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Modeling and Control of an Automated Paint Mixing System

Thi – Thanh Pham, Thu Thi – Hien Nguyen, Cong – Anh Hoang
[1]*Faculty of Technology and Engineering, Hai phong University, Haiphong, Vietnam*
Corresponding Author: thanhpt85@dhhp.edu.vn

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ABSTRACT: In the context of industrialization and modernization, the application of automation systems in manufacturing has become an inevitable trend to enhance productivity, reduce errors, and ensure product quality. Particularly in the paint industry, the accuracy of mixing ratios and color consistency plays a critical role in determining the quality of the final product. However, in practice, paint mixing processes in many production facilities still rely heavily on manual operations and operator experience, resulting in limited accuracy, low productivity, and difficulties in maintaining consistency across different mixing batches.

Based on these practical requirements, this study focuses on the research, modeling, and development of an automated paint mixing system based on PLC control, integrated with electromechanical and pneumatic components, as well as HMI/SCADA monitoring and control systems. The proposed system is designed to include main processes such as can feeding, filling, cap supplying, capping, and paint mixing. In particular, the color dosing process is implemented using flow sensors and solenoid valves operating according to predefined ratios programmed in the PLC, ensuring high accuracy and repeatability.

Based on the theory of subtractive color mixing using three primary colors (red, yellow, and blue), this study develops a mathematical model and control algorithms for the mixing process, while also designing the hardware architecture and control software structure of the system. The system allows operators to select color codes, adjust mixing ratios, and configure operating modes through an HMI interface, while enabling real-time monitoring and supervision via a SCADA system.

The experimental results demonstrate that the automated paint mixing system operates reliably, meeting requirements in terms of dosing accuracy, color uniformity, and production productivity. The system reduces dependence on manual operations, improves manufacturing efficiency, and offers significant potential for practical industrial applications, particularly for small- and medium-sized manufacturing facilities.

KEYWORDS: Automated paint mixing system, Modeling, PLC-based control, Process control, Industrial automation

I. INTRODUCTION

The rapid advancement of science, technology, and industrial automation has fundamentally transformed traditional manufacturing methods, driving the transition toward intelligent, flexible, and highly efficient production systems. In this context, the paint industry plays a significant role ini in various sectors such as construction, mechanical engineering, automotive manufacturing, and electronics, where the accuracy of color mixing processes and component ratios directly determines product quality, aesthetic properties, and long-term stability.

However, in many production facilities, particularly small- and medium-sized enterprises (SMEs), paint mixing processes still rely primarily on manual operations or operator experience. Such approaches not only reduce mixing accuracy and process repeatability but also lead to inconsistent product quality, low productivity, and a strong dependence on human factors. Moreover, the increasing diversity of color requirements and the growing demand for product customization pose significant challenges to traditional mixing systems.

In recent years, the application of automated control systems based on programmable logic controllers (PLCs), sensors, actuators, and SCADA/HMI monitoring and control platforms has been widely implemented in industrial production lines to enhance precision, operational stability, and automation capability. These systems enable precise dosing control, real-time monitoring of operating conditions, and optimization of production workflows.

Nevertheless, existing research on automated paint mixing systems mainly focuses on hardware implementation and basic logical control, while

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comprehensive studies on dynamic process modeling, system dynamics analysis, and the design of optimal control strategies remain limited. In particular, the interactions among system components, as well as the effects of nonlinearities, disturbances, and measurement errors on mixing quality, have not been fully investigated within a unified theoretical framework.

Motivated by these challenges, this paper proposes an integrated approach to the modeling and control system design of an automated paint mixing system. The study focuses on developing a mathematical model of the mixing process, designing a PLC-based control architecture, integrating HMI/SCADA monitoring systems, and implementing an experimental prototype to evaluate the effectiveness of the proposed control strategies.

The main contributions of this research include: (i) the development of mathematical and functional models for an automated paint mixing system; (ii) the design and implementation of a PLC-based control architecture integrated with sensors and actuators; (iii) the proposal and evaluation of control strategies aimed at improving mixing accuracy, operational stability, and system efficiency; and (iv) experimental validation through a prototype system.

By combining control theory, system modeling, and experimental implementation, this study provides both scientific and practical foundations for the development of automated paint mixing systems and opens opportunities for extending the proposed approach to other material mixing processes in modern industrial applications.

