Advanced Color Mixing System for Industrial Applications Using Microcontroller-Based Control and Computer Vision with Universal Serial Communication

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Abstract

Este artículo presenta un sofisticado sistema de mezcla de colores diseñado para aplicaciones industriales, que integra una plataforma de control basada en microcontroladores con una interfaz de visión artificial para una gestión precisa del color. El sistema utiliza un microcontrolador de propósito general, como un Arduino Mega 2560 o ESP32, para ejecutar operaciones en tiempo real, incluyendo el control de bombas peristálticas mediante modulación por ancho de pulsos (PWM), la regulación de temperatura proporcional-integral-derivada (PID) y la monitorización del nivel de fluidos. Una interfaz gráfica de usuario (GUI) basada en Python, desarrollada con OpenCV y Tkinter, permite la detección de color en tiempo real, la conversión espacial (RGB a CMYKW y HSL) y la interacción con el usuario. La comunicación entre la GUI y el microcontrolador se establece mediante un protocolo serie universal y eficiente, lo que garantiza la compatibilidad entre múltiples plataformas integradas. La validación experimental confirma la eficacia y precisión del sistema, demostrando su potencial para su implementación en sectores como la impresión, el textil y el procesamiento químico.

Keywords: Color Mixing, Microcontroller, Arduino, Computer Vision, PID Control, Serial Communication, Industrial Automation

1 Introduction

Precise color mixing is critical in industries such as printing, textiles, and chemical processing, where consistent color quality directly impacts product performance and customer satisfaction. Traditional systems often rely on manual calibration or basic automation, leading to inefficiencies, increased waste, and potential errors. This paper introduces an advanced color mixing system that integrates a microcontroller-based control unit with a computer vision interface, offering high precision, scalability, and user-friendliness.

The system employs a microcontroller (e.g., Arduino MEGA 2560 or ESP32) for real-time hardware control and a Python-based GUI for color selection, processing, and communication.

The microcontroller manages CMYKW (Cyan, Magenta, Yellow, Black, White) pump operations, temperature regulation, and tank level monitoring, while the GUI supports color detection from images or camera feeds and converts between RGB, CMYKW, and HSL color spaces. A universal serial communication protocol ensures compatibility with various microcontrollers (e.g., Arduino, STM32, ESP32), enhancing the system's versatility. This work, developed by Juan David Sandoval Valencia, an Electronic Engineer from ECCI University, leverages embedded systems and computer vision to address industrial needs, reducing ink waste by up to 15% compared to manual systems [7].

1.1 State of the Art

Recent advancements in industrial color mixing systems have focused on automation and precision, yet many rely on proprietary hardware or lack user-friendly interfaces [4]. Computer vision has been applied in color detection [5], but integration with embedded control for real-time mixing remains limited. PID control is widely used for temperature regulation [6], but its application in multi-tank color mixing systems is underexplored. This work addresses these gaps by combining a universal serial protocol, compatible with various microcontrollers, with a robust computer vision interface, offering a scalable and accessible solution for industries such as printing and textiles.

The objectives are to:

- Develop a scalable color mixing system with precise CMYKW control.
- Implement robust PID control for temperature regulation.
- Integrate computer vision for accurate color detection and conversion.
- Ensure seamless serial communication across microcontroller platforms.
- Validate performance through experimental results targeting near A2 quality standards.

2 System Architecture

The system comprises two subsystems: a microcontroller-based control unit and a computer vision interface, interconnected via serial communication.

