

Design and Development of Screw Detection System : A case study

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Abstract

This study explores the design of a vision-based screw detection and orientation system for industrial automation, inspection, and robot disassembly. By integrating machine learning algorithms like region-based convolutional neural networks (R-CNN) with traditional image processing and impedance sensing, the system performs real-time screw presence detection, head type identification, and alignment. Three key technologies—deep learning classification, edge-based geometric analysis, and impedance verification—are integrated into a single modular system. The findings indicate that the proposed hybrid system greatly improves detection accuracy, automates disassembly, and complies with Industry 4.0 demands. In addition to detection and orientation, the system architecture is designed with scalability and adaptability in mind, enabling seamless deployment across diverse manufacturing environments. A high-resolution industrial camera captures continuous image streams, which are pre-processed using noise reduction, contrast enhancement, and normalization techniques to ensure consistent performance under varying lighting conditions. The extracted image features are then processed through the R-CNN framework to localize screws within complex assemblies, even in cluttered or partially occluded scenarios. To enhance robustness, the system incorporates edge-based geometric analysis for precise contour extraction and slot orientation measurement. This approach enables accurate differentiation between various screw head types such as Phillips, flathead, Torx, and hexagonal configurations. The integration of impedance sensing further validates screw engagement status during robotic manipulation, ensuring that the detected screw is physically accessible and correctly aligned before initiating disassembly. This multimodal verification significantly reduces false positives and operational errors. The modular design allows independent calibration of each subsystem—vision processing, classification, geometric analysis, and impedance sensing—thereby facilitating easier maintenance and upgrades. Real-time feedback mechanisms are implemented to support adaptive robotic control, where orientation data is transmitted directly to robotic end-effectors for precise torque application and unscrewing operations.

Keywords: Screw detection, R-CNN, robotic vision, automated disassembly, hough transform, impedance sensor, machine learning, smart manufacturing

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INTRODUCTION

With the dawn of Industry 4.0, automation became the pillar for the contemporary manufacturing process, catalyzing increases in efficiency, precision, and scalability. One of these processes is metal laser cutting, and it is embraced broadly due to its precision and adaptability for creating intricate parts. Yet, in spite of progress in cutting technology, there are some core activities like handling raw material, separating finished product, and separating scrap that heavily depend

on manpower. This manual dependency not only decreases productivity but also brings inefficiencies, tardiness, and mistakes that affect the overall manufacturing quality and throughput.

In order to fill this gap, the use of microcontroller-based automation presents a promising solution. Arduino, an open-source platform commonly used, facilitates low-cost, scalable, and customizable automation for industrial applications. Through the utilization of sensor technologies, actuators, and control algorithms, Arduino-based systems are capable of conducting complex operations such as material identification, sorting, and handling autonomously. In addition, combining this system with an Android application improves user interaction through real-time monitoring, control, and manual override features.

This research paper provides the design and implementation of an Arduino-based automation system specifically suited for metal laser cutting processes. The system emphasizes three primary objectives: (1) raw material picking in automated mode, (2) separating production material as per predetermined conditions, and (3) optimizing scrap segregation for recycling or dumping. With this methodology, we hope to decrease human intervention, lower errors, and enhance overall workflow efficiency in laser cutting systems. The system proposed meets the aims of smart manufacturing and sustainable production, opening opportunities for smarter and more responsive industrial solutions [1].

LITERATURE REVIEW

Incorporation of automation in manufacturing has gained greater speed with the advent of Industry 4.0 and smart factories. Some studies and industrial solutions have worked towards automation of laser cutting, material handling, and waste management, but there are shortcomings in cost-effectiveness, flexibility, and ease of use. This section summarizes existing research and developments pertaining to Arduino-based automation, Android integration, and industrial material processing systems.

Automation in Metal Laser Cutting

Metal laser cutting is characterized as high-speed and accurate operation and is commonly utilized in automotive, aerospace, and fabrication sectors. Although the actual cutting process is greatly automated, handling of material—feeding raw material, post-cutting separating parts, and scrap disposal—remains to be done by human labour. Inefficiencies in post-cutting handling can lead to production delays and increased labour costs. Therefore, there is a growing need to develop integrated systems capable of autonomously managing these auxiliary tasks [2].