II. THEORETICAL BACKGROUND OF PAINT COLOR AND PAINT MIXING

2.1. Overview of Paint

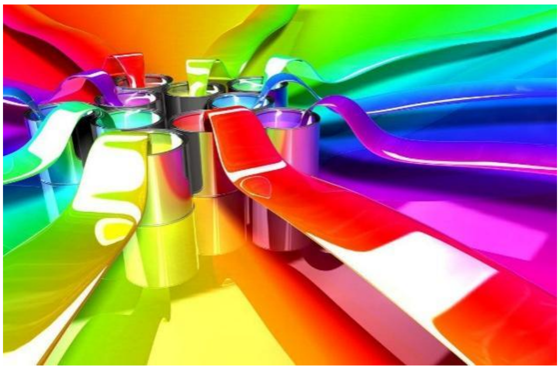

Figure 1. Illustration of Paint

Main Components of Paint

Resins (40% – 60%): Alkyd, Acrylic, Epoxy, Polyurethane, Fluorocarbon.

Provide bonding between paint components

Ensure adhesion of the coating to the substrate

Enhance durability and mechanical strength of the paint film

Pigments (7% – 40%): Primary pigments, extender pigments, anti-corrosion pigments.

Provide color to the paint

Improve hardness and durability of the coating film

Additives (0% – 5%): Substances used to enhance paint performance, including color stability, weather resistance, glossiness, hardness, and covering power, as well as extending storage life and providing special functional properties. Examples include:

Drying agents and surface tension modifiers

Anti-fungal and anti-mold agents

Solvents (10% – 30%): Used to dissolve resins and disperse pigments, helping control viscosity and application properties.

2.2. Paint Manufacturing Technology

The paint manufacturing process is illustrated in Figure 2 :

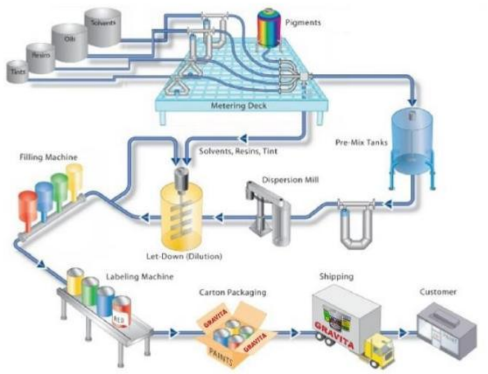

Figure 2. Paint Manufacturing Process

The paint manufacturing process consists of four main stages:

Salt Aging (Premixing/Soaking Stage)

During the salt aging process, raw materials including pigments (metal oxides such as titanium oxide, tin oxide, lead compounds, etc.), fillers ($CaCO_3$, silica, clay, etc.), additives (dispersants, surfactants, foaming agents, etc.), a portion of film-forming binders such as latex resins (vinyl-acrylic, styrene-acrylic), and organic solvents (clean water) are introduced into a premixing tank and stirred at low speed. The materials are allowed to age for several hours to achieve sufficient wetting by the binder and solvent, forming a paste-like mixture suitable for the subsequent grinding stage.

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Paint Grinding (Dispersion Process)
This is the primary stage in water-based paint manufacturing. The aged paste mixture is transferred to a grinding or milling system, where the dispersion process produces a fine and homogeneous liquid suspension. The grinding duration depends on the type of pigments, fillers, and the required fineness of the paint. During this stage, the grinding equipment typically uses cooling water to prevent excessive temperature rise, which could cause solvent evaporation or negatively affect the stability of the paste components. The cooling water is usually maintained at approximately 5–7°C before entering the milling system.
Paint Mixing (Let-Down Process)
Following grinding, the paste is transferred to the mixing stage to produce the final paint formulation. The ground paste is introduced into a mixing tank, where multiple batches may be combined. Continuous agitation is applied to ensure uniform blending. At this stage, additional binders, solvents, and required additives are incorporated into the mixture. Once the desired homogeneity and formulation specifications are achieved, the product is ready for packaging.
Product Packaging
Packaging may be carried out using automated filling lines or manual operations. Water-based paint is typically packaged in plastic or metal containers depending on product specifications. The finished products are then transferred to storage warehouses. Inventory management is conducted according to batch control procedures. Storage facilities must be equipped with appropriate fire protection systems due to the potential fire hazards associated with solvent-based paint products.
In addition, several auxiliary processes are required, such as cleaning paint tanks to ensure product quality, cooling operations to minimize solvent evaporation, and other maintenance procedures.

