International Journal of Technology

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CORRIGENDUM TO:

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https://doi.org/10.14716/ijtech.v16i3.7287
Received September 2024; Revised October 2024; Accepted December 2024

International Journal of Technology 16(3) 914-932 (2025)

International Journal of Technology

http://ijtech.eng.ui.ac.id

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Automated Assembly Line with 2D Cartesian Robot and Conveyor Belt

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Abstract: Industrial automation is constantly developing and considered critical to process optimization and efficiency. The integration of automated systems is traditionally focused on improving precision and productivity to significantly enhance assembly lines in producing general-purpose models in different materials such as polylactic acid (PLA) plastic. The models include toys, tools, complex mechanism components, and consumer or industrial products. Therefore, this study aimed to present the specifications for the design and testing of a low-cost teaching system for production lines using a 2D Cartesian robot and a conveyor belt. The purpose was to show how innovation in teaching industrial robotics could address the challenge of expensive systems. The proposed solution was to integrate a 2D Cartesian robot into a pneumatic gripper and a conveyor belt controlled by a Programmable Logic Controller (PLC) using a wireless connection and advanced electronic components to achieve efficient communication and operation. The results showed an accuracy of 100% in functional tests and the implications of the advances were to ensure considerable potential for reducing costs and improving learning in industrial and educational environments. The intention was to subsequently promote the implementation of new developments in the field of mechatronics.

Keywords: Assembly line; Cartesian robot; Mechatronic system; Production line

1. Introduction

Automated assembly lines are important for increasing productivity and expediting logistics (Chakraborti et al., 2020). Productive sectors such as automotive (Ashari et al., 2018), chemical (Eriawan et al., 2024), agriculture (Moya et al., 2024), food production (Novandra and Putri, 2022), and pharmaceuticals (De Carlo et al., 2014), depend on automated assembly lines for continuous and efficient production. Moreover, the technology can also reduce human physical and cognitive workload while simultaneously increasing safety during the production process (Cross, 2021). The benefits are strongly motivated by efficiency, precision, quality improvements, and cost reductions (Moreira et al., 2017). Typically, an automated assembly line starts with a component feeding stage where raw materials and components are used as the inputs. There are also assembly stations specialized to execute specific tasks such as attaching (Robeller et al., 2017), welding (Carlson et al., 2014), and others (Hu et al., 2011). Several assembly stations perform quality checks and inspections of the processed materials. Examples of automated machines mostly used within assembly stations are robots and specifically programmed machines that execute actions with high precision and speed (He et al., 2017). Moreover, conveyor belt systems are commonly used to transport materials and

https://doi.org/10.14716/ijtech.v16i3.7287
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parts during automation processes and are considered important in moving items from one station to another. The completion of the activities associated with automated assembly lines is often followed by the packaging and transportation of the final product for distribution (Arjun and Mirnalinee, 2016; Rashid et al., 2012).

The implementation of automated assembly lines can be a complex and multidisciplinary task that requires planning, coordination, simulations and a significant monetary investment. The system has been applied in several industrial companies, leading to the specialization of Festo, Siemens, Allen Bradley, and Amatrol in industrial automation and learning technologies. Each company offers products and solutions, including hardware, software, and support, to efficiently address different processes. Strong relationships are also maintained with academic institutions that have laboratories containing commercial technologies for educational and training purposes, such as the Festo Modular Production Systems (MPS) (Belda and Jirsa, 2021; Ahmad et al., 2020). The educational or training systems are composed of modules with pneumatic cylinders, valves, sensors, actuators, and motion control systems. These systems are useful for simulating real industrial situations, which can be emulated using methods such as sequencing, motion control, Programmable Logic Controller (PLC), industrial communication, and others.

Companies with specialization in robotic design and distribution, such as ABB, KUKA, Fanuc, Universal Robots, and Yaskawa, provide systems specifically designed for automated assembly processes that demand accuracy, speed, and repetitive work. However, the costs of utilizing robots and automated assembly lines can be high despite their several advantages, leading to the need for several analyses for cost reduction (Burggräf et al., 2019). Part of the motivations for this study was to reduce these costs by developing customized robotic systems as a viable alternative to the procedures of commercial automated assembly lines and robotic solutions.

1.1. *State of The Art*

Several methods related to automated assembly lines can be identified in the literature. The search conducted on Scopus using the keywords *automated assembly line* and *robotics* led to the discovery of 479 documents. This was used to develop a state-of-the-art representation of the terms mostly used for the topic in literature, including automation, robotic assembly, industrial applications, and intelligent robots.

The results further showed that production control, sensing, planning, inspection, assembly, product design, product printing, optimization, decision making, and ergonomics were the most commonly associated terms with *automated assembly line* and *robotics* topics in previous studies. It was also observed that manipulator robots, mobile robots, and human-robot interaction systems dominated the industry.

Research and developments using the combination of machine learning technologies such as computer vision and image processing algorithms is significant in the field of robotic applications in recent years. Different studies conducted on the topic are further compared comprehensively in Table S1 of the Appendix. The inference is that the application of automated assembly lines with robots has led to important contributions and potential benefits for different applications in industry and academics.

Mechatronics systems integration has revolutionized learning institutions and industries by combining mechanical, electronic, and software engineering to produce effective and efficient automation systems. The systems are critical for developing the next generation of engineers and assist in applying Industry 4.0 to enhance manufacturing, supply chains, and others. In an academic context, mechatronics is used as a utility to integrate knowledge and practical experience. The trend is observed from the robot prototype presented by Garduno-Aparicio et al. (2018) which is used in mechatronics courses and reported to have satisfied ABET accreditation. This educational model allows the students to assemble circuits with servo motor controls, connect with Modbus, and even program microcontrollers in order to be ready for real-environment engineering applications. The practical experience also assists in developing cross-functional experience, which is highly valuable for companies focused on producing embedded systems and using automation. Natesan et al.

(2023) argued the need to introduce automated welding systems in education, especially for automobile and aerospace engineering. The casework of using the OTC FD-V8 MAG welding robot sets out the positioning of students to comprehend the commercial application of precision welding procedures for natural products. This is important for capturing the design and implementation details of most contemporary mechatronics systems. A similar study by Kudryavtseva and Skhvediani (2020) emphasized the use of robotic systems in improving agricultural studies by applying mechatronics to ease a process such as the protection of plants. The trend shows that automation is not limited to a particular sector.

Industry 4.0 is a revolutionary concept in industrial automation because mechatronic systems are considered the building blocks of smart manufacturing (Wang and Li, 2013). For example, Ryalat et al. (2024) showed real-time data exchange, predictive maintenance, and control changes through the incorporation of mechatronics systems with the Internet of Things (IoT), Artificial Intelligence (AI), and extensive data systems. These capabilities confirmed an intelligent factory notion that focused on autonomous systems to make single-aperture and fast decisions.

Yousif et al. (2024) investigated the application of computer vision and digital twins in industrial facilities to determine the possibility of imperfections without human interference. The efforts were made to support Industry 4.0, specifically in terms of efficiency, quality, and costs within production chains. Asrol (2024) also performed excellently in establishing the urgency of Industry 4.0 in supply chains and identifying how mechatronics enabled companies to move seamlessly to digital manufacturing environments. This incorporation of mechatronic systems into organizational automatism has become vital for organizations as conveyance processes and supply channels become more volatile. Another real-world method reported by Costa et al. (2022) was the recycling of decommissioned robots to perform a plastic injection manufacturing workflow in order to reduce reliance on manual labor and increase the usage and helpful life of industrial tools. The reusability is consistent with the Industry 4.0 concept aiming to produce sustainable manufacturing processes that consume minimal resources (Hultman, 2022).

