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Implementation of a Robotic Arm-Assisted PCB Diagnostic and Measurement System

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ABSTRACT

This paper presents the development and implementation of an automated Printed Circuit Board (PCB) diagnostic system that integrates a Dobot Magician robotic arm with an Arduino-based measurement platform for autonomous electrical testing. The proposed system automates voltage and resistance measurements at predefined PCB test points, reducing manual intervention, improving measurement consistency and enhancing diagnostic efficiency. Unlike conventional visual inspection approaches, the system performs direct electrical verification of PCB functionality through robotic probing and real-time parameter measurement. The robotic arm was programmed using a teaching-and-playback approach to achieve accurate and repeatable probe positioning, while the Arduino-based measurement module acquired and displayed measurement results through a Liquid Crystal Display (LCD) interface. Experimental evaluation was conducted by comparing the measured values against a calibrated digital multimeter. Results showed resistance measurement errors ranging from 2% to 6%, while voltage measurement errors remained below 3% for the 5 V rail and below 12% for the 3.3 V rail. The system was also able to identify common PCB faults, including open circuits, short circuits and incorrect resistor values. The findings demonstrate the feasibility of integrating low-cost robotic automation with embedded measurement systems for automated PCB diagnostics. The proposed platform offers a practical and cost-effective solution for educational laboratories, research environments and low-volume industrial applications. Future enhancements may include higher-resolution data acquisition modules, automated calibration techniques, machine vision-assisted probe positioning and intelligent fault detection algorithms to further improve system accuracy and diagnostic capability.

Keywords: Automated Inspection, Dobot Magician, Printed Circuit Board (PCB), Voltage and Resistance Measurement

1. INTRODUCTION

Printed Circuit Boards (PCBs) are fundamental components in modern electronic systems, providing electrical interconnections between electronic devices and components. As electronic products continue to evolve towards higher complexity, miniaturization and functionality, the demand for reliable PCB inspection and diagnostic systems has increased significantly. Faults such as open circuits, short circuits, damaged traces and incorrect component placements can lead to system malfunction, reduced product reliability and increased manufacturing costs. Therefore, efficient and accurate PCB diagnostic techniques are essential to ensure product quality and operational reliability.

Conventional PCB diagnostic and inspection processes are commonly performed manually or through semi-automated methods using handheld measuring instruments. Although these approaches are widely used, they are often time-consuming, labour-intensive and highly

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dependent on operator skill and experience. In addition, repetitive manual probing may introduce measurement inconsistencies and increase the possibility of human error, particularly in high-density PCB layouts. With the advancement of Industry 4.0 (IR4.0) technologies, the integration of automation, robotics and intelligent systems has become increasingly important in modern manufacturing environments to improve productivity, consistency and process efficiency [1][2]. In particular, robotic systems integrated with IoT-based monitoring platforms enable real-time data acquisition, process monitoring and intelligent decision-making in industrial applications. Recent developments in robotic navigation, smart sensing and IoT-enabled monitoring systems further demonstrate the growing role of connected and data-driven technologies in supporting efficient and reliable automated operations [3][4][5][6][7][8][9][10].

Robotic arm systems have gained considerable attention in industrial automation applications due to their high positioning accuracy, repeatability and flexibility. These characteristics make robotic systems suitable for applications involving automated probing, component handling and inspection tasks. Previous studies have demonstrated the successful implementation of robotic systems in electronics manufacturing applications such as automated desoldering processes, machine vision-based PCB inspection and defect detection systems [11][12]. Furthermore, robotic arms can provide stable probe positioning and controlled contact force, which are important factors for obtaining reliable electrical measurements during PCB diagnostics.

Despite the growing use of robotic systems in manufacturing automation, the application of robotic arms for automated PCB diagnostics involving direct voltage and resistance measurements remains relatively underexplored. Most existing PCB inspection systems focus primarily on visual inspection techniques rather than electrical parameter measurements [13][14]. Electrical diagnostics using automated probing systems can provide more direct information regarding circuit functionality and component integrity, thereby improving diagnostic reliability and fault identification capabilities [15].