2.3.Principles of Paint Color Mixing
From an optical perspective, when a beam of white light passes through a prism, it is dispersed into seven spectral colors: red, orange, yellow, green, blue, indigo, and violet. This phenomenon represents the separation of light into different wavelengths. Therefore, in terms of optics, color can fundamentally be understood as a property of light.
The colors perceived by the human eye originate from the reflection of light from objects into the visual system. Different materials absorb and reflect specific wavelengths of light, resulting in the perception of different colors. (Figures 3 and 4).

Figure 3. Color spectrum from red to violet representing the seven colors of the rainbow

Figure 4. Achromatic Color Scale

Fundamental Elements of Color
- *Tone:* The variation in the depth or lightness of a color achieved by mixing it with white or black. Tone describes how a base color changes in shade or tint.
- *Value:* The relative lightness or darkness of a color, representing the visual brightness level and the relationship between different light and dark gradations. For example, within the color spectrum, yellow typically exhibits the highest brightness value, while violet appears darker due to visual perception characteristics.
- *Intensity:* The strength or saturation level of a color, describing how vivid or dull a color appears as perceived by human vision.
Examples:
Yellow — high brightness value
Orange — strong intensity (high visual saturation)

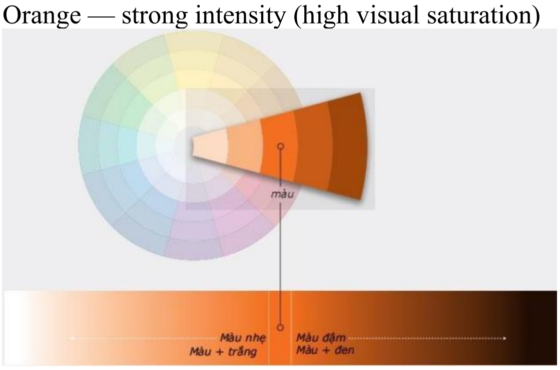


Figure 5. Comparison between Value (Brightness) and Intensity of Two Colors
a. Additive Color Mixing Principle (Figure 6)
The three primary colors of light are red (R), green (G), and blue (B).
Red light combined with green light produces yellow (Y).
Green light combined with blue light produces cyan (C).
Blue light combined with red light produces magenta (M).
Magenta is a color closely related to violet; however, unlike violet, magenta does not exist as a single wavelength within the natural visible spectrum. Instead, it is a perceptual color created by combining red and blue light.

Magenta (M), yellow (Y), and cyan (C) are referred to as secondary colors of light because they are formed by combining two primary light sources.

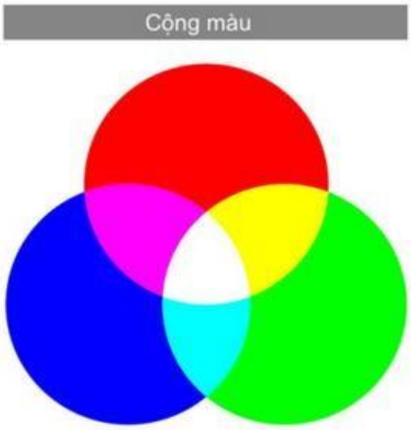


Figure 6. Additive Color Mixing Principle in the RGB Color Model

When all three primary light beams — red (R), green (G), and blue (B) — are combined, white light is produced. This phenomenon is known as additive color mixing.

b. Color Mixing Methods Applied in This Study

Primary color mixing to produce secondary colors

There are three primary pigment colors: red, blue, and yellow. These colors cannot be created by mixing other pigments; however, they can be combined to form secondary colors:

Red + Blue → Purple (Violet)
Blue + Yellow → Green
Red + Yellow → Orange

It should be noted that when primary pigments are mixed, the resulting secondary colors are generally less bright and vivid compared to additive light mixing. This occurs because pigment mixing follows a subtractive color model, where pigments absorb portions of the light spectrum and reflect only specific wavelengths. As more pigments are combined, less light is reflected, causing the resulting colors to appear darker or less saturated.

Avoid mixing pigments to produce white

Pigment-based colors operate under subtractive color principles. Each pigment absorbs certain wavelengths while reflecting others, which determines the perceived color. Mixing multiple pigments increases light absorption, resulting in darker tones. Therefore, white cannot be produced by mixing pigments; instead, white pigment must be used directly.