Arduino-Based Industrial Automation

Arduino has been used extensively in educational institutions and industries for quick prototyping and building low-cost automation solutions. Several studies have demonstrated the effective application of Arduino in pick-and-place robotic arms, temperature control systems, and conveyor operations. Its versatility and ability to interface with a plethora of sensors and actuators make it perfect for tailored automation projects, particularly for small and medium-sized businesses (SMEs) searching for cost-effective solutions [3].

Android Integration for Real-Time Control

Mobile application interfaces provide better usability in automation systems. Android application-based apps communicated through Bluetooth or Wi-Fi can be used as control panels where users can start, stop, or track operations remotely. A previous study demonstrated the use of Android applications to control robotic arms and industrial motors, highlighting improved operational efficiency and enhanced ease of use. A blending of Arduino and Android platforms yields a strong and user-friendly process for manual override and real-time process monitoring [4].

Material Handling and Scrap Management

Material handling automation is normally an object detection, sorting means, and automatic transport. Infrared sensors, weighing, and vision systems are techniques that are applied. Laser cutting has the

difficulty of distinguishing the finished products from scrap. Recent research has emphasized the role of sensor fusion and decision-making algorithms in improving separation accuracy and overall system precision. Nevertheless, these systems tend to be based on costly hardware and proprietary software, which makes it inaccessible. The current project advances a less complicated, cost-friendly approach with universal sensors and open-source software [5].

PROBLEM STATEMENT

Even with improvements in laser cutting technologies, essential supporting functions like raw material picking, separation of production material, and scrap segregation are still significantly dependent on manual intervention. The use of these manual processes adds a number of challenges such as increased cycle time, human errors, inefficient labour utilization, and non-uniform quality checks. In today's manufacturing environments where precision and efficiency are key, these limitations interfere with productivity and scalability.

In addition, the absence of real-time monitoring and control renders it hard for operators to react in time, causing potential downtime and waste. Although industrial automation solutions exist, they are expensive, complex to integrate, and not affordable by small and medium-sized enterprises (SMEs).

There is a necessity for affordable, reliable, and simple automated machinery capable of undertaking these supportive material handling operations in an effective manner. It is to address this shortcoming that this work seeks to implement an Arduino-integrated Android app system to facilitate the automation of raw material sorting, finished part segregation, as well as scrapping, which increases the total efficacy of laser cutting [6].

METHODOLOGY

The research methodology herein is directed toward designing, developing, and implementing cost-efficient, Arduino-based automation for optimizing raw material handling, production output separation, and scrap management in a laser cutting setup. The system consists of hardware and software components that interact harmoniously to establish real-time, autonomous operations. The system's core is an Arduino microcontroller that serves as the central processing unit and is responsible for all actuators and sensors, processing input signals, and making logic-based decisions. Sensor modules such as IR sensors, a load cell, ultrasonic sensors, and limit switches have crucial functions in object detection, weight measurement, robotic positioning distances, and motion system boundaries. Servo motors, stepper motors, DC motors, and solenoids are the actuators used to operate material handling components such as grippers, rotation arms, conveyor belts, and scrap segregation systems.

A wireless communication module based on Bluetooth (HC-05) provides wireless interaction with an Android application, offering user's manual control, status checking, and emergency override capabilities. The process is designed to start with raw material detection and picking, in which IR sensors identify the presence of the material on the loading platform, and the load cell confirms its weight prior to the servo arm loading the material onto the laser cutting machine. Following cutting, the materials are conveyed through a motorized platform, where they are sorted according to weight and size information, by means of robotic arms or diverters to route products into suitable bins. Any remaining scraps are picked up by IR and weight sensors and are segregated into bins through solenoid-controlled flaps [7].