Some studies combined digital simulation models, such as digital twin methods with smart manufacturing systems, which include AI, big data, or robotics during the automation line (Bendowska and Zawadzki, 2023; Xie, 2023). For example, a smart factory laboratory that was capable of obtaining high-performance assembly times was designed and implemented for Poznań University (Bendowska and Zawadzki, 2023). The system allowed proper supervision, analysis, and control of different tasks during the production process associated with different types of plastic blocks. Moreover, Chen et al. (2008) proposed an intelligent robotic system to load wheels into a wheel hub. The system used vision, force, and position sensors to track and assemble moving objects on a conveyor belt. Another study by Lee et al. (2018) controlled and compared a delta robot and manipulator robots for an automation line process that included engraving, visual inspection, as well as pick and place tasks.

Newer developments in vision systems, control methods, and AI have made the mechatronic systems accurate and flexible in their operations (Ma'ruf et al., 2024). For example, Li et al. (2024) proposed a gray-scale matching method to join liquid crystal display (LCD) TV diffuser plates. The system enhanced precision and accuracy while minimizing errors and was considered preferable for sizeable electronic manufacturing requiring high accuracy levels. Furthermore, Dimény and Koltai (2023) adopted mathematical models of MILP and CP to assign tasks performed in hybrid assembly lines using humans and robots. It was evident that human-robot collaboration was important in ensuring efficiency and quality in delivering the products at the correct cost. The trend was observed with due consideration for different industries, such as automotive and electronics, to strike a balance between the cost of production and quality.

The Petri net model and genetic algorithm-based was presented by Pires et al. (2022) for scheduling of Automated Guided Vehicles (AGVs) in no-buffer assembly lines in order to achieve high efficiency in obstacle detection applications. Giberti et al. (2022) also simplified programming for collaborative robots using methods such as Interactive Refinement Programming (IRP). The results showed that non-experts could configure collaborative robots in small-scale production environments in a fast manner.

The workflow organization of assembly lines has been examined thoroughly for optimized collaboration between humans and co-bots. For example, Chutima (2023) analyzed interventions for human-robot interaction based on human, robot, and organizational factors associated with assembly lines including the environment and material arrangements. Neitmann et al. (2022) also used mobile units with assembly jigs using a smart system compensation that allowed mounting parts in airplanes. These studies showed different advantages of using robots on assembly lines, such as higher output, better quality, and greater adaptability in addition to the reduction of the need for human work and stabilization of the economy.

Academic works related to assembly lines with robots led to the development of several automation architectures based on PLC to control welding guns, pneumatic actuators, servomotors, hydro pump systems, and others (Osejo Sornoza and Berrú Pontón, 2020; Tigse Soto, 2017; Paucar Tenorio and Quinllay Ramos, 2014). The studies can potentially benefit educational centers, industries, companies, and universities by providing an economical and accessible solution to improve the quality of teaching in industrial robotics.

Mechatronic systems are advantageous but cost and resource prerequisites are identified as the main limitation for large-scale applications, particularly in educational settings and small-to-medium-sized businesses. From the industrial perspective, consideration of the economic feasibility of applying robotics is an important factor. Jupir et al. (2023) claimed that effective project management and coordination required attention to resources related to the implementation of systems and interaction with stakeholders.

This study focused on the need to incorporate mechatronics in teaching and practice to train students for intricate automation practices. The trend is associated with the usefulness of delta robots where increased speed and accuracy are required and manipulators in a functional larger working area. In this case, appropriate robots, sensors, and actuators need to be determined to meet the most production objectives. Mechatronics can assist learners and professionals in understanding the natural world and connect theoretical knowledge with practical methods of setting up flexible assembly lines for accomplishing particular production aims.

1.2. Main Contribution

The study gap identified is the absence of low-cost automated assembly line systems considered affordable to educational and small-scale industrial establishments. Therefore, the latest automated systems such as high-speed delta and collaborative robots were discussed with a focus on applications from large-scale manufacturing contexts. Certain limited solutions were observed to address the question of achieving affordability with reasonable performance capability. This study adds a blend of a 2D Cartesian robot and a pneumatic gripper, under the control of a PLC with wireless human-machine interface (HMI), which is viable for training, as well as low-capacity industrial applications. The system differs from the commercial systems which are often too expensive or too complicated to implement in educational settings or small businesses. A detailed explanation of the contributions of this study is presented as follows:

- Innovative Integration of 2D Cartesian Robot and Pneumatic Gripper: A Cartesian robot that uses a 2D Cartesian robot coupled with a pneumatic gripper and an automated conveyor belt managed by a PLC. The purpose is to produce a highly accurate, universally applicable, and affordable system for industrial handling allowing for small, contained automation solutions in between large systems.
- Robust Wireless Communication Setup: The wireless connection between the PLC and HMI, including optocouplers and operational amplifiers, assists in ensuring a stable and interferences-resistant communication of the system, necessary for industrial applications.
- Accessible, Educational Mechatronic Platform: This affordable industrial automation line provides a viable solution for industrial automation and robotics education and training, where

complex advanced Robotic handling and control theories can be taught and understood by students and practitioners.

1.3. Outline

The remaining aspects of this study include Section 2 used which is used to explain the control and structure assembly such as the system architecture, control mechanisms, and communication between components. Meanwhile, Section 3 describes the system assembly and initial functional tests. Section 4 provides information on system validation and the results. Section 5 shows the cost analysis of the machine and the comparison with similar machines in the market and the conclusions are presented in Section 6.

2. Control and Structure Assembly

The prototype was proposed to be integrated into an assembly line to produce polylactic acid (PLA) plastic models for general use, such as toys, tools, components of more complex mechanisms, and other consumer or industrial products. The design offers a solution to automate the repetitive task of assembling two PLA pieces, male and female, with subsequent classification based on color. The system receives, transports, and locks a male piece with its corresponding female counterpart.

2.1. System Architecture

The proposed design consists of a conveyor belt, a 2D robotic arm with a pneumatic gripper attached, a control platform where the operator can interact with the machine, and two platforms on each side of the belt to store the female pieces waiting for assembly. The design picks and places circular, square, and octagonal male pieces of two colors into the female counterparts.

The joint 2D robotic arm and the pneumatic gripper were selected due to the advantages of both configurations. For example, cartesian robots moved in straight lines rather than relying on rotational motion (Zhang Bin and Editors, 2017). This linear movement along the two axes offered precise control and predictable paths, making cartesian robots ideal for tasks that demanded high accuracy and straight-line travel, such as assembly and pick-and-place operations. Moreover, Cartesian robots are easy to assemble using commercial guides and bearings on the market and this leads to scalability feasible for a low-cost robot (Rubenstein et al., 2014). Pneumatic grippers offer several advantages in industrial automation which is the reason for the high popularity in handling tasks. Birglen and Schlicht (2018) validated that electronic grippers had better precision and force control in addition to the ease of having a sensor depending on the application. However, pneumatic grippers are lightweight and compact and this leads to cheaper cost and consideration as ideal for a low-cost machine. The application of an appropriate shape can allow the modification of grippers to hold different objects (Cui et al., 2021).

