Design and Analysis of a Metal Detection System Based on an Inductive Sensor

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This article presents the development and analysis of a metal object detection system utilizing an inductive sensor. The project covers everything from the fundamental operating principles of inductive sensors to their practical application within a circuit controlled by an ESP32 microcontroller. A detailed noise analysis of the system was conducted, comparing theoretical quantization noise with experimentally measured noise. This allowed for the identification of predominant interference sources. The results demonstrate the system's effectiveness in metal detection and quantify the measurement errors, thereby validating the application of inductive sensors in industrial automation and process control systems.

Keywords: Inductive Sensor. Metal Object Detection. ESP32 Microcontroller. Noise Analysis. Digital Filtering.

In industrial automation, high-precision detection of metallic objects is fundamental to protecting equipment and maximizing the efficiency of production lines. The advancement of smart sensors and integration with Industry 4.0 paradigms require a deep understanding of physical principles, implementation strategies, and technological limitations. Inductive sensors remain robust and versatile solutions that can be used in both harsh industrial environments and in portable and wearable devices. In wearable and antenna applications, inductive textile sensors made with conductive yarns offer stable performance, low cost, and ease of manufacturing [1], while in industrial environments, shielded construction ensures immunity to dust, dirt, and oil [2].

Inductive sensors operate based on an LC oscillator circuit coupled to a high-permeability coil; the approach of a metal induces eddy currents that drain energy from the oscillator and alter the inductance, allowing for the rapid and precise detection of the object [3]. Due to their robustness and immunity to contaminants such as dust, dirt, and oils [2], these sensors are widely used for position control, parts counting, and speed monitoring. In high-frequency inductive sensors, the switching frequency can reach up to 5 kHz, enabling pulse counting to calculate motor rotation [3].

The integration of these sensors with microcontrollers like the ESP32 requires analog-to-digital conversion (ADC). The ESP32's internal ADC offers a nominal resolution of 12 bits but exhibits non-linearities as it does not differentiate between close voltages, such as 3.3 V and 3.2 V or 0.1 V and 0.1 V [4], and is sensitive to noise. The documentation from Espressif, the developer of the ESP32, recommends using a 0.1 μF decoupling capacitor on the input pin and applying multisampling (multiple samples) to reduce intrinsic noise [5]. Furthermore, different sources of noise, such as quantization, thermal noise, flicker (1/f noise), and electromagnetic interference, can degrade the quality of the measurements [6]. Oversampling and filtering techniques are applied to reduce quantization noise or disperse noise energy to other frequencies. Implementing digital filters improves the signal-to-noise ratio [6].

Spectral analysis using the Fast Fourier Transform (FFT) converts the signal from the time domain to the frequency domain and allows

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for the identification of unwanted components and their amplitude [7]. To attenuate components outside the band of interest, digital finite impulse response (FIR) or infinite impulse response (IIR) filters are applied. Low-pass filters are used to remove high-frequency signals; high-pass filters attenuate low-frequency signals; band-pass filters select only the desired range.

Thus, the present work develops and analyzes a system for detecting metallic objects using an inductive sensor coupled with an ESP32 microcontroller. The objective is to reliably measure the rotation of a motor from the passage of a metal plate, quantify the limits imposed by ADC quantization and noise, and apply digital filtering techniques to mitigate interference and increase accuracy.

The following sections present the theoretical foundation of the sensors and filtering techniques, describe the materials used and the mathematical methods employed in the generation and filtering of noise, detail the development of the circuit and the interface with the ESP32, and discuss the experimental results and the performance of the system under test conditions.

Theoretical Framework

This section covers all the material used as a theoretical basis for the project's development, from the operation/actuation of inductive sensors to more specific concepts about signal reading and processing.

Inductive Sensors in Automation

Inductive sensors are widely used in industrial automation for the non-contact detection of metallic objects, offering robustness, durability, and immunity to polluted or humid environments [8-10]. They operate by means of an oscillator that generates an electromagnetic field; the proximity of a metallic object alters this field and, consequently, the inductance, which is detected by the circuit [11,12]. Typical applications include parts counting, position control, and limit switches.

Electrical Inductance in Inductive Sensors

The inductance L of a coil is given by:

$$L = \frac{N^2 \mu A}{l},$$

Where N is the number of turns, μ is the magnetic permeability, A is the cross-sectional area, and l is the length of the coil [11]. In inductive sensors, the approach of metallic objects alters this inductance, enabling detection [13].