To contextualize the unique contribution of this work, the proposed system is compared against existing automated PCB inspection and testing approaches. Contemporary electronics manufacturing predominantly relies on Automated Optical Inspection (AOI) systems and Flying Probe Testing (FPT) platforms. While AOI systems provide high-speed visual inspection capabilities for detecting soldering defects, component misalignment and surface-level anomalies, they are inherently limited in assessing electrical functionality, such as voltage integrity, resistance verification and active circuit behaviour under operating conditions [12][16]. Conversely, commercial flying probe testers offer highly accurate electrical measurements without requiring dedicated test fixtures; however, their high acquisition costs, complex programming requirements and maintenance overhead often restrict their adoption to medium- and high-volume manufacturing environments [16]. Recent research has explored various approaches for automating PCB inspection and quality assurance. Fonseca et al. presented a comprehensive survey of PCB inspection technologies, highlighting the increasing adoption of machine vision, artificial intelligence and automated inspection systems to improve defect detection efficiency and manufacturing quality [17]. Similarly, Chung et al. proposed a keypoint-based automated component placement inspection framework capable of accurately identifying component positioning errors on assembled PCBs using computer vision techniques [18]. These studies demonstrate significant progress in automated visual inspection; however, they primarily focus on image-based defect identification rather than direct electrical verification of circuit functionality. Consequently, faults such as abnormal voltage levels, open circuits, component parameter deviations or intermittent electrical connections may remain undetected without complementary electrical testing approaches.

In contrast, the proposed system integrates a 4-degree-of-freedom Dobot Magician robotic arm with an Arduino-based measurement platform to perform automated electrical diagnostics through direct probing of predefined PCB test points. Unlike machine vision-based inspection systems that primarily assess physical defects and component placement, the proposed approach directly evaluates electrical parameters, including voltage and resistance, enabling functional verification of PCB circuitry. By combining robotic manipulation with low-cost embedded measurement hardware, the system offers a practical and cost-effective alternative for educational laboratories, research environments and low-volume manufacturing applications.

Unlike most existing PCB inspection systems that primarily rely on machine vision and image-processing techniques for defect detection, the proposed work focuses on automated electrical diagnostics through robotic probing and direct parameter measurement. The main contribution of this study is the development of a low-cost robotic PCB diagnostic platform that integrates a Dobot Magician robotic arm with an Arduino-based measurement system to perform autonomous voltage and resistance verification at predefined test points. Constructed for a fraction of the cost of industrial FPTs, this platform provides a 4-degree-of-freedom articulated architectural workspace. In addition to reducing manual probing effort, the proposed approach enables direct assessment of circuit functionality, which cannot always be inferred through visual inspection alone. The work further demonstrates the feasibility of combining robotic automation, embedded measurement systems and IR4.0 concepts into an affordable platform suitable for educational laboratories, research environments and small-scale manufacturing applications.

2. METHODOLOGY

The proposed automated PCB diagnostic system aims to improve the efficiency and reliability of PCB inspection by integrating robotic automation with electrical measurement systems. The system consists of three primary components, namely the Dobot Magician robotic arm, the Arduino-based multimeter platform and the PCB under test. The integration of these components enables automated voltage and resistance measurements to be performed at predefined PCB test points with minimal human intervention.

The core of the system is the robotic arm and Arduino-based measurement platform, where the robotic arm is programmed to position the measurement probe accurately at designated PCB locations using predefined coordinate positions. Meanwhile, the Arduino Uno functions as the central processing unit responsible for acquiring voltage and resistance measurements through analog input channels and displaying the obtained readings in real-time via an I2C Liquid Crystal Display (LCD) module. The measured values are subsequently compared against predefined threshold values to identify possible PCB faults such as open circuits, short circuits and incorrect resistor values.

2.1 System Workflow

The system workflow illustrated in Figure 1 was developed to automate PCB diagnostic procedures by integrating the Dobot Magician robotic arm with an Arduino-based multimeter system. The workflow enables automated voltage and resistance measurements to be performed sequentially at predefined PCB test points with minimal human intervention.

The process begins with system initialization, where the robotic arm and Arduino Uno controller are powered on and serial communication between both systems is established. Following initialization, the robotic arm undergoes a calibration process to ensure accurate positioning and repeatable movement throughout the diagnostic operation. Once calibration is completed, the user manually inserts and records the PCB test point coordinates using the teaching-and-playback feature available in DobotStudio. This approach simplifies robotic programming by eliminating the need for complex inverse kinematic calculations while enabling faster setup and improved operational flexibility.