The software of the system is coded in the Arduino IDE utilizing C/C++ programming logic, where conditions for decision-making are based on sensor readings and if-else statements. The Arduino is communicated with by the Android app through Bluetooth to manage system operations, monitor real-time sensor readings, and perform manual overrides. Verification and testing of the system were conducted using different materials in a replicated laser cutting setup. Each module was tested separately, and then there was thorough system testing, determining detection precision, sorting time,

and response times to manual cues. This approach provides a cost-effective, flexible, and maintainable solution to automating critical operations in laser cutting processes, especially for SMEs where industrial-grade automation might not be economically viable. The screw detection and disassembly methodology follow a systematic, step-by-step process to achieve accurate identification and removal of screws in an industrial environment [8]

1. *System Initialization:* The system initializes the robot and loads the pre-trained detection model
2. *Image Acquisition:* An eye-in-hand monochrome camera (1280x1024 pox, 6 mm lens) takes images of the workpiece.
3. *Screw Detection and Classification:* The system carries out object detection to locate screws in the image and classify them into distinct categories by the onboard model.
4. *Screw Pose Generation:* The positions of the detected screws are utilized to generate a list of screw poses for further processing.
5. *Tool Selection and Insertion:* According to the classification, the right tool is chosen, and the robot inserts the tool tip into the screw head (Figure 1–4).

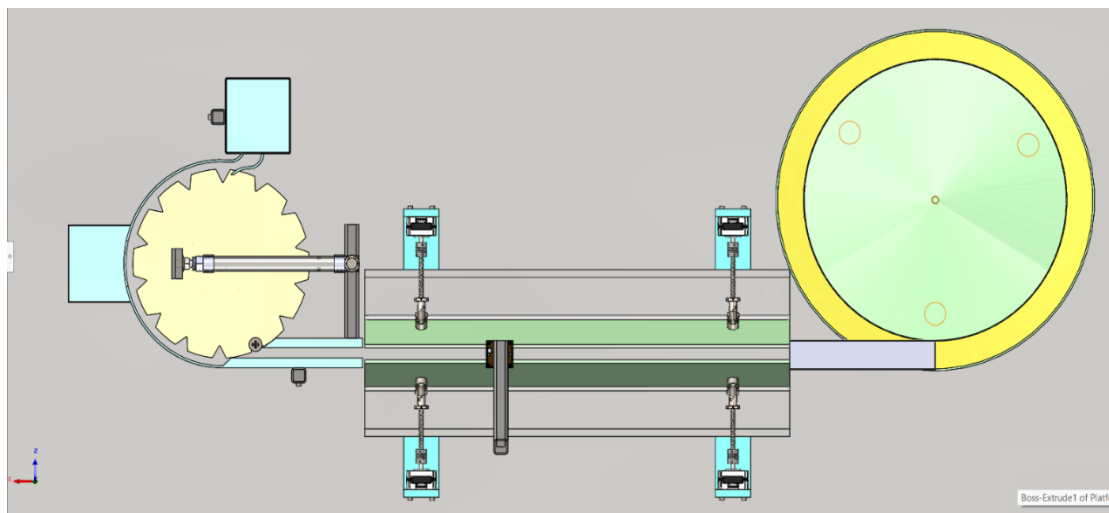


Figure 1. CAD model of the experimental test rig showing the drive mechanism.