Correction Factor and Inductive Coupling

Sensors are calibrated for standard targets like steel (factor ≈ 1) (Table 1), and have a reduced range for aluminum, brass, and copper, among others [11]. Inductive coupling involves eddy currents induced in the metal, which modify the coil's properties and are interpreted by the detection circuit [14].

Table 1. Calibration for standard targets.

Material	Correction Factor
Steel (Fe360)	1.0
Stainless steel	0.7–0.9
Aluminum	0.4–0.5
Brass	0.3–0.4
Copper	0.25–0.35

Noise in Sensor Systems

Noise in sensors can be intrinsic (circuit-related) or extrinsic (environmental), classified according to its source or spectrum [15].

Intrinsic Noise

Among the main sources of signal degradation in measurement systems are electromagnetic and radiofrequency interference (EMI/RFI), which can induce spurious readings and compromise data reliability. Added to this is thermal noise, also known as Johnson-Nyquist noise, originating from the thermal agitation of charge carriers, whose spectral density is constant and imposes a physical limit on the system's sensitivity. Another relevant factor is quantization noise, introduced during the analog-to-digital conversion (ADC) process due to the discretization of signal levels, which, in high-resolution converters, can be modeled as white noise [16] (Figure 1).

In quantization, the values of an already-sampled analog signal are approximated to a limited number of discrete levels. Essentially, it rounds each sample value to the nearest quantized level, transforming a continuous range of amplitudes into a finite set of digital values that can be represented and stored. Quantization noise can be modeled as white noise because, for most signals, the rounding error of each sample is random and uncorrelated with the signal. This randomness distributes the noise energy uniformly across the entire frequency spectrum, which is the main characteristic of white noise.

Quantization Noise and Standard Deviation

The formulas used to obtain the value of these variables for later analysis are demonstrated below. The standard deviation is relevant for assessing an average rate of variation between the measured and the real value, and the quantization step is for analyzing the signal's digitization.

- Quantization step Δ:

$$Q = \frac{V_{FS}}{2^N} \quad (1)$$

Where VFS is the full-scale voltage and N is the number of bits of the ADC. For a 12-bit ADC with VFS=3.3 V, we get Q≈0.805 mV, a value that indicates the smallest difference detectable by the converter. Variations smaller than this value are rounded to the nearest level, generating what is called quantization error. The standard deviation of the quantization noise allows for estimating the impact of this error on the measurements and is used in precision analyses and the calculation of the signal-to-noise ratio (Figure 2).

- Theoric standard deviation:

$$\sigma_{quant} = \frac{Q}{\sqrt{12}} \approx 0,232 \text{ mV.}$$

- Practical comparison: The measured noise was approximately 32.445 mV, a value about 140 times higher than the estimated theoretical thermal noise. This significant difference indicates that, in addition to thermal noise, there is a relevant contribution from other sources, the main one being electromagnetic interference (EMI), evidenced by the excess magnitude and the measurement environment being subject to inductive and capacitive couplings.

Figure 1. Example of continuous signal quantization.

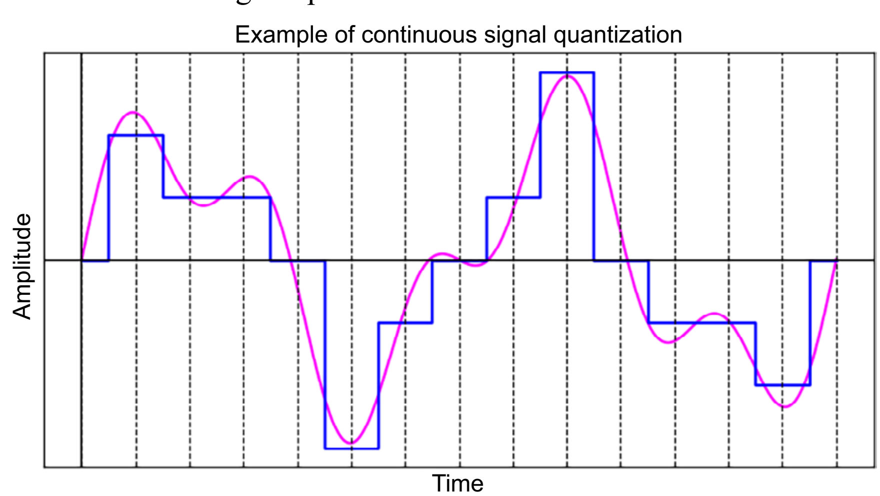


Figure 2 represents the system's baseline voltage signal (without material detection). From its analysis, it was possible to identify the signal's characteristics and obtain the necessary samples to calculate the standard deviation of the actual noise.