Figure 1 shows a simplified machine operation diagram where the user places the male piece on the conveyor belt for subsequent transportation down to reach the color sensor to identify and store the color in memory. The male piece continues through the conveyor belt until it reaches the presence sensor when it is stopped and the robotic arm is activated. The information obtained from the presence sensor allows the gripper of the arm to move into position and graze the piece. The last stage is for the gripper to lift and transport the piece to the platform containing the female counterpart for the joining process to occur. The gripper releases the piece and moves to its resting position until another part has reached the presence sensor.

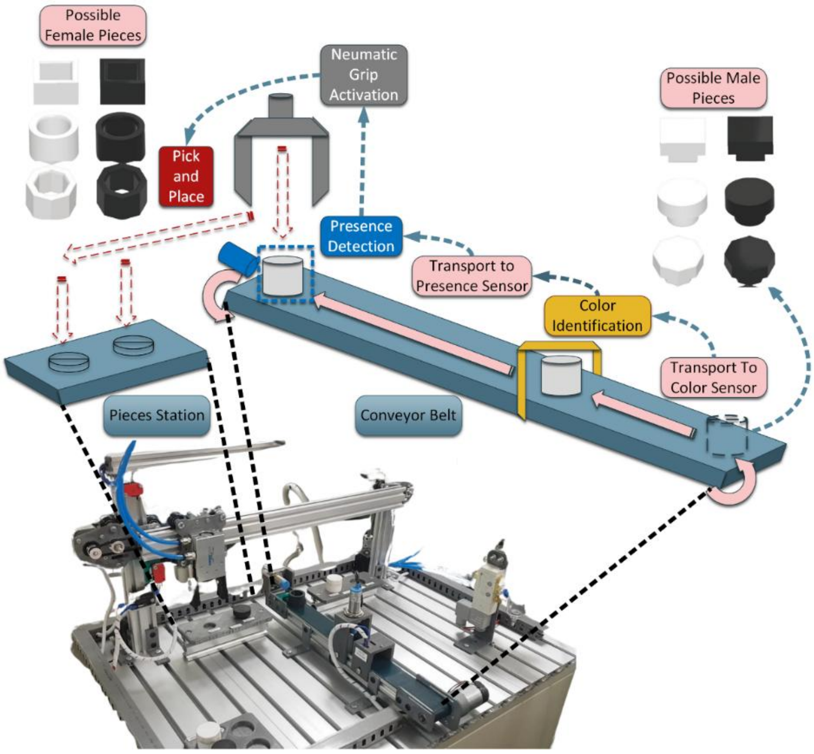


Figure 1 General Sequence of the Proposed Assembly Process

2.1.1. Motor requirements and sizing

This subsection estimated the torques the cartesian robot motors required in the X- and Z-axes. Moreover, the Y-axis of the machine corresponded to the conveyor belt, and the torque was analyzed to determine the size of the motor moving the objects. The torque related to the X-axis movement was evaluated using the transmission mechanism of the pulley and belt. The process required determining the force produced at the beginning of the transmission system using the following Equation 1:

$$F_{X-axis} = N \cdot \left(\frac{v^2}{2 \cdot d \cdot g} + u_K \right), \tag{1}$$

Where, N is the normal force to the X-axis 4.37 N, v is the approximate travel speed 50 mm/s, d is the pulley center distance 500 mm, g is the gravity 9.81 m/s^2, and u_k is the friction factor between guide wheels and the aluminum profile 0.31.

The minimal force required to move the cartesian robot on the X-axis was 1.35 N. This value was used in addition to the radius of the pulley r set at 6 mm to estimate the torque $T_{x\text{-axis}}$ as 0.008 Nm. The calculation was further used to select a NEMA 17 motor with a torque of 0.5 Nm considered sufficient to produce the horizontal movement.

The torque for the movement in the vertical direction of the cartesian robot, Z-axis, was estimated using the force of the power screws. This study used a power screw with an 8 mm diameter (*d*), a pitch of 2 mm (*p*), and a feed rate of 8 mm per revolution (*fr*).

The upward movement of the cartesian robot requires the power screw to surpass the weight of the beam with all its components (1.71 kg) and the weight of the pneumatic gripper (0.236 kg). Therefore, the minimum force required was determined using the following Equation (2):

$$F_{Z-axis} = (beam + pneumatic\,gripper) \cdot g. \tag{2}$$

The total force to move the cartesian robot in the vertical direction was $F_{Z\text{-}axis}$= 19.09 N which was divided into two because the proposed system had two actuators on the Z-axis, including one power screw per column of the robot. This led to the estimation of the torque for each power screw using Equation (3):

$$T_{z-axis} = \frac{F_{Z-axis} \cdot D_m}{2} \cdot \frac{l + \pi \cdot f \cdot D_m}{\pi \cdot D_m - f \cdot l} + \frac{F_{Z-axis} \cdot f_c \cdot d_c}{2}, \tag{3}$$

Where, $F_{Z\text{-}axis}/2$ is the lifting load 9.54 N, D_m is the average diameter = $d - p/2$ = 7 mm, d_c is the nut diameter = 22 mm, f is the screw friction coefficient 0.19, and f_c is the coefficient of friction of the nut 0.08. The results from Equation (3) show that the minimum torque required $T_{z\text{-}axis}$ was 0.028 Nm. This showed that a NEMA 17 motor with a torque of 0.5 Nm satisfied the movement requirements in the Z-axis.

Another motor was needed to move the pieces on the conveyor belt on the Y-axis. This led to the determination of the minimum force required to move the belt through three main aspects, including the need for the motor to move the weight of the belt, the rollers, and the pieces.

The power required by the motor to move the conveyor belt depended on several aspects. First, the force required by the conveyor belt to carry was calculated using the weights of a female piece and the PVC belt as follows:

- Female pieces characteristics:
  - Transport piece mass = 18.27 g.
  - Transport weight = 0.01827kg . 9.81 m/s^2 = 0.18 N.
- Belt characteristics:
  - Belt weight= 2.5 kg/m^2.
  - Belt width = 38 mm.
  - Belt length = 0.794 m.

The characteristics of the belt were used to determine the total area which was subsequently used to calculate the total weight as 0.76 N. Moreover, the friction and stretching forces required to be overcome by the belt to produce the movement were calculated using Equations (4) and (5), respectively:

$$f_r = \mu \cdot m \cdot g, \tag{4}$$

Where, μ is the friction factor 0.25, m is the transport mass 0.093 kg, and g is the gravity 9.81 m/s^2. Therefore, the value of the friction force was found to be f_r = 0.22 N.

The elongation force for the belt at 1% stretch is 8 N/mm according to the manufacturer. The belt length was 0.794 m and 1% of the length was 0.00794 m ≈ 7.94 mm. Therefore, the stretching force was calculated using the following Equation (5):

$$F_e = 8\ N / mm \cdot 7.94\ mm = 63.52\ N. \tag{5}$$

The total load on the system was determined by adding the values of the forces as follows:

$$F_t = 0.18 + 0.76 + 0.22 + 63.52 = 64.64\ \text{N}. \tag{6}$$

The travel speed v was 10 mm/s and this showed that the power required was $P = F_t \cdot v$ = 6.464 w. Moreover, the consideration of 10% losses showed that the real power P was 7.11 w.