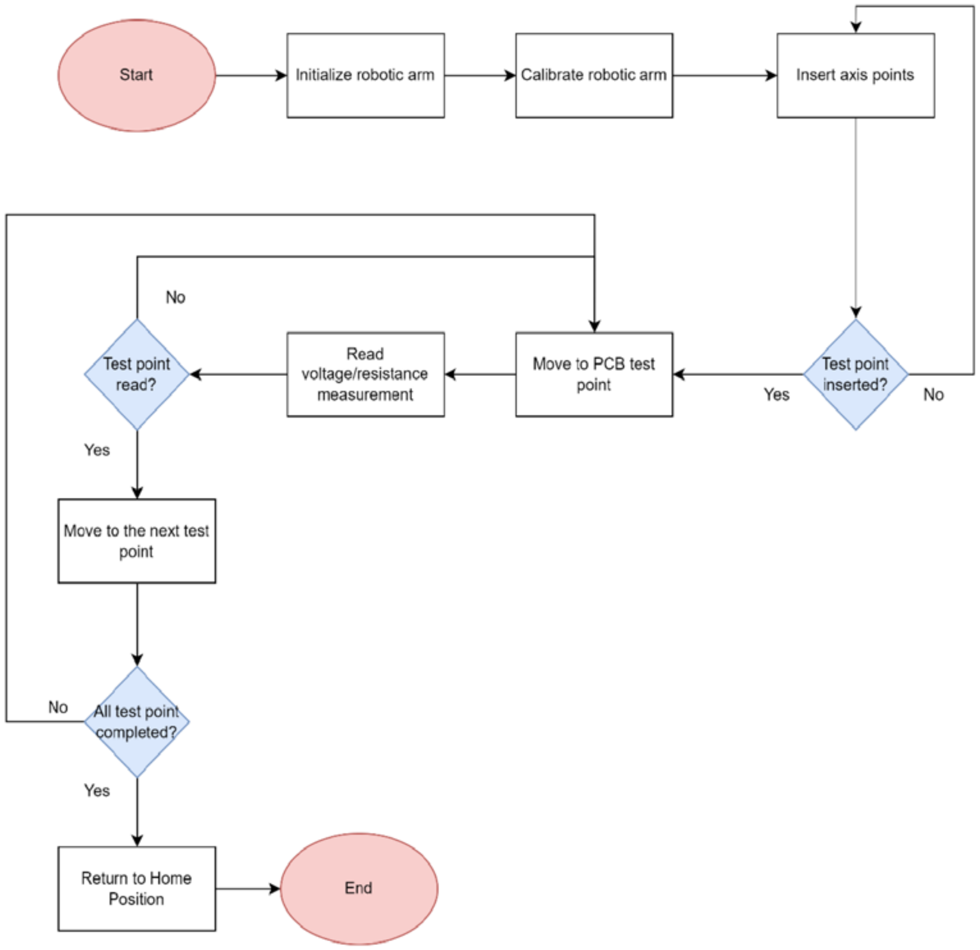


Figure 1. Proposed workflow for robotic-assisted PCB diagnostics, integrating automated probe positioning, electrical measurement and fault detection

After all required test points have been inserted successfully, the robotic arm automatically moves to the designated PCB test point using Point-to-Point (PTP) or linear movement commands. At each measurement location, the robotic arm pauses briefly to ensure stable probe contact before the Arduino-based multimeter performs voltage or resistance measurements. The measured values are acquired through the Arduino analog input channels and displayed in real-time through the LCD module.

To improve measurement stability and consistency, basic signal filtering techniques are implemented within the measurement algorithm to minimise electrical noise and reading fluctuations. The obtained measurements are subsequently compared against predefined threshold values or acceptable tolerance ranges to determine whether faults such as open circuits, short circuits or incorrect resistor values are present. If the measurement at a particular test point is incomplete or unstable, the system repeats the reading process until valid data are obtained.

Once the measurement at the current test point is completed, the robotic arm proceeds to the next predefined test location. This sequence continues iteratively until all PCB test points have been measured successfully. After completing the entire diagnostic cycle, the robotic arm automatically returns to its home position, indicating the end of the testing process.

The developed workflow provides a structured and repeatable automated PCB diagnostic process that reduces manual probing errors, improves measurement consistency and enhances inspection efficiency. In addition, the integration of robotic automation with embedded measurement systems supports low-cost smart manufacturing and educational applications aligned with IR4.0 objectives.

2.2 Schematic Connection

The schematic diagram in Figure 2 shows an Arduino Uno interfaced with an I2C LCD for display, and connected to multiple voltage divider networks designed to measure different resistor values and input voltages for PCB diagnostics. Three terminals are connected through resistors of 1 kΩ, 10 kΩ and 100 kΩ respectively, linked to analog pins A1, A2 and A3 to enable resistance identification by reading voltage drop across known resistor values. Another voltage divider formed by R4 (30 kΩ) and R5 (7.5 kΩ) connects to analog pin A0 to measure input voltages up to a calculated range safely within Arduino's analog to digital converter (ADC) limits.