Spectral Noise

Classification of noise based on frequency [17]:

- White Noise: Constant spectral density across all frequencies;
- Pink Noise (1/f): Decreasing density (3 dB/octave or 10 dB/decade), concentrating energy at low frequencies.

Figure 3 shows how a signal's power is distributed across frequencies. For white noise, the Figure is a straight, horizontal line, indicating that the energy is distributed uniformly across all frequencies.

For pink noise, however, the graph has a negative slope of -3 dB per octave. This means that the noise power is greater at lower frequencies and decreases as the frequency increases. Because of this, pink noise is perceived by the human ear as having a more balanced and pleasant sound than white noise.

Detection System with Inductive Sensor

This section covers the constructive aspects of the detection system, including the electrical schematic and the integration of the inductive sensor with the microcontroller.

Following that, an analysis of the noise present in the system is presented, an essential step to ensure the accuracy and reliability of the detection. The electrical schematic of the metallic detection system, illustrated in Figure 4, is based on the integration of an inductive sensor with the ESP32 microcontroller, which is responsible for signal processing and controlling the display interface.

The sensor, positioned near an iron plate coupled to the motor's shaft, is powered and connected to the circuit in a way that provides an output signal compatible with the ESP32's logic level. With each complete rotation of the plate, the sensor generates an electrical pulse, which

Figure 2. Resting voltage signal used to measure the standard deviation of real noise.

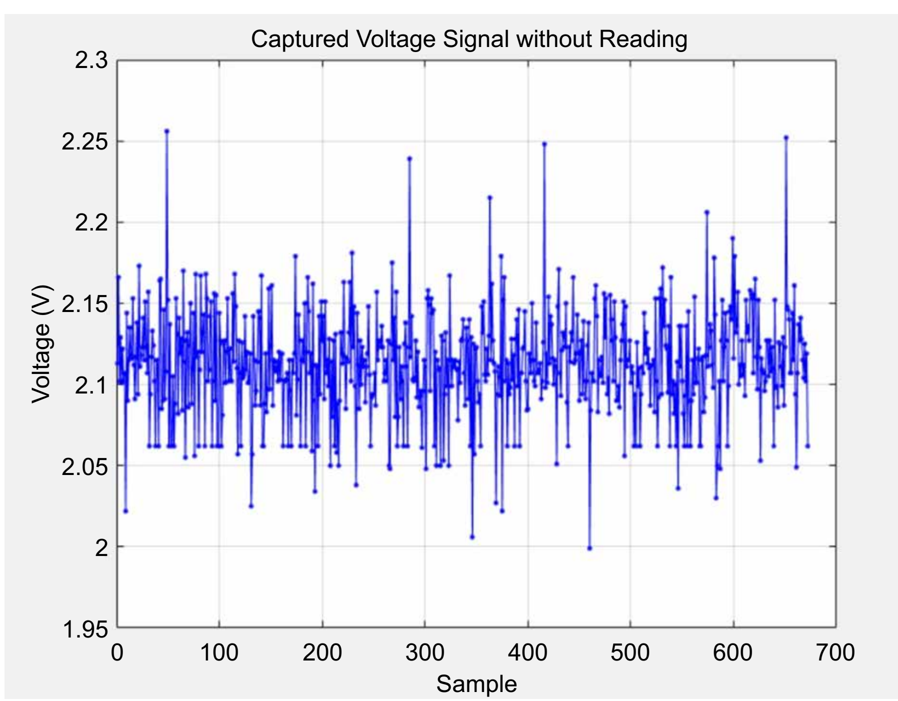


Figure 3. Spectral density for white and pink noise.