The torque necessary to rotate at a speed of 10 mm/s with a radius of gyration of 9 mm of the drum was used to determine the angular speed as 110 rpm (11.51 rad/s). Therefore, the necessary torque was $T_{y\text{-}axis}$ = 7.11 w/ (11.51 rad/s) = 0.618 Nm which led to the selection of a Pololu-type 37D motor with power specifications of 10 w and a torque of 0.98 Nm.

2.2. Control and Communication of System Components

The control system of the prototype was managed by electronic components that received information from different sensors of the machine to execute tasks properly. The following subsections explain the electronic components used, their communication protocols, and the control system. Moreover, the algorithm followed by the machine during its operation is presented in Algorithm 1.

2.2.1. Electronic Components

Electronic components were used in the prototype to effectively control the mechanical parts during the execution of tasks. The system was managed by a PLC as the central core. Two drivers were connected to the PLC for the purpose of providing control to the 2D cartesian robotic arm equipped with the pneumatic gripper. The other components connected were the presence sensors and limit switches to provide boundaries to the movement of the conveyor belt and the robotic arm. Another critical component connected was the ESP-32 controller and the primary function was to regulate the DC motor of the conveyor belt and the color sensor. Meanwhile, the PLC was connected to the HMI screen in order to provide essential information about the status of the machine and the current task for the operator. The entire system is internet-connected through a router in order to enable remote access and management. Figure 2 shows the connection of all electronic parts used in the model while Figure 3 summarizes the electronic hardware and the main specifications.

Algorithm 1 Functionality of the System

Algorithm 1: Functionality of the System

1. Start Initialization:
- Power up and perform self-checks on all sensors, actuators, lights, buttons, and communications links.
- Activate the conveyor belt to start transporting pieces.

2. Part Detection and Assessment:
- Use sensors to detect the presence and color of pieces at the entry point.
- If a piece meets predefined color criteria, signal the system to continue, otherwise, reject the piece

3. Positioning for Pick-Up:
- Conveyor moves the piece to a designated pick-up position and stops.
- System ensures the piece is stable and ready for handling.

4. Gripper Engagement:
- Activate the robotic gripper to align with and descend
- Close the gripper to grasp the piece securely.

5. Lifting and Transporting Part:
- Lift the piece off the conveyor and transport it to a specified placement location using a predetermined path.
- Use motion control to ensure smooth and precise handling.

6. Placement of Part:
- Lower the gripper to the placement position and release the piece onto its designated spot.
- Retract the gripper and clear the area for the next operation.

7. Conveyor Reactivation and Part Queue Management:
- Reactivate the conveyor to position the next piece.
- Check for the presence of additional pieces and loop the process if necessary.

8. End of Cycle Check:
- If no further pieces are detected, initiate cleanup and prepare for shutdown.
- Perform any final system checks and reset configurations.

9. System Shutdown:
- Power down all components safely.

2.2.2. Communication

The communication interfaces for each system component are shown in Figure 4a). It was observed that each part of the machine interacted with the remaining system during the execution of tasks as follows:

- The machine connects to the Internet via an Ethernet connection between the Router and the Siemens PLC. A second Ethernet cable connects the PLC with the HMI Screen to allow user interaction and monitoring. This communication assigns an IP address to each component and provides a secure and well-performing bus to interchange data and information about the execution of tasks. On the control side, the PLC communicates with the ESP-32 Controller via Wi-Fi. The method is highly efficient despite its potential unreliability for long-distance communication because the PLC is in close proximity to the EPS-32 controller. The proximity enables fast data exchange from the color sensor and the DC motor moving the conveyor belt without generating incorrect data.
- The limit and presence sensors are important in detecting the presence of objects or movement boundaries within different components and are directly interfaced with the PLC. These sensors transmit essential information, which the PLC processes and translates into commands. The commands are subsequently relayed to the motors of the robotic arm and the pneumatic gripper, both directly controlled by the PLC.

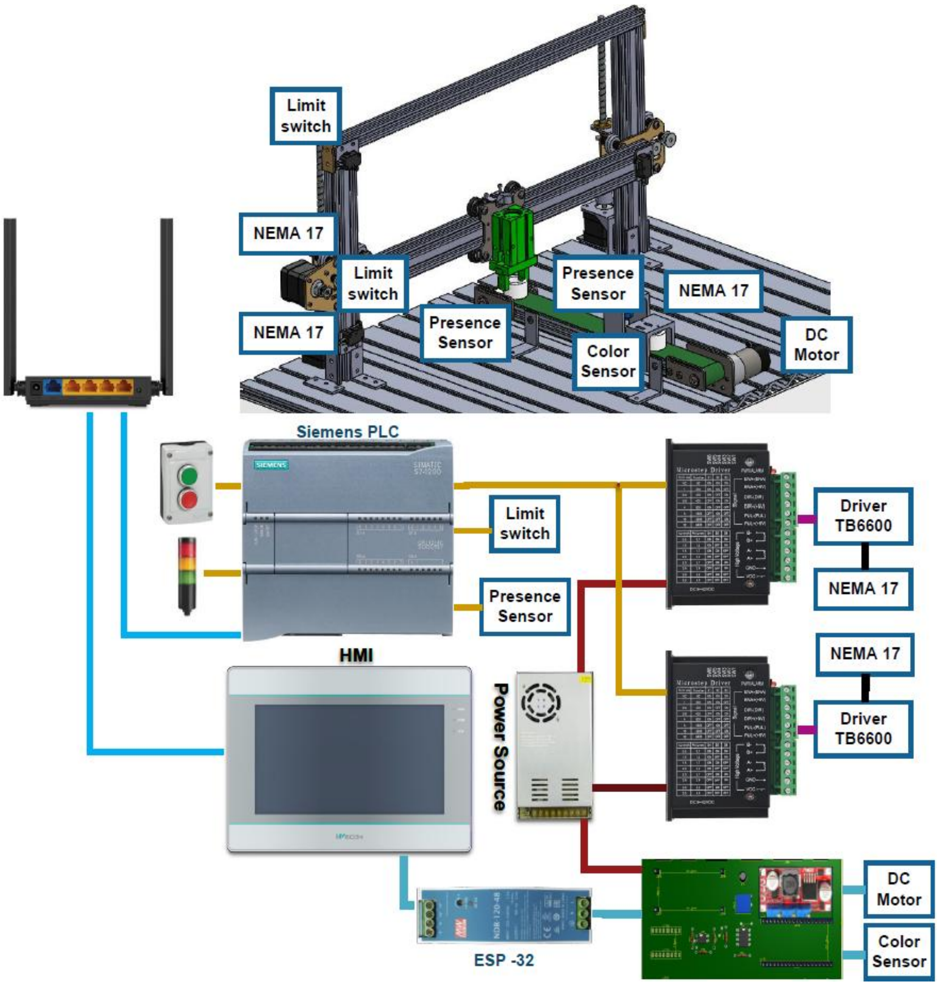


Figure 2 Prototype's Electronic Diagram for Control, Actuators and Sensors

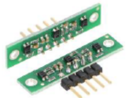
PLC	HMI Screen	Microcontroller	Solenoid Valve	Pneumatic Actuator	Limit Switch	Presence Sensor	Driver for Stepper Motors
SIMATIC S7-1200	HMI WECON 7" IG-O	ESP32 Module	Solenoid valve 5/2	P1-32 Pneumatic Gripper	Microswitch	M12 Capacitive Proximity Sensor	Driver TB6600
							