Creating lighter colors (tints)

Lighter color variations are achieved by adding white pigment to a base color:

Increasing the amount of white results in a lighter tint.

For example, adding white to red produces pink, which is a lighter variation of red.

If excessive white is added, the original color can be restored by introducing additional base pigment.

III. MODELING OF THE AUTOMATED PAINT MIXING SYSTEM

3.1. System Requirements

Mechanical Requirements

The mechanical structure of the model must be robust, stable, and precise to minimize operational errors. The automated paint mixing and can capping system consists of five main stages:

+ Can Feeding Unit: Paint cans are stored in a cylindrical plastic tube, and feeding is performed using a pneumatic cylinder.
+ Filling Unit: Includes three solenoid valves and three flow sensors responsible for dispensing paint into the can according to predefined color ratios.
+ Cap Feeding Unit: Consists of a dual-rod pneumatic cylinder and a sliding chute mechanism.
+ Capping Unit: Uses a single-acting pneumatic cylinder for pressing the cap onto the can.
+ Mixing Unit: Includes one cylinder to move the can into the mixing mechanism and another to eject it after mixing. The paint inside the can is homogenized using a stepper motor-driven shaking mechanism.

Electrical System Requirements

The electrical system includes two main power sources:AC power supply (220V) used to power a 24V power supply unit.

DC power supply (24V) used for the main PLC, expansion modules, sensors, indicator lights, solenoid valves, DC motors, and related components.The electrical design must ensure safety, reliability, and accurate wiring connections. The electrical cabinet should be organized neatly to facilitate operation, maintenance, and troubleshooting.

3.2. Design Calculations and System Operation

System Operating Procedure

- Switch to Auto mode.
- Select paint color code and number of capping strokes via the HMI interface.
- Select paint mixing ratio.
- After confirming the color code and quantity, press START to begin system operation.

Operation sequence:

- The conveyor starts operating, and Cylinder 1 feeds a can onto the line.
- When Sensor 1 detects the can, the conveyor stops. Solenoid valves dispense paint according to

the programmed ratio. After filling is completed, the conveyor resumes operation.

- When Sensor 2 detects the can, the conveyor stops, and Cylinder 2 positions the cap onto the can opening. After cap feeding is completed, the conveyor restarts.
- When Sensor 3 detects the can, the conveyor stops, and Cylinder 3 performs the capping operation according to the preset number of strokes configured via HMI.
- When Sensor 4 detects the can, the main conveyor stops, and Cylinder 4 transfers the can into the mixing unit. The stepper motor rotates to homogenize the paint inside the can.
- After mixing is completed, Cylinder 5 ejects the can, and the conveyor transports it to the end of the production line.

System control during operation:

- Pressing the STOP button resets all actuators and allows fault handling if necessary. To resume operation, the STOP button must be reset to its initial state.
- Pressing the Emergency (EMC) button immediately halts the system until manually restarted.

System Block Diagram

The overall block diagram of the automated paint mixing system is shown as follows:

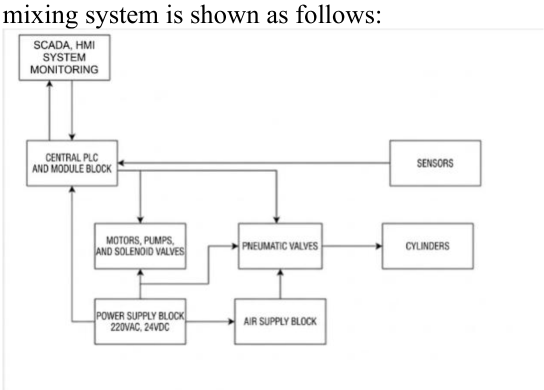


Figure 7. Overall System Architecture Diagram

Functions of Each Block

220VAC and 24VDC Power Supply Unit: The power supply unit provides two types of electrical sources for the system:A single-phase 220VAC power supply used to operate solenoid valves and power conversion adapters.A 24VDC power supply used to provide operating voltage for the main PLC, expansion modules, sensors, pneumatic valves, DC motors, and pump motors.

Central Processing Unit and Expansion Modules: This unit serves as the main controller of the system. It communicates with sensors, collects and processes input signals, and generates output signals to control actuators such as motors and pneumatic valves. Additionally, it establishes communication with the SCADA system for monitoring and supervisory control.