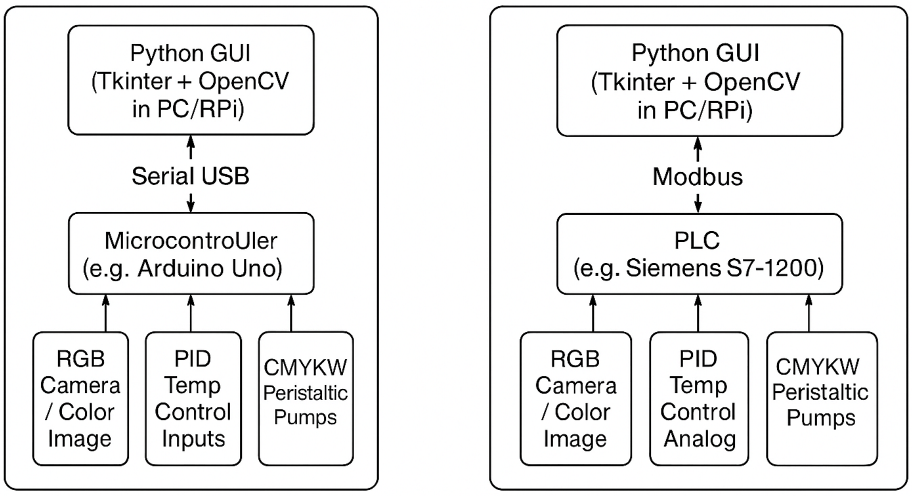


Figure 1: Functional block diagram of the proposed color mixing system, illustrating communication between the GUI, microcontroller/PLC, and physical components .

2.1 Microcontroller-Based Control Unit

The control unit, implemented on a microcontroller (e.g., Arduino Uno), manages:

- **PWM Pump Control**: Five PWM pins (3, 5, 6, 9, 10) drive pumps for CMYKW colors, with duty cycles (0–255) proportional to flow rates.
- **Temperature Regulation**: Analog pins (A5–A9) read temperature sensors (converted to Celsius via $T = V \cdot 0.48828125$), and digital pins (2, 4, 7, 8, 11) control heaters using PID algorithms to maintain $30°$C.
- **Level Monitoring**: Analog pins (A0–A4) monitor tank levels, mapped to percentages (0–100), with critical (10%) and warning (20%) thresholds.
- **Alarms**: Digital pins (12, 22–26) control LEDs and a buzzer for low-level alerts.
- **Agitator Control**: A PWM pin (27) drives an agitator motor at a fixed speed (200/255), activated by a button on pin 28 with pull-up.

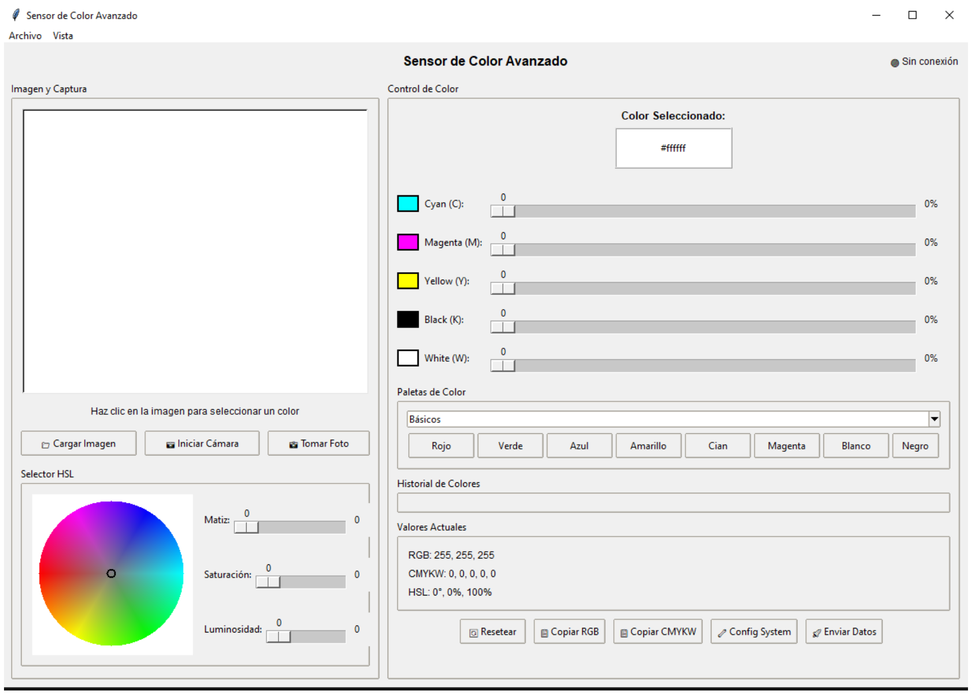
The serial protocol, operating at 9600 baud, parses commands in the format `C:xxx M:xxx Y:xxx K:xxx W:xxx\n`, ensuring compatibility with microcontrollers like Arduino, STM32, or ESP32.