CPU 1214C, compact CPU, DC/DC/DC, onboard I/O: 14 DI 24 V DC; 10 DO 24 V DC; 2 AI 0-10 V DC, power supply: DC 20.4-28.8 V DC, program/data memory 150 KB	uCPU A35 1.2GHz, 128M Flash, 128M DDRAM uDisplay:7 inches; Resolution: 800*480; Display colour: 16,000k colours	USB Type C, 38 Pins, Dual Core Microcontroller, WIFI, Bluetooth, RF Filter AMP AP STA for Arduino IDE, 38 Pin, 2.4 GHz	5/2-double solenoid-valve, 1/4" NPT, full stainless steel A4	MHZ2 Series Parallel Type Air Gripper Standard 2 Finger Gauge 6/10/16/20/32/40mm Open/Close 4/6/10/14/22/30mm Double Acting Parallel	16A 250V 125V SPST 4.8mm Width 2Pins NO Normally Open 16mm 52mm Arc Roller Lever Touch Switch Microswitch	Switch Shield Type LJC12A3-2-Z/BY Detector 1-2mm 10-30VDC 200mA PNP Normally Open (NO) 3 Wires	4A 9 -42V Nema 17 Stepper Motor Driver CNC Controller Single Phase Hybrid Stepper Motor for CNC42 57 86 Stepper Motor
Colour Sensor	**Stepper Motors**	**DC Motor with Encoder**	**Relay**	**Driver for DC Motor**	**Power Supply**	**Control Power Supply**	**Pneumatic Maintenance Unit**
QTR-3A Reflectance Sensor Array	Motor NEMA 17 42HS48-2504	Metal Gearmotor 37Dx70L	Relay OMRON MK2P-I MK2P	VNH5019 Motor Driver Carrier	Power Supply 12V 240W 20A	85-264V/24VDC 2.50A 60W	8Fr+l Ac3010-02a 1/4 Sns Pneumatic
							
Voltage: 5.0 V. Supply current: 50 mA. Output format: 3 analogue voltages. Output voltage range: 0V at supplied voltage. Detection distance: 0.125" (3mm).	Nema 17 Stepper Motor 48mm 2.5A 0.5NM 71oz.in 42HS48-2504 1.8 Degree 4-Lead Nema17 Staple Motor for 3D Printer Shaft diameter: 5mm	Gear ratio: 50:1 Speed @ 6V: 100 rpm1 Current@6V: 2500 mA Torque@6V: 85 oz·in1 Lead length: 11 in 12V with 64 CPR Encoder (Helical Pinion)	8 Pin Round Power Relay Coil Voltage: 24VDC With LED Indicator Standard Certification: UL Listed, CUL, TUV & CE Approved Weight: 70g	Motor channels: 2 Voltage: 5.5 V -16 V Output current per channel: 14 A – 30A Parallel current: 25 A 0.13 V/A Max PWM frequency: 20 kHz	Input: 110V/220V 60Hz Output:12V/240W/20A	Universal AC 1ph input of 85~264V AC 47~63 Hz or 120~370V DC. Power rating of 60W. Output voltage of 24V DC. Current rating of 2.5A.	Clapboard: with Clapboard Filter Number: 32 Medium Material: Nylon Mesh Efficiency: F9 Filtration Grade: Medium Filter

Figure 3 Electronic components used

2.2.3. Conveyor Belt Control

The proposed system presented in Figure 4b) allows the control of speed movement for the conveyor belt by the operator before the execution of tasks. The desired speed parameter is received as input and generates an output speed value using the data provided by the DC motor controller, its driver, and the motor. Meanwhile, error is provided as feedback to the system in order to decrease the difference between the actual and set speed.

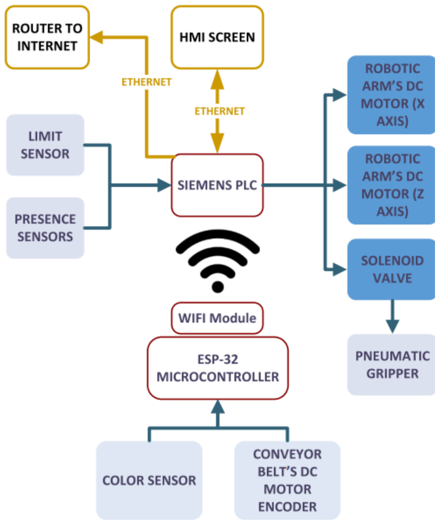
The Proportional–Integral–Derivative (PID) controller of the conveyor belt was tuned in steps by combining the Ziegler-Nichols method and the TIA PORTAL environment as well as the theoretical direction and empirical fine-tuning of the control system. The first aspect was to use the Ziegler-Nichols method to set up the baseline values of the parameters. The proportional gain (Ku=0.08) and proportional time (Tu=4) were determined by turning the controller into proportional-only control and increasing the gain up to the period oscillations were continuous. These values were applied to calculate the initial PID parameters, including Proportional Gain (Kp): 0.6×Ku, Integral Time (Ti): 0.5×Tu, and Derivative Time (Td): 0.125×Tu which were subsequently used to fine-tune under TIA PORTAL.

The software enabled the setting of the control parameters such as the process, output, and PWM limit while the default values of the proportional gain time constant and derivative action time were assigned. The process further allowed fine-tuning using real-time responses to the system in order to determine a critical damping factor as well as the little overshoot and undershoot. The empirical tuning process was achieved by setting the controller values as follows:

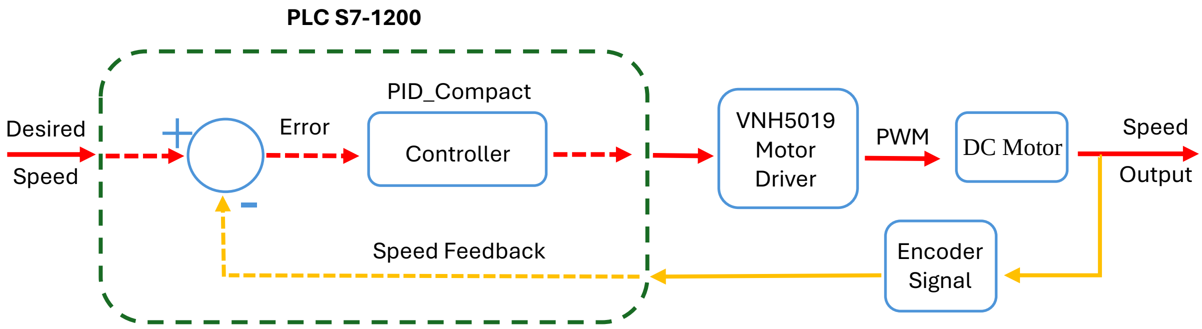
• **Proportional gain:** 0.05
• **Integral action Time:** 2.2
• **Derivative action time:** 0.1

These final tuning values provided a satisfactory and critically damped response which offered an acceptable degree between response and stability. The values were also assessed for further accuracy under different load levels to allow the parameters to work optimally.