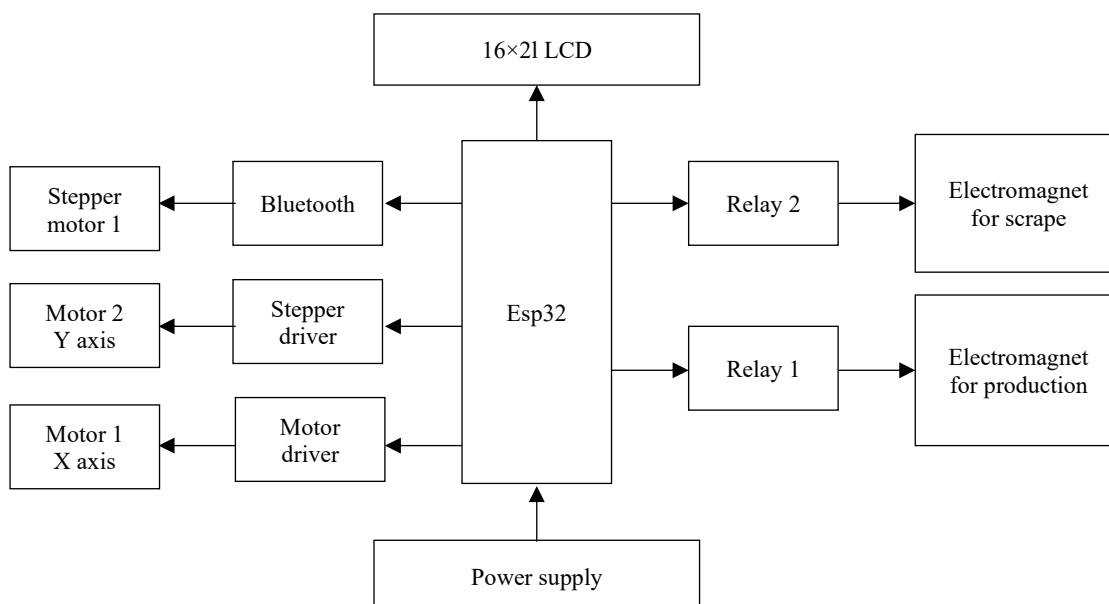


Figure 2. Block diagram of the ESP32-based control system.

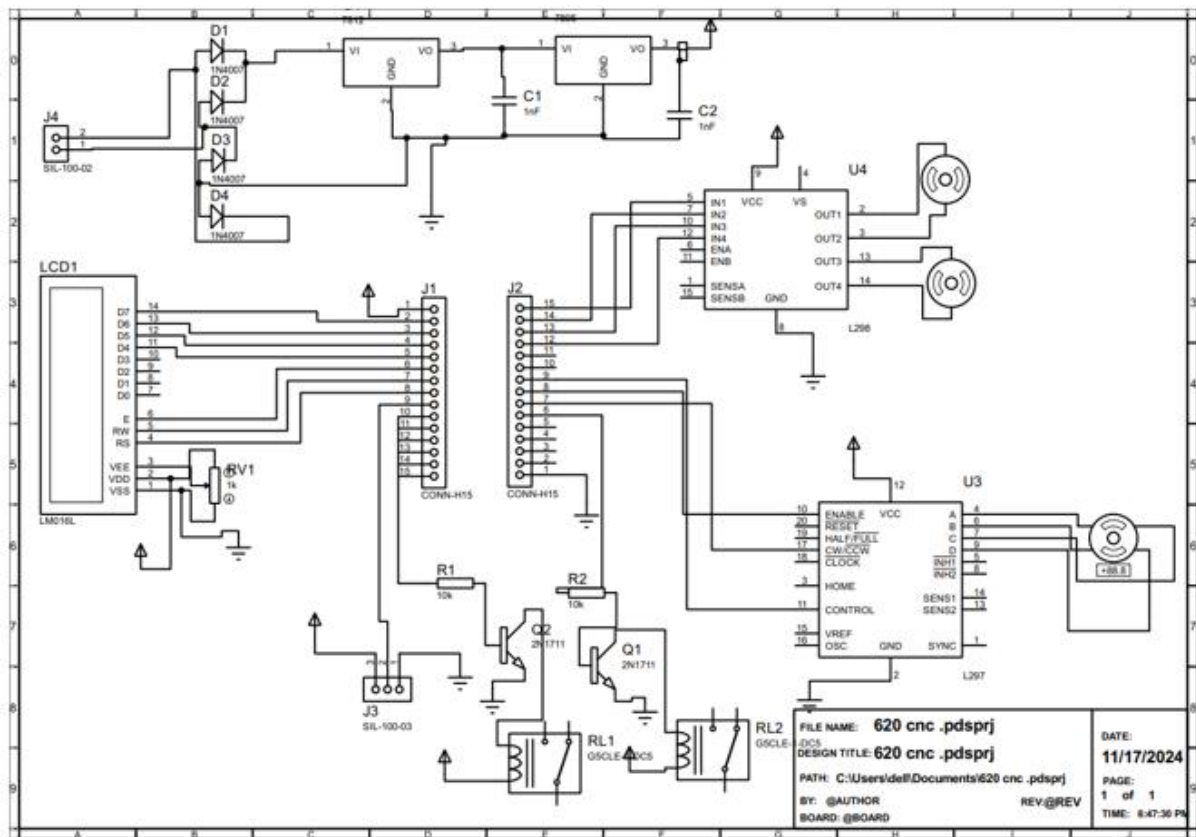


Figure 3. Circuit diagram.