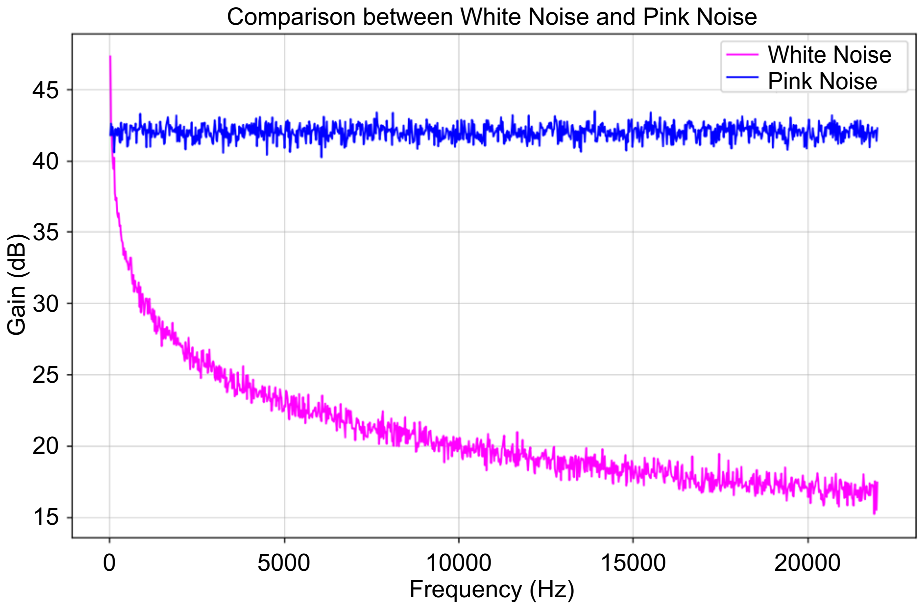
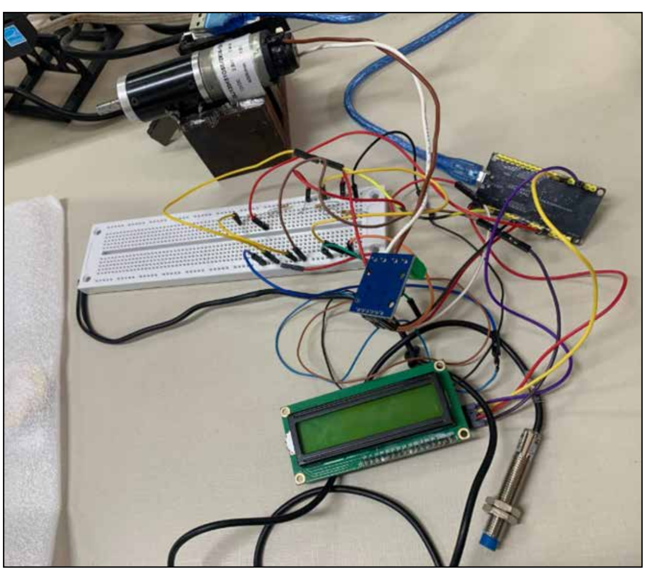


Figure 4. Physical assembly of the prototype in the laboratory.



is sent to the microcontroller's digital input. In addition to reading the signal from the inductive sensor, the ESP32 also receives information from a piezoelectric sensor, used for comparisons in additional tests.

The inductive sensor's signal is processed to determine the rotations per minute (RPM) in real-time, while the piezoelectric sensor provides complementary measurements for experimental analysis. The LCD display is connected to the ESP32 to show, in real-time, the RPM and voltage values, enabling direct monitoring during tests.

The electric motor, coupled to the iron plate, constitutes the mechanical element being evaluated, simulating real detection conditions. The physical assembly of the circuit, shown in Figure 5, was carried out on a protoboard, using jumpers and resistors to interconnect the components.

Next, the noise analysis is presented, aiming to improve the precision of the metal detection system.

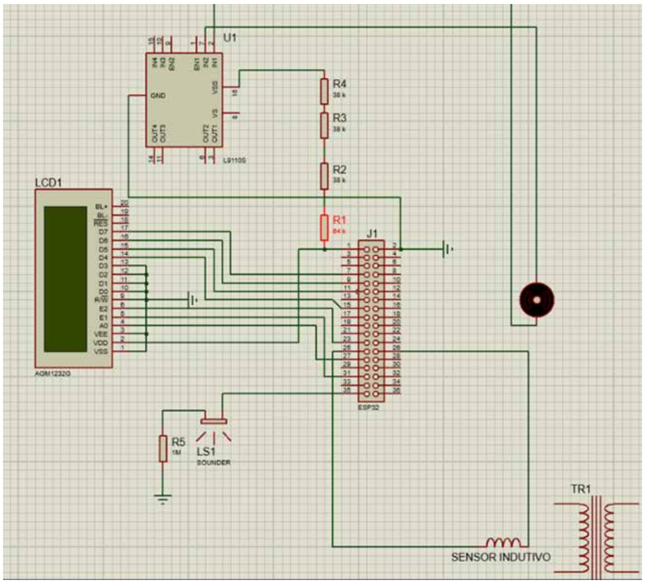
<u>Noise Analysis Method</u>

To examine the quality of the captured signal and the robustness of the method, the study was divided into two approaches: quantization analysis and spectral analysis with digital filtering.