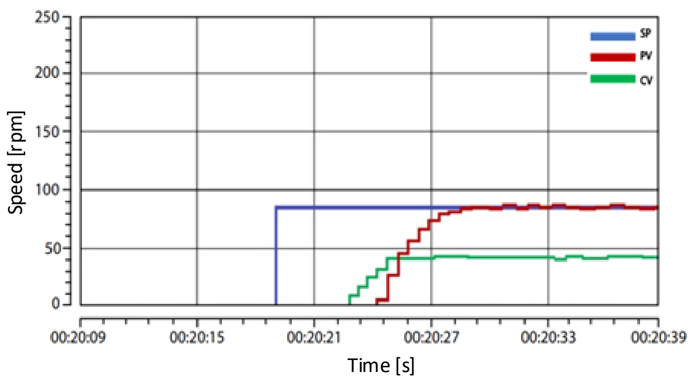
The control system developed in Figure 4 c) shows the control curve of the conveyor belt and the performance tests in terms of the response to the Cartesian robot. The graph shows the critically damped response of the system which is characterized by the absence of both overshoot and undershoot. The process variable (PV) closely tracks the setpoint (SP) to precise and efficient response of the system to varying operating conditions. Meanwhile, the control variable (CV) refers to the parameter adjusted to influence the behavior of the PV to ensure it remains as close as possible to the desired SP. The CV is the output signal from the PID controller and the critically damped behavior shows that the control parameters have been properly tuned. The trend further presents the stability and precision achieved in the implementation of the mechatronic system. The figure also shows the real-time control plot as visualized on the HMI screen.



a)



b)



c)

Figure 4 a) General communications connections, b) Conveyor belt close loop control, and c) Conveyor belt control, showing the established setpoint (SP), the process variable (PV), and the control variable (CV)

Table 1 presents information on the characteristic parameters of the conveyor belt control curve measured empirically using a stopwatch. The settling time is the period necessary for the PV to reach and maintain its reference value (SP) within an acceptable range. The response or rise time represents how quickly the system reaches 90\% of the total variation from its initial position to stabilization. The absence of overshoot and undershoot is the precision of the response provided by the system. Meanwhile, the peak time represents the instant at which the maximum value of the response is reached. These empirical values provide a quantitative assessment of control performance on the conveyor belt.

3. System Assembly and Initial Functional Tests

The definition of the entire design of the machine and selection of the required components were followed by the cutting of the structural profiles and assemblage of the machine. The entire assembly process of the structure and connections of the components were developed in-house to form the line presented in Figure 5.

The system incorporates physical control elements, including buttons for start, stop, and emergency, along with stop and start indicator lights and messages, to ensure effective management by the user. The following video https://youtu.be/9Jm9xLJmX5U shows a complete cycle to produce the ensemble of male and female parts in order to have a better understanding of the system sequence.

The female and male pieces can be white or black and this shows the possibility of two positions in the male section, including one for black and another for white. Figure 6 a) shows that the first step of the process is to place the male pieces in their respective station. Moreover, the entrance of the conveyor belt was unidirectional, and nominal speed was used for the transport of female pieces as presented in Figures 6 b) and c). The color sensor QTR-3A, which is an infrared reflectance sensor array, detects the color of the female piece entering the conveyor belt. This is necessary to ensure the Cartesian robot selects a male piece of the same color as shown in Figure 6 d). The Cartesian robot subsequently transported and placed the male piece on top of the female located at the end of the conveyor belt, as presented in Figure 6 e). The male-female assembly was also transported to the exit station as shown in Figure 6 f).

Table 1 Specification for Time Domain

Variable	Value
Settling Time	9.1s
Rise Time	3.4s
Overshoot	0%

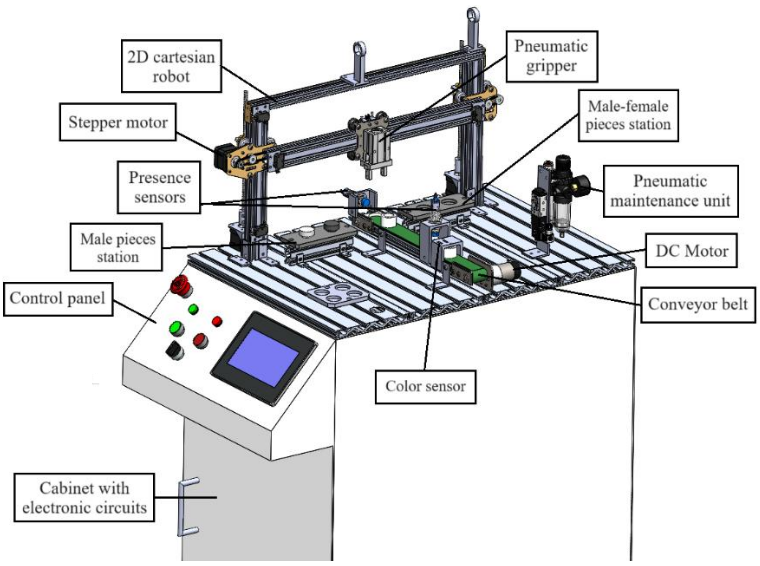


Figure 5 CAD and main components of the prototype

In terms of mechanical design, a Cartesian robot was implemented to stack the male and female pieces, and the final effect was achieved using a pneumatic gripper for precise manipulation. The Cartesian robot used NEMA 17 motors and limit switches to operate. Moreover, the inclusion of capacitive position sensors on the conveyor belt assisted in detecting when a piece arrived at the color detection module and the moment it reached the end. The module had a graphical user interface (HMI) that provided informative messages about the process, control of variables, and visualization of the manipulation. Furthermore, the variability in the color of female pieces was considered and addressed in the design to ensure accurate detection. The module also satisfied maximum dimensions of 750x350x700 millimeters, leading to the integration into the pneumatic maintenance unit and equipped with quick couplings to connect to the compressed air system. This was necessary to ensure efficient operation and easy maintenance.

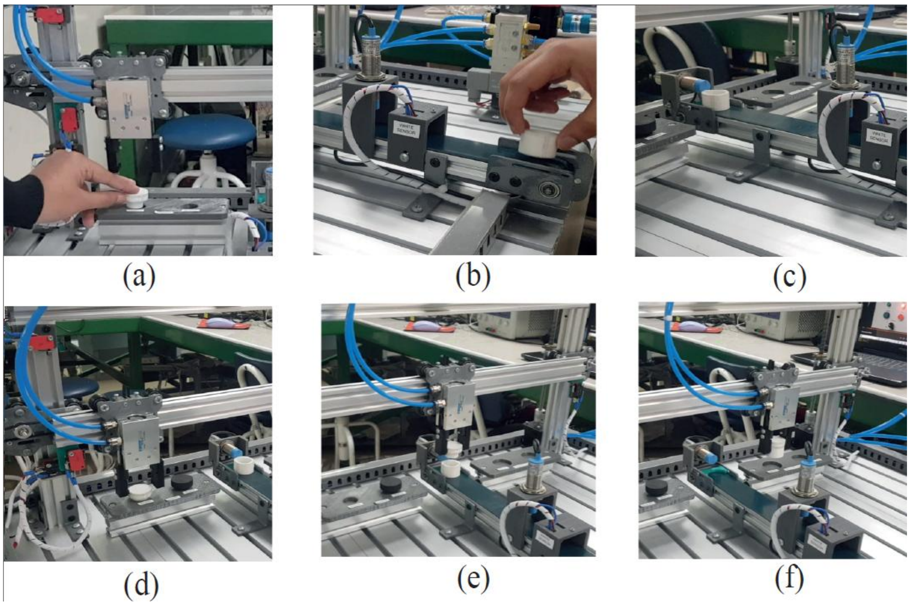


Figure 6 Operating process: (a) Placing white and black male pieces on the station, (b) placing a female piece at the entrance of the conveyor belt, (c) female piece reaches the end of the conveyor belt, (d) gripper picks up the male piece of the same color to be inserted into the female piece, (e) robot places the male piece on top of the female, and (f) the robot takes the set to the exit station