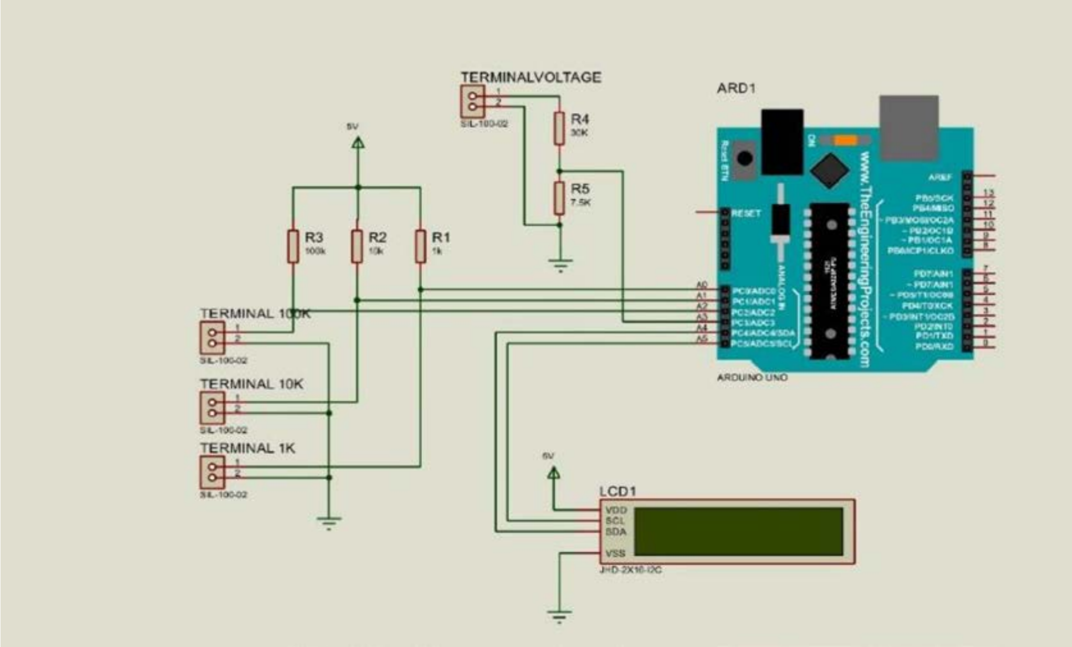


Figure 2. Schematic representation of the robotic PCB diagnostic platform and its measurement components

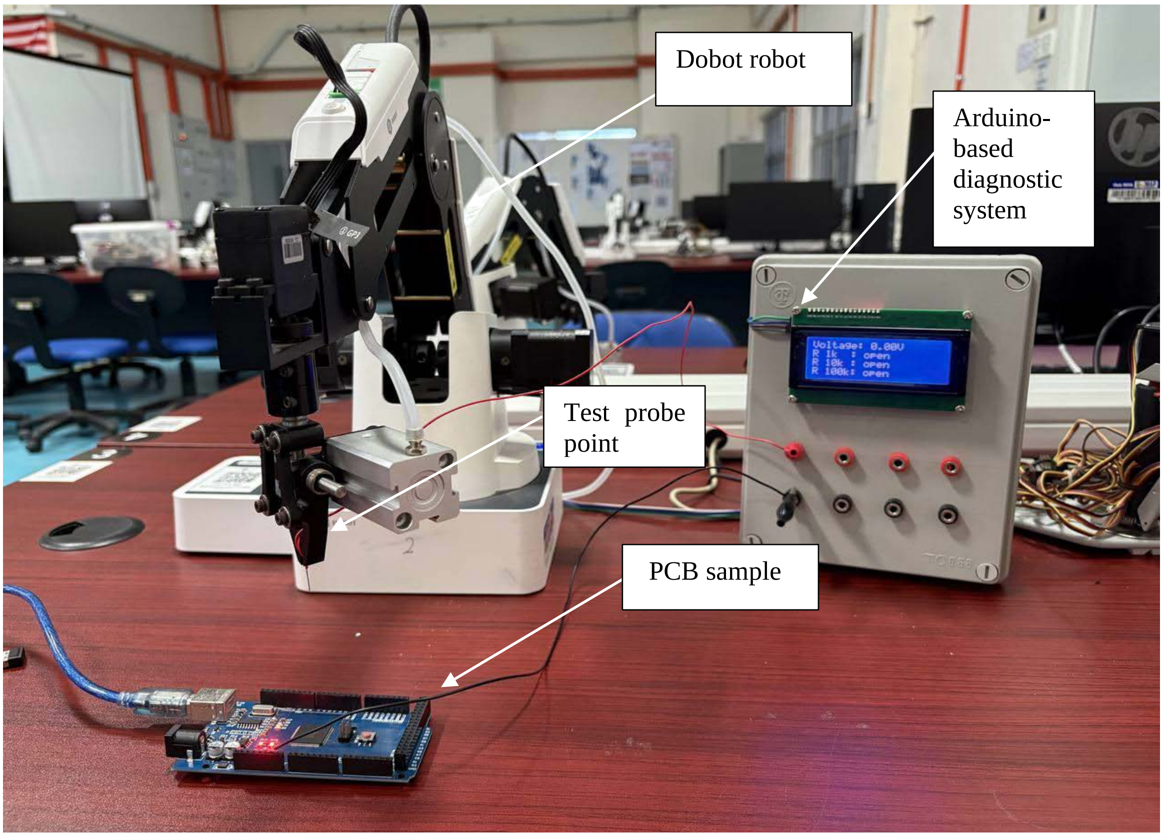
The LCD displays the measured resistance or voltage values in real-time, allowing the system to identify whether a resistor on the PCB matches expected values or to measure test point voltages for diagnostics. This setup enables automated PCB checking for common faults such as incorrect resistor placement or abnormal voltage levels, supporting efficient and systematic circuit board validation.