Quantization Noise Analysis

The ESP32's built-in ADC (12 bits, VFS range = 3.3 V) was considered. The magnitude of the quantization step Q and its theoretical standard

Figure 5. Project schematic showing the sensor actively measuring the metallic object.



deviation, σquantization, were calculated using Equations 1 and 2, based on the classic model of uniform quantization, as mentioned in the Theoretical Framework section:

$$Q = \frac{V_{FS}}{2^{N_{bits}}} \quad (1)$$

$$\sigma quantizacao = Q \sqrt{12} \quad (2)$$

In the experimental phase, the voltage signal at rest was recorded, without the presence of the plate, to evaluate the system's actual standard deviation and compare it with the theoretical value. The observed deviation in the results was approximately 140 times greater than the estimated theoretical value, highlighting the presence of additional noise sources beyond quantization noise.

Noise Mitigation in the ESP32

Knowing that the ESP32's ADC is sensitive to noise, two additional strategies were applied: (a) the inclusion of a 0.1 μF bypass capacitor at the ADC input, which filters high-frequency noise and stabilizes the circuit's power supply, and (b) averaging by multisampling with 64 samples, as recommended in the official documentation [18,19].

Spectral Analysis and Filtering: For characterization in the frequency domain

To characterize the noise and optimize detection, an analysis was performed in the frequency domain. Synthetic white and pink noises were generated in MATLAB software based on the parameters described in Omron Industrial Automation [12] and PCBgogo [20], allowing for the simulation of the system's noise conditions. Subsequently, both the original signals and those with added noise were subjected to the Fast Fourier Transform (FFT) for the analysis of their frequency components. Observing that the signal of interest was concentrated below 60 Hz, a second-order digital Butterworth filter with a cutoff frequency of 60 Hz was designed, prioritizing stability and lower distortion. Finally, the gain in the signal-to-noise ratio (SNR) before and after filtering was evaluated, verifying a considerable improvement. This approach, which combines the controlled injection of noise with digital filtering, allowed for the quantitative validation of the SNR increase, demonstrating the filter's effectiveness in cleaning the inductive sensor's signal.

Addition of Spectral Noise

For the spectral analysis, two types of synthetic noise—white and pink—were injected into a square wave signal using MATLAB software, as illustrated in Figure 6, which presents the original signal and the same signal after the addition of the noises. Next, the Fast Fourier Transform (FFT) was applied to identify the signal's frequency components, making it possible to compare the spectrum before and after the noise injection.

Figure 7 shows the frequency spectrum of the signals with and without noise, allowing for the observation of the increased spectral density at high frequencies due to the presence of the added noises.

Subsequently, a second-order digital Butterworth filter with a cutoff frequency of 60 Hz was employed to reduce the interference caused by the noise. The result of this filtering is shown

Figure 6. Original signal and with injected white and pink noise.

