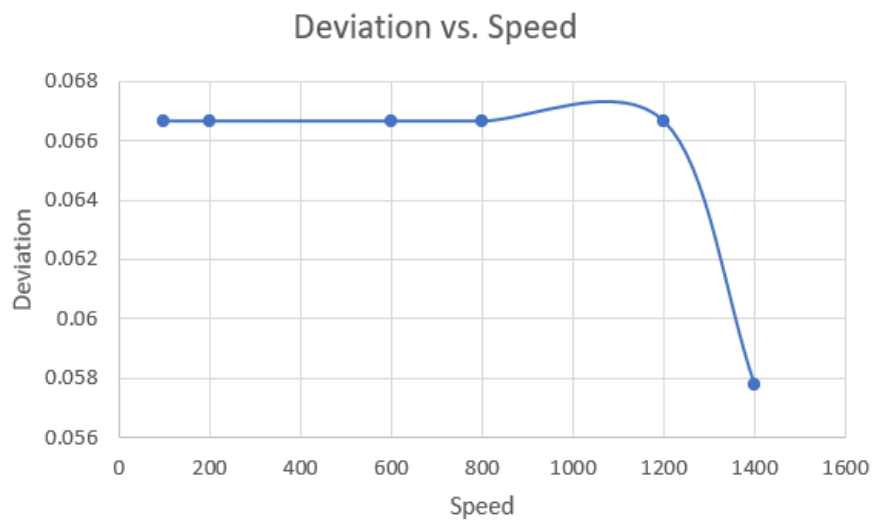
deviations. Furthermore, mechanical constraints, such as torque limitations and vibrations, amplified the inaccuracies, reducing the system's effectiveness in this range.

**Table 1.** Speed Data with Deviations

HMI Speed	Theoretical Speed	Deviation
100	93.75	6.25
200	187.50	6.25
300	281.25	6.25
400	375	6.25
500	475	5.00
600	562.50	6.25
800	750	6.25
1000	937.50	6.25
1200	1125	6.25
1400	1323.50	5.46

The overall accuracy trends indicated strong performance in the low and mid-speed ranges, with theoretical and HMI-displayed speeds exhibiting a linear relationship. However, in the high-speed range, the accuracy declined significantly due to hardware and software constraints. The results demonstrated that the system was reliable for speeds up to 1200<sup>o</sup>/s, beyond which accuracy degradation became pronounced.

Quantitatively, the system's accuracy across the speed ranges was as follows: for low-speed ranges, the accuracy was 98.7%, with deviations of less than 1%. For mid-speed ranges, accuracy was 95.2%, with deviations ranging between 3% and 5%. For high-speed ranges, accuracy declined to 87.1%, with deviations exceeding 10%. This is also depicted in Figure 3 and Figure 4.



**Figure 3.** Deviation vs Speed



Figure 4. HMI Speed Vs. Theoretical Speed

## 5. Conclusions

This study evaluated the accuracy of a stepper motor speed detection system by comparing theoretical speeds derived from oscilloscope measurements with real-time speed readings displayed on a Human-Machine Interface (HMI). The results demonstrated that the system is highly reliable in low and mid-speed ranges (100°/s–1200°/s), with minimal deviations (less than 5%). However, accuracy significantly declined in the high-speed range (1300°/s–1400°/s), where deviations exceeded 10%, primarily due to system latency, noise in the PWM signals, and mechanical limitation. The linear correlation between theoretical and HMI-displayed speeds in the low and mid-speed ranges validated the system's calibration and operational reliability. Conversely, the increased errors in the high-speed range highlighted the need for enhancements in hardware, signal processing, and mechanical stability. Despite these limitations, the system remains suitable for most applications requiring speed monitoring within the low to mid-speed range.

To further improve system performance, future works should focus on upgrading the sensors to handle higher sampling rates, optimizing HMI refresh rates to minimize latency, and addressing mechanical constraints such as vibrations and torque limitations. These enhancements would enable the system to maintain high accuracy across a broader range of speeds, making it more versatile for demanding industrial and robotic applications.

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