2.3 Robotic Arm Control and System Integration

The Dobot Magician robotic arm was programmed to perform automated probe positioning for PCB diagnostic measurements at predefined test points. The teaching-and-playback method available in DobotStudio was utilised to record the exact X, Y and Z coordinate positions for each PCB test location, as illustrated in Figure 3. This method was selected because it simplifies robotic arm programming by eliminating the need for complex inverse kinematic and joint angle calculations. In addition, the approach significantly reduces programming complexity and setup time while ensuring accurate, repeatable and consistent robotic movements throughout multiple diagnostic cycles.

The recorded coordinate positions were subsequently integrated into the Arduino Uno control program, enabling the robotic arm to move sequentially to each predefined PCB test point during system operation. Point-to-Point (PTP) and linear movement commands were implemented to ensure stable and precise probe positioning before measurement acquisition.The Arduino Uno functioned as the central controller for both robotic arm operation and electrical measurement processes. Through serial communication, the Arduino transmitted movement commands to the Dobot Magician controller and coordinated the voltage and resistance measurement sequence at each test location. Once the robotic arm reached the designated position, the Arduino-based multimeter initiated the corresponding measurement process and displayed the obtained readings in real-time.

This integrated control approach improved diagnostic efficiency by automating repetitive probing tasks, reducing human intervention, and minimising measurement inconsistencies caused by manual operation. Furthermore, the robotic arm provided stable probe positioning and consistent contact conditions, contributing to improved measurement repeatability and overall PCB diagnostic reliability.



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Voltage: 0.00V
R 1k  : open
R 10k : open
R 100k: open
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Figure 3. Experimental setup showing automated PCB probing and electrical measurement using the robotic arm

2.4 Measurement Accuracy and Error Analysis

To evaluate the accuracy and reliability of the developed Arduino-based multimeter system, measurement error analysis was conducted by comparing the obtained voltage and resistance readings with reference measurements acquired using a calibrated digital multimeter. The comparison was performed to assess the system's measurement performance under practical PCB diagnostic conditions.

The absolute error was calculated to determine the direct difference between the Arduino-based measurement and the reference multimeter reading. The absolute error equation is expressed as in Equation (1):

$$\Delta \mathrm{M} = \mathrm{MArduino} - \mathrm{MMultimeter} \tag{1}$$

where MArduino represents the measured value obtained from the Arduino-based multimeter system, while MMultimeter is the reference multimeter reading.

In addition, percentage error analysis was performed to quantify the deviation of the measured value relative to the expected reference value. The percentage error was calculated using Equation (2):

$$\text{Error (\%)} = \frac{|\text{ Measured Value} - \text{Expected Value }|}{\text{Expected Value}} \text{ x } 100\% \tag{2}$$

The calculated error values were applied to all recorded voltage and resistance measurement data to evaluate the overall accuracy, consistency and repeatability of the developed system. This analysis provided quantitative performance indicators regarding the effectiveness of the robotic arm integrated measurement platform for automated PCB diagnostic applications.