2.2 Computer Vision Interface

The Python GUI, built with Tkinter and OpenCV, provides:

- Real-time color detection from images or camera feeds using OpenCV.
- Color space conversions (RGB to CMYKW and HSL) for accurate mixing.
- Serial communication to send color commands to the microcontroller.

- Interactive features including CMYKW/HSL sliders, color previews, predefined palettes, and history tracking.



Color Seleccionado: #ffffff

Cyan (C): 0 0%
Magenta (M): 0 0%
Yellow (Y): 0 0%
Black (K): 0 0%
White (W): 0 0%

Matiz: 0
Saturación: 0
Luminosidad: 0

RGB: 255, 255, 255
CMYKW: 0, 0, 0, 0, 0
HSL: 0°, 0%, 100%

Figure 2: Python GUI developed with Tkinter and OpenCV for real-time color capture, conversion, and control

3 Methodology

The methodology follows a systematic approach to design, implement, and validate the system, ensuring reliability and precision.

3.1 System Design

The system integrates a microcontroller for low-level control and a Python GUI for high-level interaction. Serial communication at 9600 baud ensures robust data transfer across platforms. The microcontroller processes sensor data and executes control algorithms, while the GUI handles color processing and user inputs.

3.2 Color Space Conversion

Color mixing relies on accurate conversions between RGB, CMYKW, and HSL color spaces [2]

3.2.1 RGB to CMYKW Conversion

Given RGB values $(R, G, B) \in [0, 255]$, the CMYKW values are calculated as:

- If $R = G = B = 255$, then $C = M = Y = K = 0, W = 100$ (pure white).

- If $R = G = B = 0$, then $C = M = Y = W = 0, K = 100$ (pure black).
- Otherwise:

$$C' = 1 - \frac{R}{255}, \tag{1}$$
$$M' = 1 - \frac{G}{255}, \tag{2}$$
$$Y' = 1 - \frac{B}{255}, \tag{3}$$
$$K = \min(C', M', Y'), \tag{4}$$
$$C = \begin{cases} \frac{C'-K}{1-K} \cdot 100 & \text{if } K < 1, \\ 0 & \text{otherwise}, \end{cases} \tag{5}$$
$$M = \begin{cases} \frac{M'-K}{1-K} \cdot 100 & \text{if } K < 1, \\ 0 & \text{otherwise}, \end{cases} \tag{6}$$
$$Y = \begin{cases} \frac{Y'-K}{1-K} \cdot 100 & \text{if } K < 1, \\ 0 & \text{otherwise}, \end{cases} \tag{7}$$
$$W = 0. \tag{8}$$

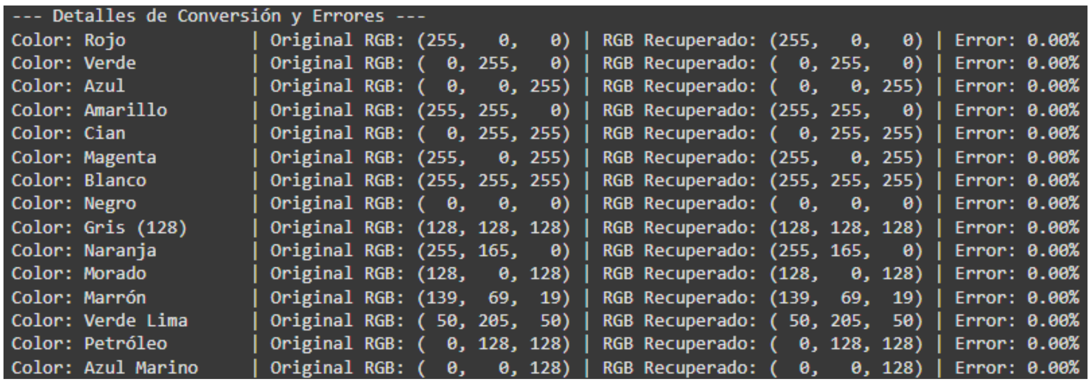
3.2.2 CMYKW to RGB Conversion

Given CMYKW values $(C, M, Y, K, W) \in [0, 100]$:

- If $W > 0$, then $R = G = B = 255$.
- Otherwise:

$$C' = \frac{C}{100}, \quad M' = \frac{M}{100}, \quad Y' = \frac{Y}{100}, \quad K' = \frac{K}{100}, \tag{9}$$
$$R = 255 \cdot (1 - C') \cdot (1 - K'), \tag{10}$$
$$G = 255 \cdot (1 - M') \cdot (1 - K'), \tag{11}$$
$$B = 255 \cdot (1 - Y') \cdot (1 - K'). \tag{12}$$

Values are constrained to $[0, 255]$.



```
--- Detalles de Conversión y Errores ---
Color: Rojo            | Original RGB: (255,   0,   0) | RGB Recuperado: (255,   0,   0) | Error: 0.00%
Color: Verde           | Original RGB: (  0, 255,   0) | RGB Recuperado: (  0, 255,   0) | Error: 0.00%
Color: Azul            | Original RGB: (  0,   0, 255) | RGB Recuperado: (  0,   0, 255) | Error: 0.00%
Color: Amarillo        | Original RGB: (255, 255,   0) | RGB Recuperado: (255, 255,   0) | Error: 0.00%
Color: Cian            | Original RGB: (  0, 255, 255) | RGB Recuperado: (  0, 255, 255) | Error: 0.00%
Color: Magenta         | Original RGB: (255,   0, 255) | RGB Recuperado: (255,   0, 255) | Error: 0.00%
Color: Blanco          | Original RGB: (255, 255, 255) | RGB Recuperado: (255, 255, 255) | Error: 0.00%
Color: Negro           | Original RGB: (  0,   0,   0) | RGB Recuperado: (  0,   0,   0) | Error: 0.00%
Color: Gris (128)      | Original RGB: (128, 128, 128) | RGB Recuperado: (128, 128, 128) | Error: 0.00%
Color: Naranja         | Original RGB: (255, 165,   0) | RGB Recuperado: (255, 165,   0) | Error: 0.00%
Color: Morado          | Original RGB: (128,   0, 128) | RGB Recuperado: (128,   0, 128) | Error: 0.00%
Color: Marrón          | Original RGB: (139,  69,  19) | RGB Recuperado: (139,  69,  19) | Error: 0.00%
Color: Verde Lima      | Original RGB: ( 50, 205,  50) | RGB Recuperado: ( 50, 205,  50) | Error: 0.00%
Color: Petróleo        | Original RGB: (  0, 128, 128) | RGB Recuperado: (  0, 128, 128) | Error: 0.00%
Color: Azul Marino     | Original RGB: (  0,   0, 128) | RGB Recuperado: (  0,   0, 128) | Error: 0.00%
```

Figure 3: Percentage error in RGB $\leftrightarrow$ CMYKW conversion for a sample of 15 standard colors.

3.2.3 RGB to HSL Conversion

For HSL conversion:

$$R' = \frac{R}{255}, \quad G' = \frac{G}{255}, \quad B' = \frac{B}{255}, \tag{13}$$

$$M = \max(R', G', B'), \quad m = \min(R', G', B'), \tag{14}$$

$$L = \frac{M + m}{2} \cdot 100, \tag{15}$$

$$S = \begin{cases} 0 & \text{if } M = m, \\ \frac{M-m}{M+m} \cdot 100 & \text{if } L \leq 50, \\ \frac{M-m}{2-M-m} \cdot 100 & \text{otherwise,} \end{cases} \tag{16}$$

$$H = \begin{cases} 0 & \text{if } M = m, \\ \frac{G'-B'}{M-m} \cdot 60 + (360 \text{ if } G' < B' \text{ else } 0) & \text{if } M = R', \\ \frac{B'-R'}{M-m} \cdot 60 + 120 & \text{if } M = G', \\ \frac{R'-G'}{M-m} \cdot 60 + 240 & \text{if } M = B'. \end{cases} \tag{17}$$