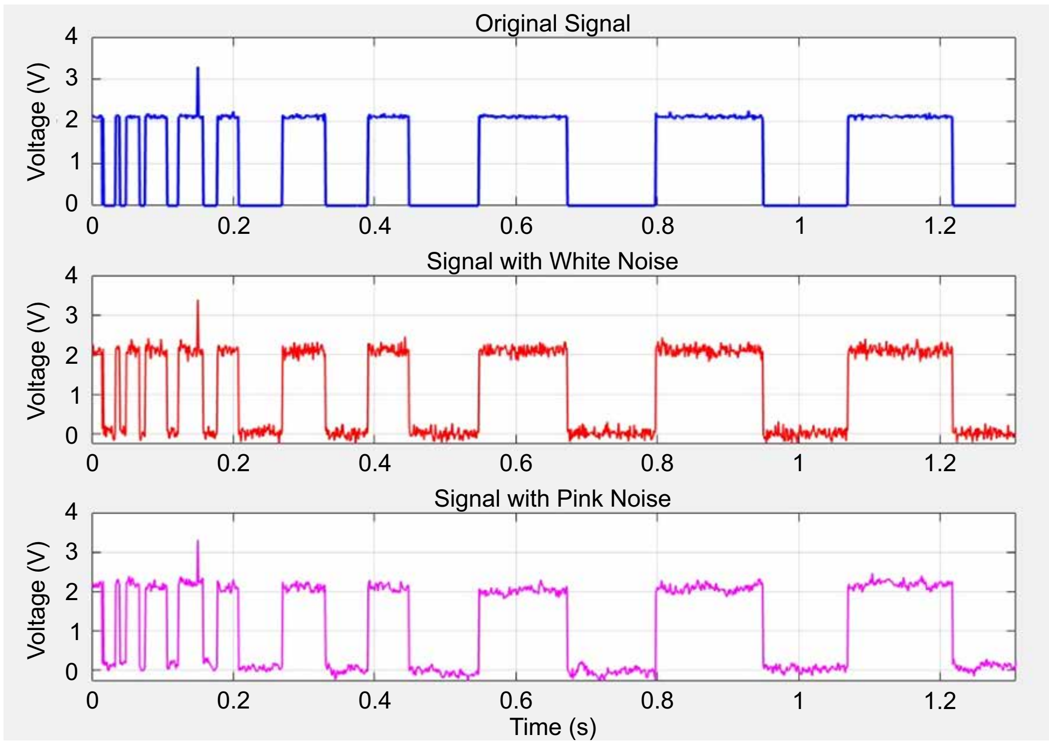
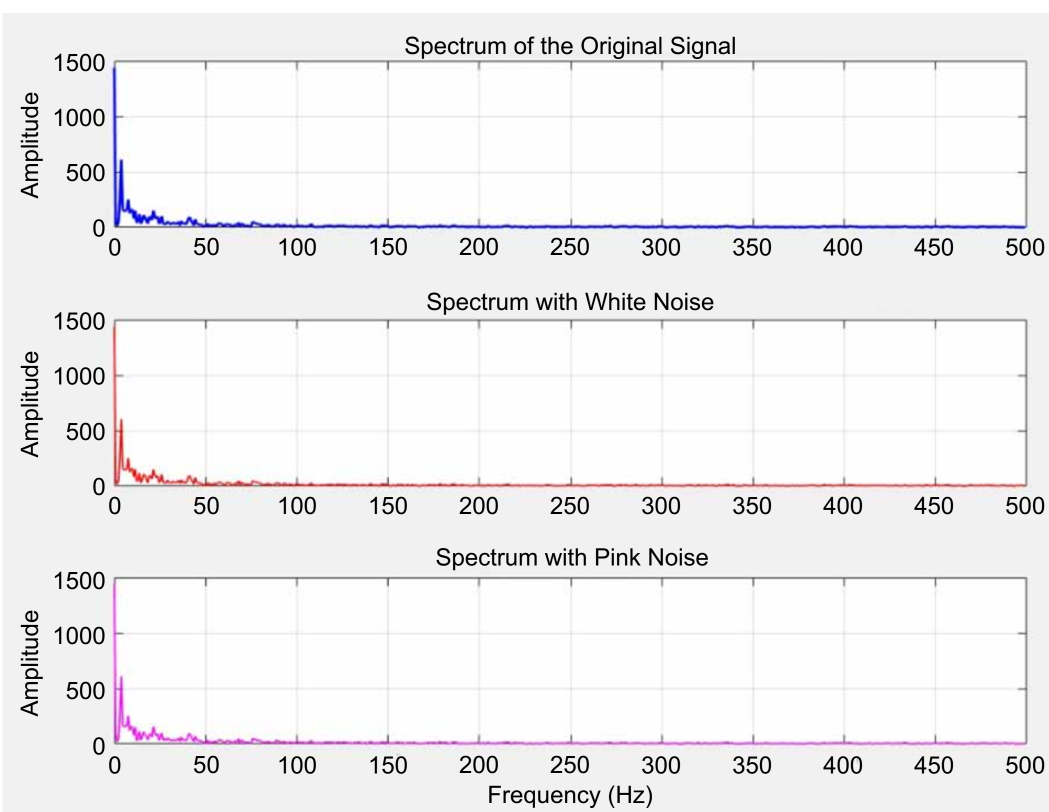


Figure 7. Frequency spectrum of signal without and with noise.



in Figure 8, in which the significant attenuation of high-frequency components can be observed, highlighting the filter's efficiency in cleaning the signal and increasing the signal-to-noise ratio (SNR).

Results

The project's execution allowed for the validation of the detection system. The system was able to identify the presence of the iron plate and measure the motor's rotation with an average of 119.7 ± 1.78 RPM. The average voltage at rest was 2.1134 ± 0.0009 V, thus making it possible to observe the motor's rotation by the delivered voltage, noting how much it differs from the cited rest voltage.

Therefore, upon analyzing the data of: voltage at rest, voltage consumed when the motor is in motion, and the variation detected by the sensor, a satisfactory performance of the sensor was validated.

Comparative Analysis of System Noise

For the analysis of white and pink noise, it was found that the measured standard deviation (32.445 mV) was about 140 times greater than the theoretical quantization noise (0.232 mV).