3. RESULTS AND DISCUSSION

The results obtained from voltage and resistance measurements using the Arduino-based multimeter system integrated with the Dobot Magician robotic arm are presented and analysed in this section. Measurement accuracy, consistency and overall system performance were evaluated by comparing the Arduino-based readings with those recorded by a standard calibrated multimeter. The findings demonstrate the system's capability for practical PCB diagnostic applications and provide insights into its operational reliability and potential areas for improvement.

3.1 Resistance Measurement Performance

The developed system was evaluated through resistance measurements conducted at multiple PCB test points, including the RX pin, TX pin and mounted resistor R16. The experimental results demonstrated that the Arduino-based multimeter system was capable of producing stable and repeatable measurements with acceptable accuracy for PCB diagnostic applications.

For the RX pin measurements, the Arduino-based system consistently produced slightly lower resistance values compared to the calibrated digital multimeter. As in Figure 4, the average measurement deviation was approximately 5.97%, indicating a relatively small error margin for practical diagnostic purposes. Similar behaviour was observed during measurements conducted at the TX pin, where the average error was recorded at approximately 5.79%. The detailed results are presented in the comparison graph shown in Figure 5. The consistency of the measurement deviations suggests that the system maintained stable operation throughout repeated testing cycles.

In contrast, as in Figure 6, measurements performed on the mounted resistor R16 showed improved accuracy, with an average error of approximately 2.49%. The reduced error for discrete resistor measurements may be attributed to improved probe contact stability and lower circuit complexity compared to PCB trace measurements. These findings indicate that the developed system is capable of performing reliable resistance measurements for component verification and fault detection applications.

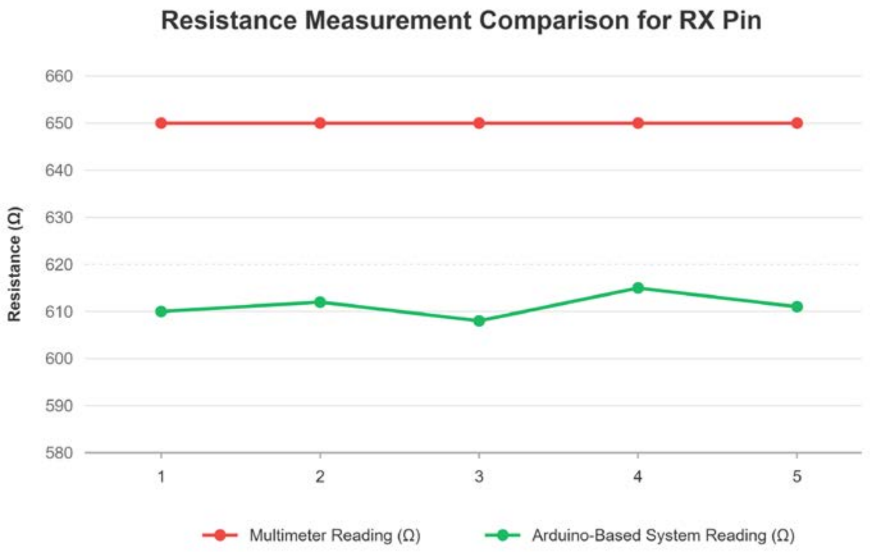

Figure 4. Comparison of resistance measurements at the RX test point, showing good agreement between the proposed system and the reference multimeter with an average error below 6%