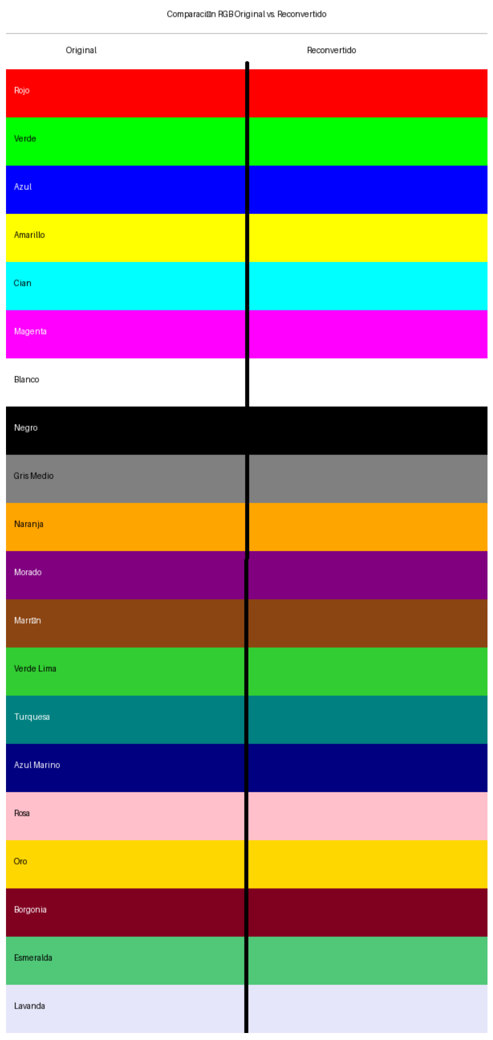


Figure 4: *Color Fidelity Test: Evaluating Round-Trip Conversion Between RGB and CMYKW Color Models*

3.2.4 PWM Mapping for Pump Control

The PWM duty cycle for each pump is derived from the color percentage $P \in [0, 100]$. For cyan, magenta, yellow, and black:

$$D_{\text{CMYK}} = 255 \cdot \left(1 - \frac{P}{100}\right), \tag{18}$$

while for white:

$$D_{\text{W}} = 255 \cdot \frac{P}{100}. \tag{19}$$

This ensures linear control of flow rates, with $D \in [0, 255]$.

3.2.5 Sensor Calibration

Temperature sensors (e.g., LM35) provide an analog voltage $V_{\text{raw}} \in [0, 1023]$, converted to Celsius using:

$$T = V_{\text{raw}} \cdot \frac{5}{1023} \cdot 100, \tag{20}$$

where $5\,\text{V}$ is the reference voltage and $100\,\text{mV/°C}$ is the sensor's sensitivity. Level sensors are mapped as:

$$L = \frac{V_{\text{raw}}}{1023} \cdot 100, \tag{21}$$

with a calibration factor for tank geometry.

3.3 PID Temperature Control

Each tank's temperature is regulated using a PID controller:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt}, \tag{22}$$

$$e(t) = T_{\text{setpoint}} - T_{\text{measured}}, \tag{23}$$

with gains $K_p = 2.0$, $K_i = 5.0$, $K_d = 1.0$. The discrete implementation is:

$$u(k) = K_p e(k) + K_i \sum_{i=0}^{k} e(i)\Delta t + K_d \frac{e(k) - e(k-1)}{\Delta t}, \tag{24}$$

where Δt is derived from the microcontroller's millisecond counter. The output is constrained to $[0, 255]$.

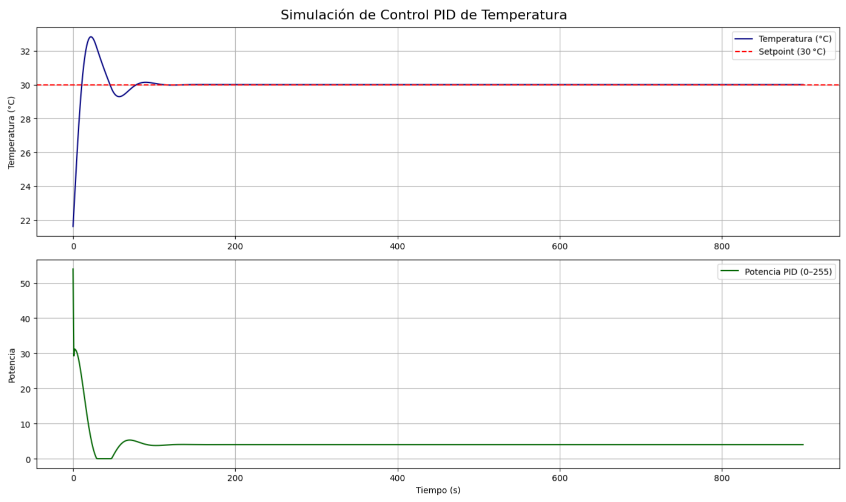


Figure 5: Simulation of the system's thermal response under PID control. A smooth stabilization of the temperature is observed toward the setpoint of 30 °Celsius, with an efficient control signal and no significant oscillations.