4. System Validation and Results

Experiments were conducted in controlled laboratory conditions to verify the functionality of the prototype towards ensuring consistent and reliable performance. The focus was on the capacity of the system to classify two colors, black and white, as well as three distinct plastic forms, including circular, square, and octagonal shapes. This was in addition to the corresponding female counterparts at three speeds of the conveyor belt, including 40 RPM, 80 RPM, and 120 RPM. The detailed list of the parameters and conditions used during the tests is stated as follows.

- Ten tests were conducted for each shape and speed to have a total of 180 runs.
- The tests were conducted in a stable environment with the ambient temperatures controlled at approximately 22°C to minimize the impact of environmental variability on the sensors and mechanical components.
- The workspace was uniformly illuminated to ensure fluctuating light levels on the prototype sensors did not affect color detection.
- The calibration of sensors as well as mechanical and electronic components were monitored and maintained to ensure the only variables used were shape, color, and speed.

The results were uniform throughout multiple experiments for each condition and this showed minimal to negligible fluctuation in completion times and sensor activations. Moreover, all discrepancies, including sensor inactivation or missing classifications, were documented. The results presented in Table 2 showed that the system attained a success rate of 100% for circular shapes in all test iterations. The trend showed the stability and reliability of the system at each evaluated speed.

Table 2 Validation Test Results

Speed	Presence Sensor 1	Presence Sensor 2	Infrared Sensor	Avr. Completion Time	Finished Tasks
			White Circle		
40	10/10	10/10	10/10	29.41	10/10
80	10/10	10/10	10/10	25.50	10/10
120	10/10	10/10	10/10	24.24	10/10
			Black Circle		
40	10/10	10/10	10/10	30.46	10/10
80	10/10	10/10	10/10	26.05	10/10
120	10/10	10/10	10/10	25.25	10/10
			White Square		
40	10/10	9/10	10/10	30.03	9/10
80	10/10	5/10	10/10	26.05	5/10
120	10/10	5/10	10/10	24.53	5/10
			Black Square		
40	10/10	8/10	10/10	30.54	8/10
80	10/10	8/10	10/10	26.42	8/10
120	10/10	9/10	10/10	25.33	9/10
			White Octagon		
40	10/10	10/10	10/10	29.46	10/10
80	10/10	9/10	10/10	25.59	9/10
120	10/10	10/10	10/10	24.28	10/10
			Black Octagon		
40	10/10	10/10	10/10	31.42	10/10
80	10/10	10/10	10/10	26.63	10/10
120	10/10	10/10	10/10	25.37	10/10

The variance in completion time for the tests performed was determined through the application of boxplots as shown in Figure 7. Each boxplot corresponds to the completion time of each shape for a specific speed and color. Moreover, the shape of the pieces was a common factor for all speeds tested. Circular pieces required less completion time than the other two variants, without considering the color, due to the mechanical design of the gripper. The circular shape ensured an easier grasp of the piece while the corners in the other two led to some difficulty in picking which caused longer completion times.

The results for the 80 RPM presented in Figures 7c) and d) showed that a faster conveyor belt led to lower completion times as expected. For this case, white pieces required less time to complete than black and the candles showed that most of the tests were conducted at times considered lower than average.

The plots in Figures 7 e) and f) show the results for the fastest speed of 120 RPM and the completion time decreased but was less than the previous test. The circular shape achieved the shortest time of all tests by finishing the assembly in 24.14 seconds. The white square pieces also produced errors on five tests because one of the presence sensors did not activate and the task was not completed. Only 17 out of the 180 tests were not completed due to the inactivation of the second presence sensor. This problem manifested mainly in the square and octagonal shapes while the circular shapes did not experience any difficulty.