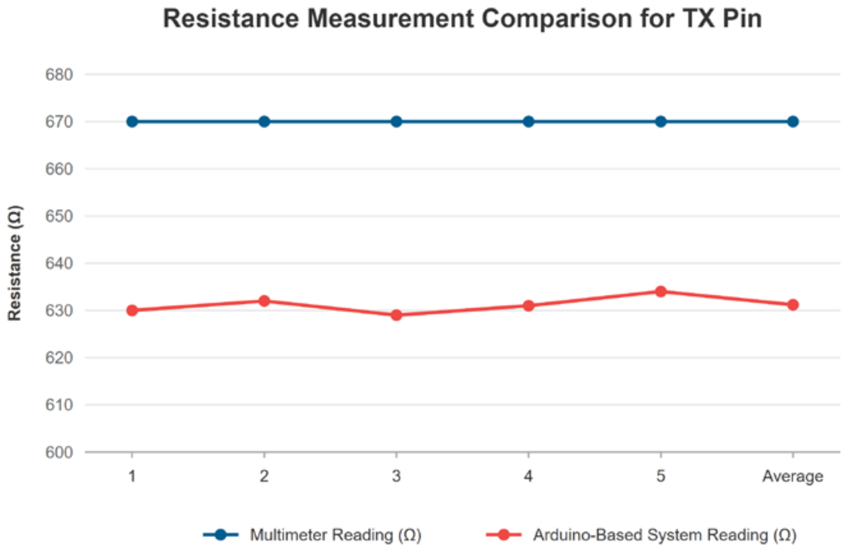

Figure 5. Comparison of resistance measurements at the TX test point, demonstrating consistent measurement performance across repeated trials

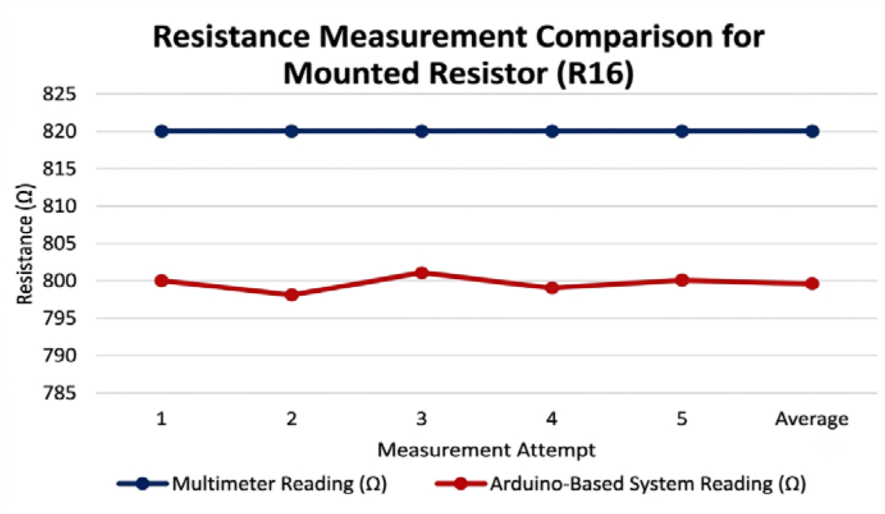

Figure 6. Comparison of resistance measurements for mounted resistor R16 obtained using the proposed automated diagnostic system and a calibrated digital multimeter

Although minor deviations were observed, the measurement accuracy achieved by the system remains acceptable for educational and low-cost industrial diagnostic applications. Several factors may contribute to measurement inaccuracies, including probe contact resistance, ADC resolution limitations of the Arduino Uno, electrical noise and slight variations in robotic arm positioning. Nevertheless, the repeatability of the measurements demonstrates the effectiveness of the robotic arm integration in maintaining consistent probing conditions.

3.2 Voltage Measurement Performance

As per Table 1, voltage measurements were conducted on the 3.3 V and 5 V rails of the Arduino Mega PCB to evaluate the performance of the voltage measurement subsystem. The measured values obtained from the Arduino-based system were compared with readings from a calibrated digital multimeter.

Table 1 Voltage measurement results

Cycle	Voltage Sensor (3.3V)	Multimeter (3.3V)	Voltage Sensor (5V)	Multimeter (5V)
1	3.67	3.30	4.79	4.66
2	3.62	3.44	4.88	4.79
3	3.21	3.78	4.65	4.79
4	3.20	3.46	4.83	4.85
5	3.41	3.44	4.82	4.86

Experimental results showed that the developed system achieved relatively accurate voltage measurements, particularly for the 5 V rail, where the percentage error remained below 3%. The voltage sensor readings closely matched the multimeter measurements, demonstrating the capability of the voltage divider circuit and Arduino ADC system to perform practical voltage diagnostics.

For the 3.3 V rail measurements, slightly larger variations were observed, with percentage errors reaching approximately 11.21%. These deviations may be caused by ADC quantisation limitations, sensor calibration inaccuracies, electrical noise or instability in probe contact during measurements. Despite these limitations, the system remained capable of identifying abnormal voltage conditions and distinguishing between normal and faulty operating states.

The experimental findings indicate that the developed system provides sufficient voltage measurement performance for general PCB diagnostic applications, particularly in educational laboratories, prototype testing environments and low-volume manufacturing setups.