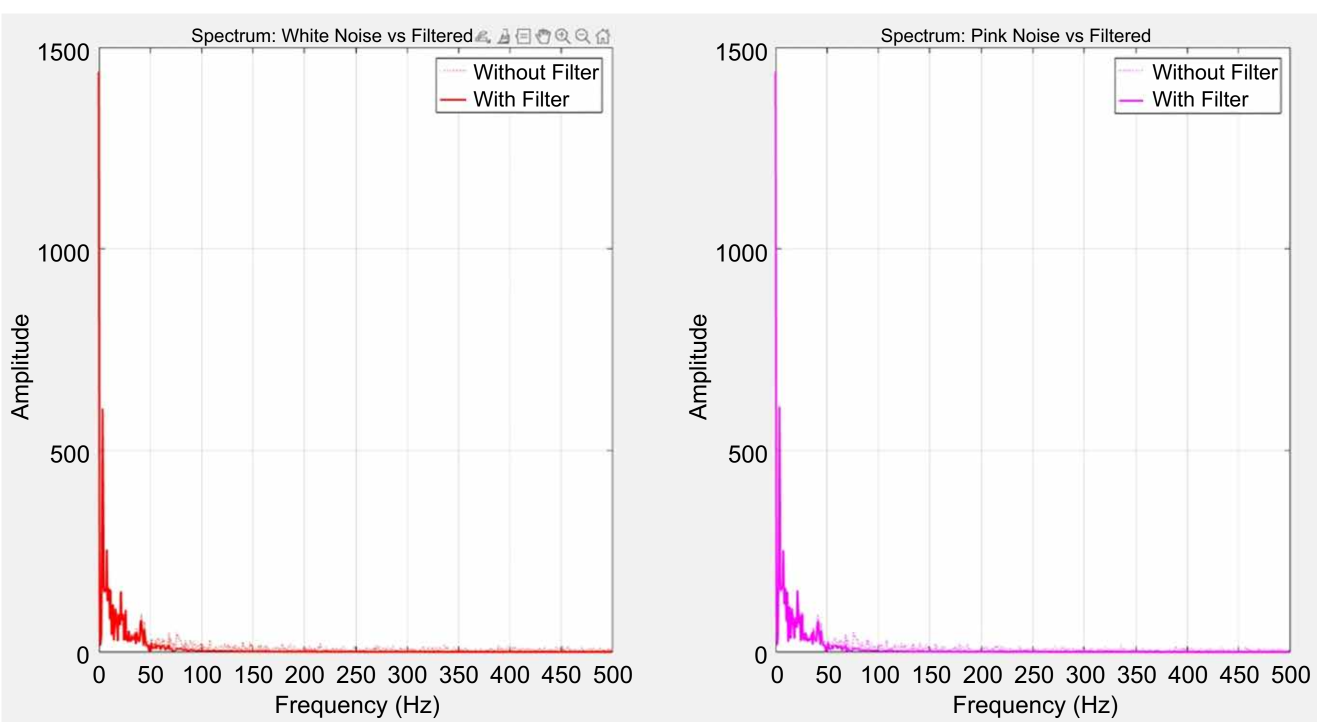
This indicates a low influence from the inserted noises and that the predominant noise sources are thermal and electromagnetic interference (EMI), not the ADC's limitation.

This concludes which are the main intrinsic sources capable of interfering with the constructed system. These are strengthened by the already known impacts on electrical systems caused by temperature and magnetic/electric fields.

Analysis of Spectral Noise Results

Fast Fourier Transform (FFT): Based on Figure 7, it was possible to identify that its components were concentrated at low frequencies [21].

Figure 8. Signals with white and pink noise after filtering.



- Low-Pass Filtering: The use of the Butterworth filter resulted in an effective elimination of high-frequency noise, constituting an 80% reduction in its presence and its components.
- Signal-to-Noise Ratio (SNR) Improvement: The attenuation of high-frequency components, as discussed in the development section, resulted in a significantly higher SNR, providing a cleaner and more precise signal—consistent with studies that demonstrate SNR gains using low-pass filters [22].

In summary, the injection of synthetic noise and its spectral analysis, after comparing Figures 6 and 9, allowed for the validation of the filtering process's effectiveness—specifically, in the application of a low-order Butterworth filter—in increasing the SNR, corroborating consolidated practices in signal processing.