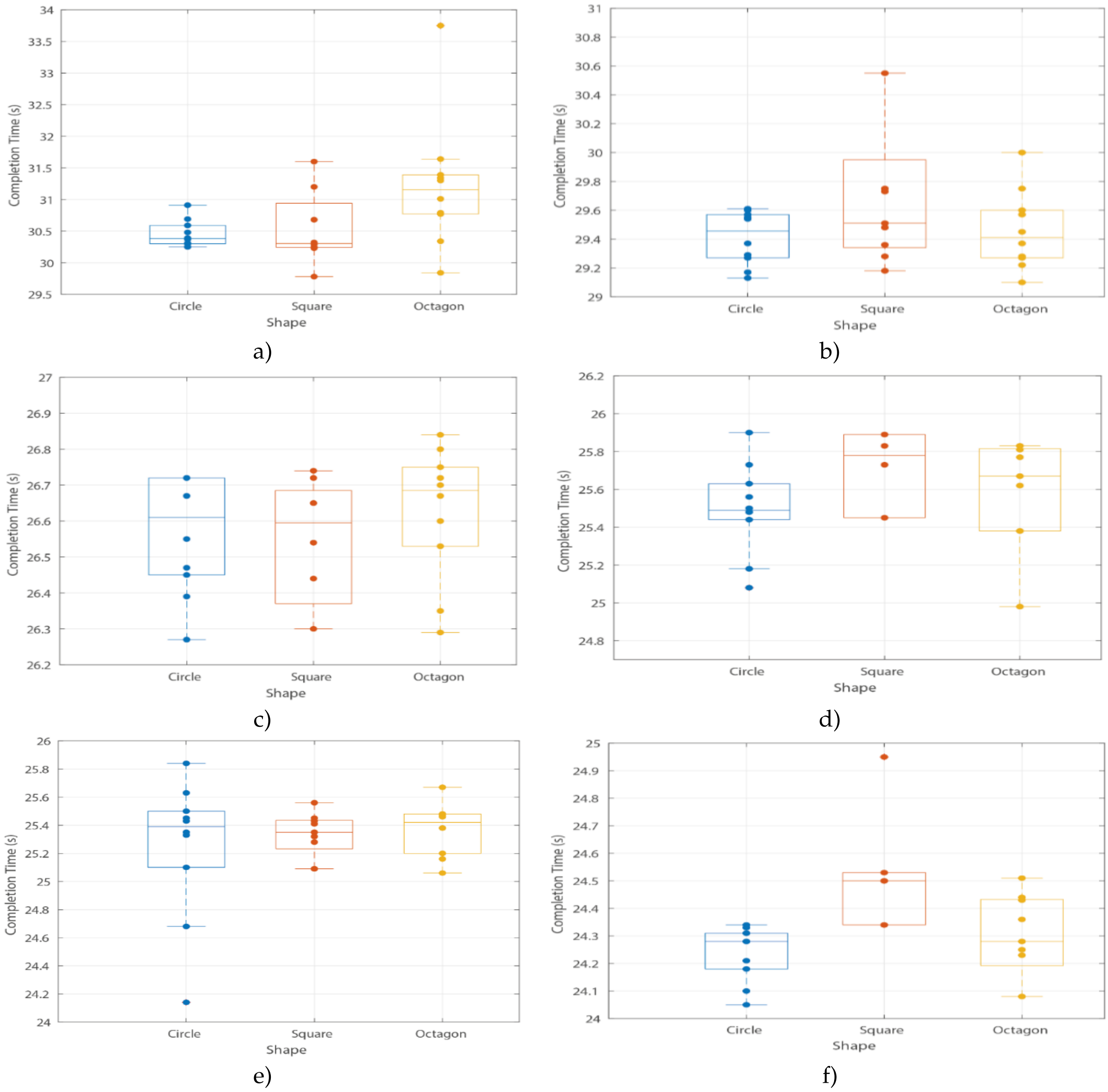
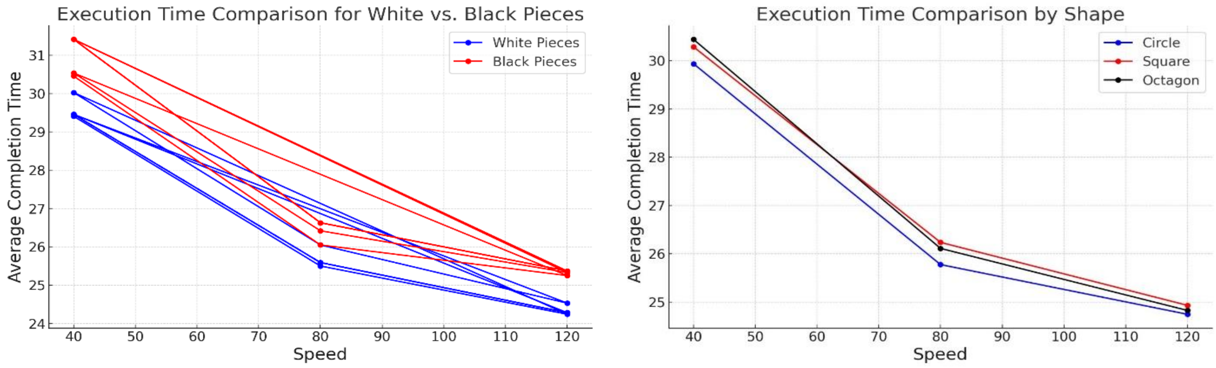


Figure 7 a) Results for 40 RPM speed - Black Pieces, b) Results for 40 RPM speed - White Pieces, c) Results for 80 RPM speed - Black Pieces, d) Results for 80 RPM speed - White Pieces, e) Results for 120 RPM speed - Black Pieces, and f) Results for 120 RPM speed - White Pieces

The module achieved a remarkable 100% accuracy rate in operational tests. The conveyor belt showed a severely damped control curve which led to excellent precision and stability in assembly line operations. The ability of the module to assemble an average of two pieces per minute was an indication of its high efficiency which led to optimism about the capacity of the system to satisfy production requirements.

An in-depth analysis was conducted to compare the shape and color with the performance of the machine. Figure 8 provides information on how shape and color affect the system and Figure 8 a) shows how white pieces tend to achieve the task in less time than black pieces. This could be due to the process used to tune the sensors to easily detect lighter colors which led to a faster reaction from the machine. Figure 8 b) shows that a circular shape achieves better completion time than the others. This is due to the ease of grabbing and placing into the female counterparts by the gripper because of the round form. There was no concern about plane sides or inadequate match which in turn could have caused a delay in the overall operation. Circular shapes fit in any position while the slight variation in position of square and octagonal pieces is capable of causing problems.



a) b)

Figure 8 a) Average Completion Time for White and Black Pieces. b) Average Completion Time for Circular, Square, and Octagonal Pieces

5. Machine Cost and Comparison

Table 3 presents the approximate costs associated with the production of the machine, including the materials, mechanical and electronic components, manufacturing, assembly, and design hours. The total expenditure for the machine was USD 3546 and the profit expected from the sales was USD 650 which led to the setting of the final price at USD 4196. The comparison with similar machines in the industry which typically range from $5000 to USD 10000 (*Semi-Automatic Screw Machine/Custom-Made Machinery/ Automatic Assembly Machine*, n.d.) shows the solution proposed offers a significant cost advantage. The specific cost-benefit advantage is approximately 16.08% to 58.04% which represents substantial savings of more than 50% of the cost, thereby showing the value and competitiveness of the machine in the market.

Table 3 Table of costs

Elements	Cost
Mechanical components	USD 850
Electronic components	USD 1820
Structure	USD 320
Working hours	USD 336
Manufacturing Hours	USD 220
Total cost	USD 3546
Expected profit	USD 650
Total sale price	USD 4196

6. Conclusion

In conclusion, the proposed automated assembly machine demonstrated adequate performance due to the benefits of PLC control and ESP32-based communication networks. The PLC system provided precise operational management, ensuring efficient synchronization between the Cartesian robot and conveyor belt, thus enhancing productivity and responsiveness to production variability. Furthermore, the integration of the ESP32 improved system functionality by enabling real-time data exchange and remote monitoring, allowing engineers with immediate access to process insights and data. The testing phase confirmed a remarkable 100% accuracy rate in piece picking and classification. However, increased motor speeds introduced variability in completion times, notably influenced by piece color and shape. At lower speeds (40 RPM), black pieces exhibited lower time dispersion compared to white pieces, although this distinction diminished at higher speeds (80 and 120 RPM), suggesting that sensor identification time could contribute to observed variances. Additionally, the Human-Machine Interface (HMI) significantly enhanced operational usability by providing intuitive, real-time data visualization, fostering informed decision-making, and promoting innovation in automated mechatronic systems. The comprehensive cost analysis underscored the economic viability of the proposed solution, presenting savings between 16.08% and 58.04% compared to commercial alternatives. Future studies should address testing under industrial conditions and extensive use to validate performance and broaden the applicability of this automation system across diverse industrial contexts.

7. Appendix

As a supplementary document to this article, Table S1 summarizes the latest developments in Automated Assembly Lines with Robots. The table emphasizes the identified problems, the methods adopted, the potential weaknesses, and the results.

Acknowledgements

The authors express acknowledgment to Universidad Internacional del Ecuador (UIDE) for providing the resources and support necessary for the completion of this project. The study was also supported by ANID (National Research and Development Agency of Chile) under Fondecyt Iniciación 2024 Grant 11240105.

Author Contributions

Conceptualization, V.M, M.Ma. and J.V.; methodology, V.M. and J.V.; software, M.Ma.; validation, F.A., V.M., and D.P.; formal analysis, V.M., J.V., and D.P.; investigation, M.Ma.; data curation, V.M. and M.Ma; writing—original draft preparation, V.M. and M.Ma.; writing—review and editing, V.M. and D.P.; visualization, M.M. and F.A.; supervision, V.M and M.M. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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