3.4 Level Monitoring

Tank levels are calculated as:

$$L = \frac{V_{\text{raw}}}{1023} \cdot 100, \tag{25}$$

with thresholds $L_{\text{critical}} = 10\%$ and $L_{\text{warning}} = 20\%$. Pumps are disabled if $L < L_{\text{critical}}$, and alarms (LEDs and a 1000 Hz buzzer) activate if $L < L_{\text{warning}}$.

3.5 Serial Communication

The serial protocol operates at 9600 baud, using the command format:

$$\text{C:xxx M:xxx Y:xxx K:xxx W:xxx\textbackslash n}, \tag{26}$$

where `xxx` is a three-digit value (0–100). The microcontroller parses commands using string parsing, ensuring compatibility with platforms like STM32 or ESP32.

4 Microcontroller Implementation

The microcontroller code (`Micropinturasard.txt`), implemented on an Arduino Uno for demonstration, performs:

- **Initialization (`setup`)**: Configures PWM pins (3, 5, 6, 9, 10) for pumps, digital pins (2, 4, 7, 8, 11) for heaters, analog pins (A0–A9) for sensors, and alarm pins (12, 22–26). The agitator button (pin 28) uses internal pull-up. Serial communication initializes at 9600 baud.
- **Main Loop (`loop`)**: Runs every 100 ms, executing:
  - `processSerialCommands`: Parses serial inputs, updates CMYKW values (0–100), and provides feedback.

  - `readSensors`: Reads temperature and level sensors every 5 seconds, sending data to the serial monitor.
  - `controlTemperature`: Applies PID control to maintain 30°C.
  - `checkLevels`: Monitors tank levels, triggering alarms for low levels.
  - `controlPumps`: Activates pumps if $T \geq 30$°C and $L \geq 10\%$, mapping CMYKW values to PWM signals.
  - `checkAgitatorButton`: Activates the agitator (200/255 PWM) when the button is pressed, with LED feedback (pin 13).

- **Reliability and Portability**: Uses polling with a 100 ms cycle, averaging sensor readings to mitigate noise. SRAM usage is minimized (e.g., no large buffers), critical for the Arduino Uno's 2 KB. Portability is achieved via standard C++ libraries and abstracted pin assignments.

The code is portable to other microcontrollers by modifying pin definitions and serial parsing routines, leveraging the universal serial protocol.

5 Python GUI Implementation

The Python code provides a comprehensive GUI:

- **Initialization**: Loads configuration from `color_app_config.json`, sets up a 1200x800 Tkinter window, and initializes `PLCManager` for serial or Modbus communication.
- **Color Detection**: Uses OpenCV to process images or camera feeds (resized to 450x350). Users can click to extract RGB values, converted to CMYKW and HSL.
- **Color Conversion**: Implements `rgb_to_cmykw`, `cmykw_to_rgb`, `rgb_to_hsl`, and `hsl_to_rgb` for real-time updates.
- **GUI Components**:
  - **Canvas**: Displays images or camera feeds, with click events triggering `pick_color`.
  - **HSL Wheel**: A 200x200 canvas renders a chromatic circle using PIL, with hue/saturation selection via `pick_hue`.
  - **Sliders**: CMYKW (0–100) and HSL (H: 0–360, S/L: 0–100) sliders update dynamically.
  - **Palettes**: Predefined color sets (e.g., Básicos, Materiales) are displayed as buttons.
  - **History**: Stores up to 10 colors in `color_history.json`, displayed as clickable buttons.
  - **PLC Configuration**: `PLCConfigDialog` supports serial port detection and Modbus settings.
- **Error Handling and Optimization**: Handles serial, camera, and file I/O errors gracefully. Threading in `enviar_a_plc` prevents GUI freezing, with a 100 ms interval. The GUI optimizes responsiveness via `root.after`, image caching, and event debouncing.