Conclusion

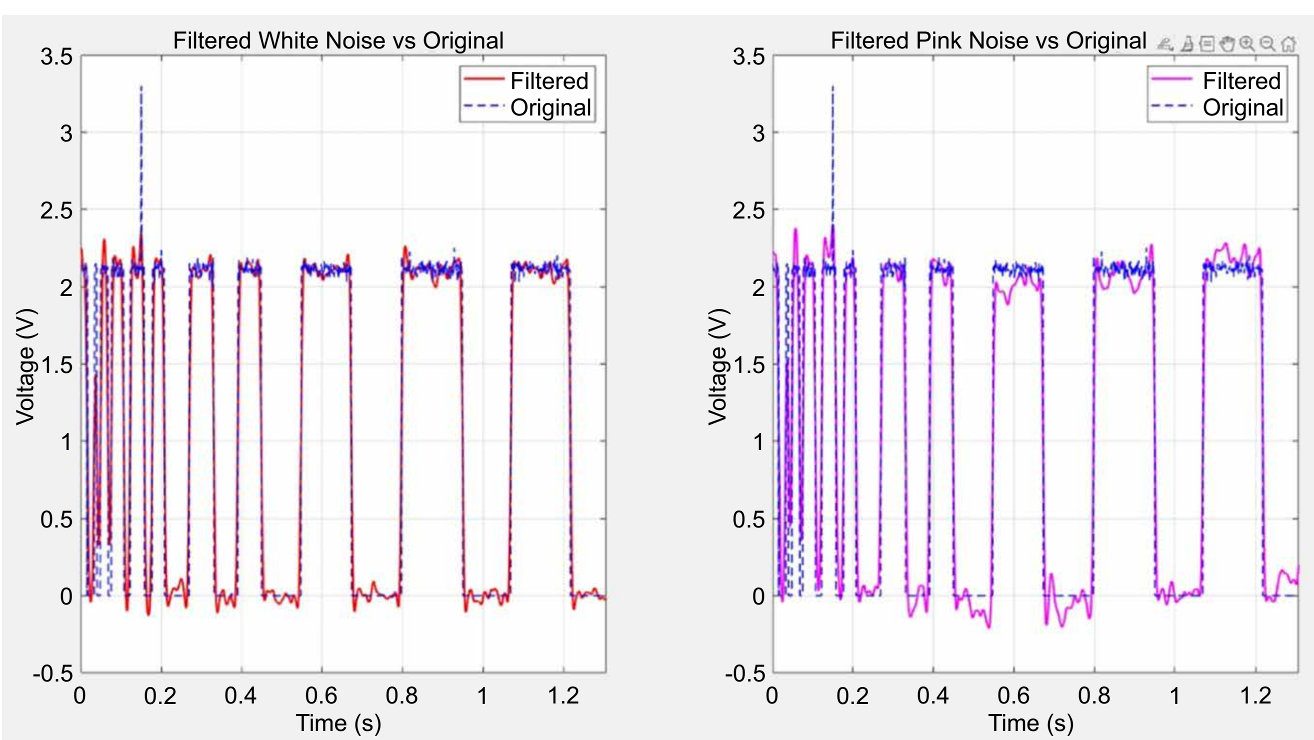
This work presented the design, implementation, and analysis of a metallic object detection system, integrating an inductive sensor, embedded processing on an ESP32 microcontroller, and an LCD display for data visualization.

The experimental results demonstrated that the system achieved a measurement error of approximately 1.5% for rotation speed (RPM), meeting the requirements of various control and industrial automation applications. The noise analysis, a central focus of the study, revealed a significant technical finding: the standard deviation of the measured noise in the system (32.445 mV) was approximately 140 times higher than the theoretical quantization noise (0.232 mV).

This finding proves that the main source of imprecision does not lie in the resolution of the A/D converter, but rather in external interferences like electromagnetic noise (EMI), directing optimization efforts towards shielding and signal filtering instead of hardware replacement. The adopted architecture, based on the ESP32, facilitates future expansions and improvements.

As future work, it is suggested to implement real-time digital filters (such as moving average

Figure 9. Frequency spectrum of the signals after filtering.



or Kalman) in the firmware to mitigate the measured noise, integrate the system with an IoT platform for remote cloud monitoring, and characterize the sensor's response to different types of metallic materials by exploring correction factors. Additionally, the use of machine learning techniques could be explored for object classification or anomaly detection in the process.

In summary, the proposed system represents a low-cost solution with satisfactory precision and great potential for expansion. It serves as a practical and didactic validation for the application of industrial sensors in embedded systems, contributing to the development of smarter and more connected solutions in the context of Industry 4.0.

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