*Sensor Unit*Responsible for detecting system states, processing measurement signals, and transmitting data to the PLC for further control actions.

Pneumatic Supply Unit: Provides compressed air to operate pneumatic valves and cylinders.

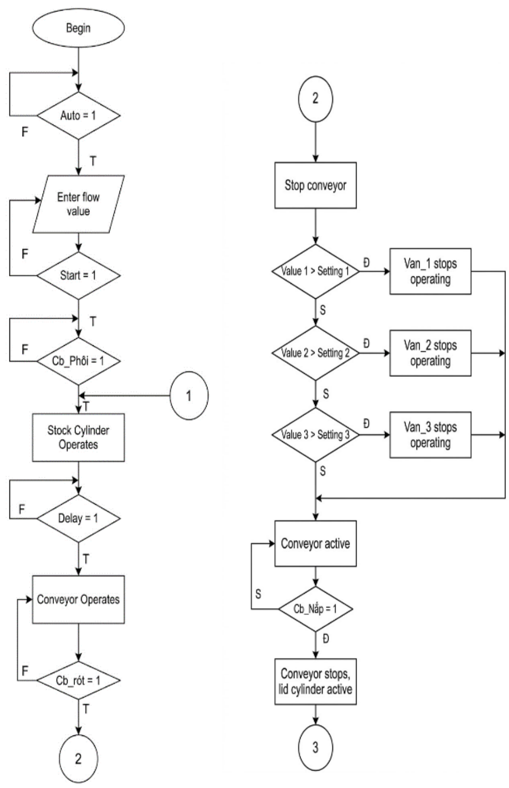
Pneumatic Valves: Receive control signals from the PLC to actuate pneumatic cylinders.

Motor, Pump, and Solenoid Valve Unit: Controls conveyor movement.Regulates the rotational speed of the mixing mechanism.Pumps and solenoid valves perform paint dosing and filling into cans according to predefined ratios.

Pneumatic Cylinders: Generate mechanical motion required for system operations, including can feeding, positioning, overflow blocking, cap handling, capping, transferring cans into the mixing mechanism, and ejecting finished cans.

SCADA Monitoring System: Acts as the human–machine interface layer, enabling operators to supervise and control the system. It provides real-time monitoring, operational visualization, and fault notifications to ensure stable system performance and rapid troubleshooting.

Algorithm Flowchart



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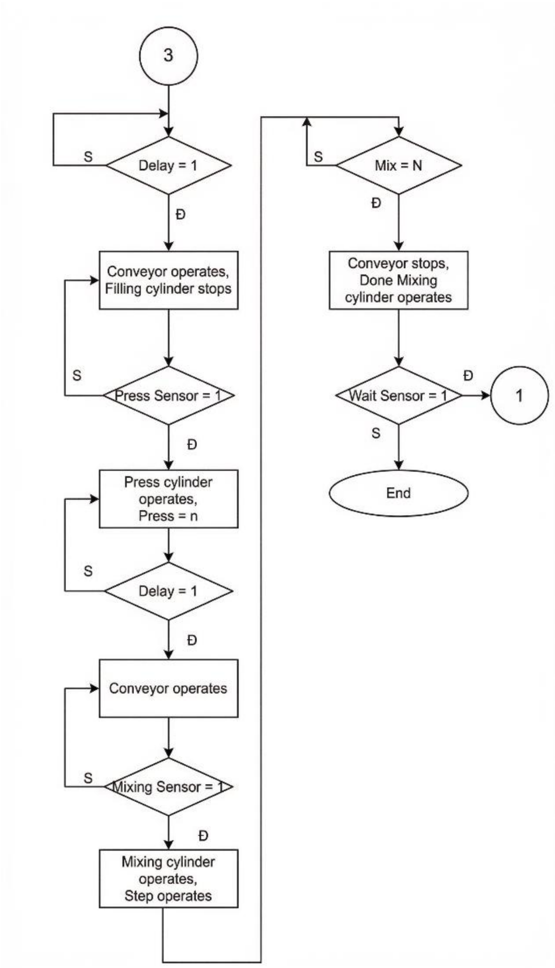

Figure 8. Operational Algorithm Flowchart of the System

3.3. System Modeling

Modeling and Implementation:

After completing the design and calculation stages, the fabrication of system components and mechanical parts is carried out. Subsequently, all components are assembled to form a complete automated system. The manufacturing and assembly processes must strictly comply with technical procedures and engineering standards to ensure system accuracy, reliability, and operational stability. After completing the design and calculations, proceed with fabricating the components and parts of the testing machine. Simultaneously, assemble the components together to form a complete machine. The fabrication and assembly process must comply with technical procedures and regulations.