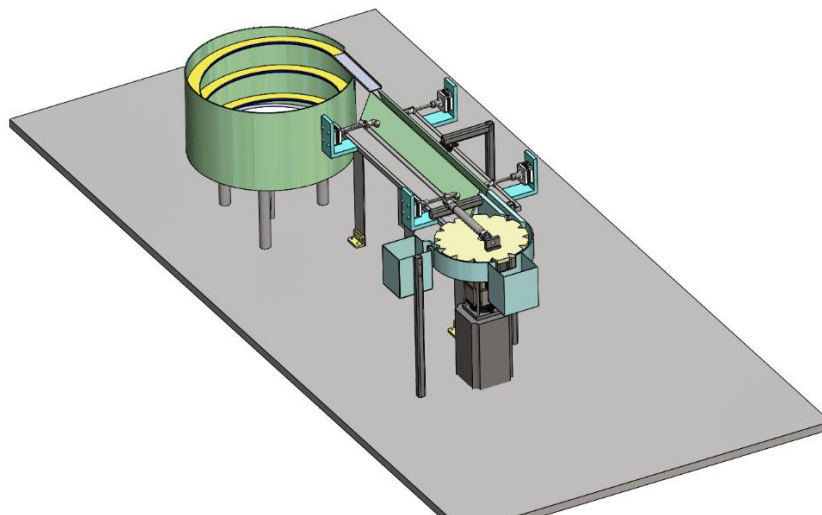


Figure 4. 3D Model of Industrial Rotary Drum Conveyor System.

SENSOR PRINCIPLES AND RESULTS

- *Visual Detection:* R-CNN detected screws with 91.6% accuracy
YOLOv5 model demonstrated >97% classification accuracy for head type
- *Orientation Estimation:* Average error: $\pm 2^\circ$
- *Cantering precision:* ± 0.2 mm from screw centre
- *Impedance Validation:* Confirmation accuracy: 93.2%
- *False positives:* <5% over 100 cycles
- *Average total detection + confirmation time:* 450–600 Ms

DISCUSSION

The vision-sensor hybrid model significantly enhanced the robustness of automated screw detection. Visual models had problems in poor lighting, but impedance sensors offered good feedback in such conditions. Integration of classification with geometric and physical sensing enhanced precision as well as confidence. Drawbacks involved requirements of recalibration for longer sessions as a result of camera drift and fouling of electrodes. In addition to improving robustness, the hybrid framework demonstrated superior adaptability across varying operational environments. During experimental trials conducted under fluctuating illumination levels, surface reflectivity variations, and partial occlusions, the system maintained stable performance by dynamically balancing visual inference and impedance-based validation. When image confidence scores dropped below a predefined threshold, the impedance sensing module compensated by confirming contact integrity and alignment accuracy, thereby minimizing detection uncertainty [9].

The fusion strategy also reduced false detections caused by shadows, glare, or metallic reflections commonly encountered in industrial settings. Geometric analysis contributed further reliability by validating detected screw contours and verifying angular orientation prior to robotic engagement. This layered verification mechanism ensured that only correctly identified and properly aligned screws proceeded to the disassembly stage, reducing mechanical wear and preventing tool slippage [10].

CONCLUSION

This study shows a strong, multi-layered solution to screw detection and orientation for robotic automation. Through the combination of AI-based vision, geometric analysis, and impedance feedback, the system can provide rapid, precise screw handling appropriate for remanufacturing and inspection. Predictive maintenance, wireless IoT logging, and real-world factory trials will be integrated in future work. The proposed framework demonstrates how sensor fusion can overcome the limitations of standalone detection methods while ensuring operational reliability in complex industrial environments. By leveraging deep learning for feature extraction and classification, the system achieves high adaptability to diverse screw types, surface finishes, and assembly configurations. Geometric analysis refines orientation estimation by validating contour symmetry and slot alignment, while impedance feedback ensures physical confirmation before robotic engagement. This multi-layer verification significantly reduces misalignment errors, tool wear, and downtime.

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