3.3 Overall System Performance and Discussion

Overall, the developed automated PCB diagnostic system successfully achieved its primary objective of integrating robotic automation with electrical measurement capabilities for PCB inspection and fault diagnosis. The Dobot Magician robotic arm demonstrated consistent positioning performance throughout the experimental trials, enabling reliable probe placement at predefined PCB test points. Based on the manufacturer's specifications, the robotic arm provides a positioning repeatability of ±0.2 mm, which contributes to stable and repeatable measurement acquisition during successive testing cycles.

A key advantage of the proposed system is its ability to reduce human intervention during diagnostic procedures. By automating the probing and measurement process, the system minimizes operator-dependent errors, improves measurement consistency and enhances inspection efficiency. Furthermore, the teaching-and-playback programming approach simplifies robotic deployment by eliminating the need for complex motion programming, making the system particularly suitable for educational laboratories, research environments and low-volume manufacturing applications.

Experimental results demonstrated satisfactory agreement between the automated measurement platform and a calibrated digital multimeter, validating the feasibility of the proposed approach for PCB diagnostics. The system was capable of identifying common electrical faults, including open circuits, short circuits and incorrect resistor values, through automated voltage and resistance verification at designated test points. These findings highlight the potential of combining robotic manipulation with low-cost embedded measurement platforms to support automated testing, smart manufacturing and IR4.0-driven inspection systems.

Despite its promising performance, the current implementation remains a proof-of-concept platform and has several limitations. Measurement accuracy may be influenced by factors such as ADC resolution, probe contact resistance and PCB test point accessibility. Future work will focus on incorporating higher-resolution data acquisition hardware, force-controlled probing mechanisms, comprehensive repeatability studies and intelligent fault classification algorithms to further enhance system accuracy, reliability and industrial applicability.

3.4 System Limitations and Future Improvements

While the proposed system successfully demonstrates the feasibility of automated PCB diagnostics using robotic probing, several limitations remain. First, the measurement accuracy is constrained by the 10-bit ADC resolution of the Arduino Uno, which limits the precision of voltage and resistance measurements. Second, probe-to-test-point alignment errors and contact resistance may introduce measurement variability, particularly when testing small PCB pads or densely populated circuit boards. Third, the current implementation relies on predefined coordinate positions through a teaching-and-playback approach, which limits adaptability to PCB layout variations and requires reprogramming when board designs change.

Furthermore, the present study focuses primarily on validating the functionality and measurement capability of the proposed system rather than conducting large-scale fault detection assessment. Although the system successfully identified common PCB faults such as open circuits, short circuits and incorrect resistor values, comprehensive evaluation of fault detection performance was beyond the scope of this work. Future studies should incorporate larger PCB datasets containing known fault conditions to enable statistical analysis of fault detection accuracy, sensitivity, specificity and false-positive rates.

Although the proposed system demonstrated successful automated voltage and resistance measurements, it was primarily intended as a proof-of-concept validation of robotic-assisted PCB diagnostics. Comprehensive quantitative evaluation, including robotic positioning repeatability, measurement repeatability, execution time benchmarking and comparison against manual inspection approaches, was not conducted. Future work should include repeated measurement trials, multiple PCB configurations and benchmarking against conventional inspection methods to further validate the robustness, scalability and industrial applicability of the proposed system. Additional enhancements may include force-controlled probing, machine vision-assisted test-point localization, higher-resolution data acquisition hardware and machine learning-based fault classification algorithms to improve measurement accuracy, operational flexibility and diagnostic intelligence.

4. CONCLUSION

This project has successfully developed an automated PCB diagnostic system by integrating a Dobot Magician robotic arm with an Arduino-based multimeter platform. Experimental results demonstrated that the developed system achieved resistance measurement errors ranging from 2% to 6%, while voltage measurement errors remained below 3% for the 5 V rail and below 12% for the 3.3 V rail. Although the measurement accuracy is influenced by ADC resolution, probe contact conditions and circuit noise, the system successfully differentiated normal and abnormal operating conditions, making it suitable for educational, research and low-volume industrial diagnostic applications. Furthermore, the implementation proved highly effective in detecting common manufacturing faults, including open circuits, short circuits and incorrect resistor values, thereby significantly enhancing diagnostic speed and consistency compared to conventional semi-automated methods. The use of the teaching-and-playback method for probe positioning ensured high precision and repeatability while reducing setup complexity. Ultimately, this system provides a practical, low-cost solution for enhancing production reliability and diagnostic efficiency in both educational and low-volume industrial environments

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