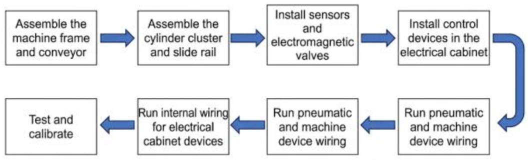

Figure 9. System Modeling Diagram

a. Can Feeding Unit

In this stage, a long plastic tube is designed as a storage container for empty cans, and a single-acting pneumatic cylinder is used to push the cans onto the conveyor belt.

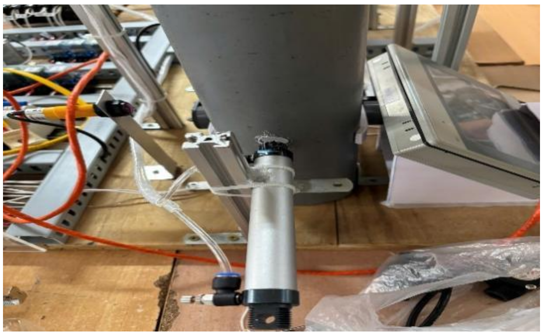

Figure 10. Can Feeding Unit

b. Filling Unit (Figure 11)

In the automated paint mixing system, the filling unit plays a crucial role in accurately dosing and dispensing the paint mixture after it has been blended according to the desired ratio.

In the proposed model, the filling unit utilizes three flow sensors and three solenoid valves, where each valve corresponds to a primary color component (red, yellow, blue, and white). These solenoid valves control the opening and closing of paint flow into the mixing chamber based on predefined timing and ratio parameters programmed in the PLC.

The use of solenoid valves provides several advantages:

High level of automation, reducing dependence on manual operations.

High accuracy in dosing volume and filling time.

Easy integration with PLC-based control systems for full process automation.

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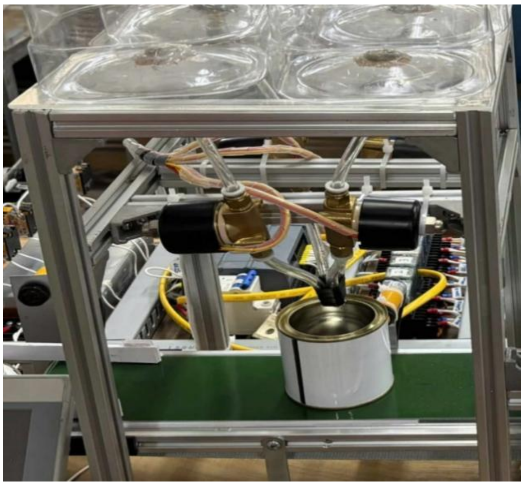

Figure 11. Filling Unit

c. Capping Unit (Figure 12)

After the filling process is completed, the cans are transported by a conveyor to the capping position. The capping unit consists of a double-rod pneumatic cylinder and a sliding chute used to guide the caps.

When the filled can reaches the cap feeding position, the photoelectric sensor detects its presence and sends a signal to the PLC controller. The PLC processes the signal and activates the cylinder, which pushes the cap from the sliding chute so that it falls precisely onto the can mouth, ensuring accurate and synchronized operation within the production line.

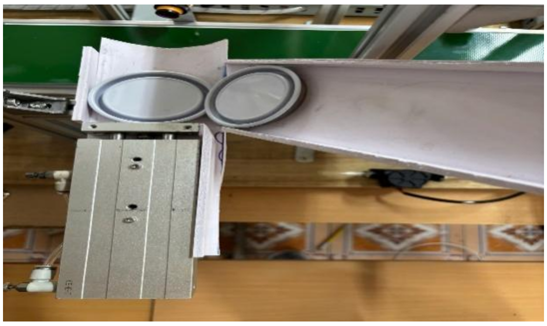

Figure 12. Cap Feeding Unit

d. Capping/Sealing Unit (Figure 13)

This stage completes the product after the container has been filled with paint and the cap has been positioned. The function of this unit is to tightly seal the cap onto the can mouth to prevent paint leakage and ensure safe storage and transportation.

After the cap is correctly placed on the can and reaches the sealing position, the cylinder mechanism is activated to generate a downward pressing force, firmly securing the cap onto the can opening.

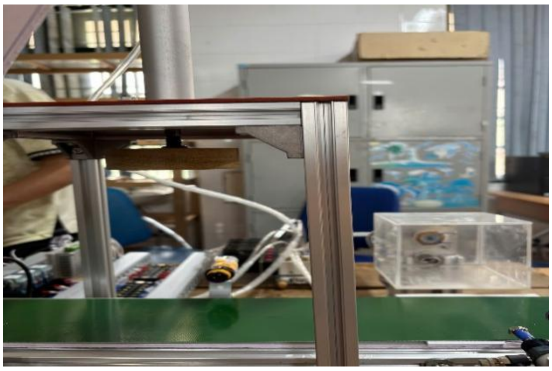

Figure 13. Capping Unit

e. Paint Mixing Unit (Figure 14)

After the system completes the capping stage, it proceeds to the final step to finish the production process and produce the required paint can. This stage is responsible for mixing the paint to achieve a smoother texture and more accurate color consistency inside the can.

Once the paint can has been sealed, it is conveyed to the mixing position, where a photoelectric sensor triggers the operation. A single-acting cylinder pushes the can into the mixing chamber. A stepper motor rotates according to the programmed number of cycles, while the mixing speed and duration are precisely controlled to ensure uniform color blending without creating bubbles or sedimentation.

After the mixing mechanism stops, the single-acting cylinder pushes the finished can back onto the conveyor, completing one finished product.

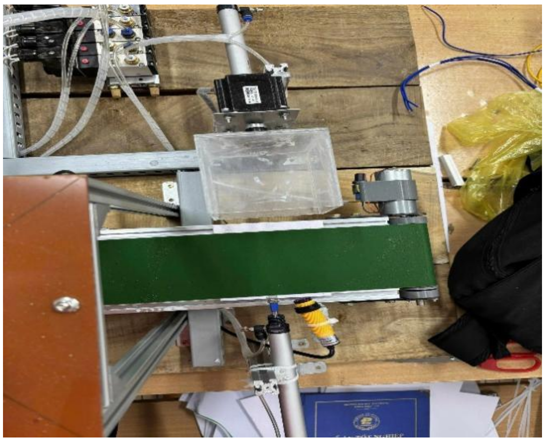

Figure 14. Paint Mixing Unit

f. Completed Model

This figure shows the overall completed model after the construction and assembly process (Figure 15).

Figure 15. Completed Model

g. Electrical Control Panel
The electrical control cabinet serves as the central control unit of the system. It includes the PLC, HMI display, time-delay relays, circuit breakers (CB), and other essential electrical components required for system operation and protection.
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III. CONCLUSION

This paper presents a comprehensive approach to modeling and designing a control system for an automated paint mixing system, integrating theoretical analysis, system design, and experimental implementation. Based on an analysis of the paint mixing process characteristics and system architecture, a mathematical model of the mixing process was developed to describe the relationships among input variables, system states, and outputs.

Based on the proposed model, a PLC-based control architecture integrated with sensors, actuators, and an HMI/SCADA monitoring platform was designed and implemented. Control strategies were developed to ensure accurate mixing ratios, process stability, and fully automated system operation. Experimental results demonstrate that the automated paint mixing system achieves high accuracy, good repeatability, and flexible responsiveness under various operating conditions.

The obtained results confirm the feasibility and effectiveness of the proposed modeling and control approach, while also demonstrating the potential for practical application in industrial production. This research not only contributes to enhancing automation in paint mixing processes but also provides a methodological framework that can be extended to other industrial material mixing systems.

However, certain limitations remain, such as the incomplete consideration of complex nonlinear characteristics of the mixing process, environmental influences, and variations in material properties. Future research directions may focus on integrating advanced control methods such as adaptive control, model predictive control (MPC), intelligent control based on artificial intelligence, as well as developing digital twin models and data-driven monitoring systems to further improve system performance and reliability. Overall, this study provides a scientifically and practically valuable solution for automating paint mixing processes and proposes a new approach for the design and optimization of industrial mixing systems in modern manufacturing environments.

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