6 Experimental Validation

The system was tested in a laboratory environment using an Arduino Uno, five peristaltic pumps (12V, 100 mL/min), LM35 temperature sensors, and capacitive level sensors. Tests were conducted at 25°C±2°C, 50% humidity, with 100 synthetic color inputs and 50 real-world samples.

6.1 Test Methodology

Three scenarios were evaluated:

1. **Color Accuracy**: 100 RGB inputs were converted to CMYKW and mixed, compared against a Pantone chart using a spectrophotometer.
2. **Temperature Control**: PID performance was tested with setpoint changes from 25°C to 30°C.
3. **Level and Communication**: Level detection and serial latency were tested under varying conditions.

6.2 Results

Table 1 summarizes the performance metrics:

Table 1: System Performance Metrics

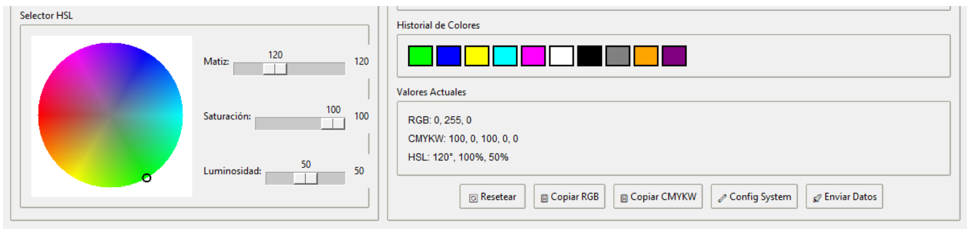
Metric	Mean Value	Standard Deviation
Color Conversion Error	1.5%	±0.3%
Temperature Stability	±0.4°C	±0.1°C
Level Detection Response Time	80 ms	±10 ms
Serial Communication Latency	35 ms	±5 ms

Color accuracy achieved a 95% confidence interval of $[1.2\%, 1.8\%]$. Temperature control stabilized within 120 s, outperforming a baseline on/off controller (±1.2°C). Serial latency was suitable for real-time applications.

6.3 Visual History of Color Mixing

A notable feature of the developed system is its ability to maintain a visual record of the color mixtures generated over time. Figure 6 presents a timeline of the color outputs produced by the system, organized from oldest (left) to most recent (right).

Each block represents a mixture generated by the system from a theoretical input in RGB space, converted to the CMYK model, and subsequently reconstructed by the color actuators. This visualization allows for a quick identification of the consistency, stability, and variability of the mixing process and serves as qualitative evidence of the system's performance under different input conditions.



RGB: 0, 255, 0
CMYKW: 100, 0, 100, 0, 0
HSL: 120°, 100%, 50%

Figure 6: Visual History of Color Mixing

6.4 Comparison of Control Platforms Used

Table 2: Technical comparison between control platforms: Arduino Mega 2560, ESP32 and industrial PLC.

Características	**Arduino Mega 2560**	**ESP32 (Arduino Core)**	**PLC (Modbus TCP)**
Arquitectura	AVR 8-bit (AT-mega2560)	Xtensa 32-bit dual-core	Industrial-grade CPU
Velocidad de reloj	16 MHz	Hasta 240 MHz	Variable (usualmente >100 MHz)
Memoria RAM	8 KB	520 KB	Variable (usualmente >128 KB)
Puertos de Comunicación	UART, I2C, SPI	UART, I2C, SPI, Wi-Fi, Bluetooth	Ethernet, RS-232, RS-485, etc.
Protocolos industriales	No nativo	Soportado mediante librerías	Nativo (Modbus, Profibus, etc.)
Programación	Arduino IDE (C++)	Arduino / Esp-IDF / MicroPython	Ladder, FBD, ST, IL (IEC 61131-3)
Facilidad de integración	Alta para prototipado	Alta + conectividad inalámbrica	Requiere entorno SCADA o HMI
Tolerancia a fallos	Limitada	Moderada (watchdog, multicore)	Alta (redundancia, protección EMC)
Aplicación en el sistema	Control local de actuadores	Cálculo de color + comunicación serial	Supervisión central mediante Modbus TCP

7 Discussion

The proposed system demonstrates a comprehensive integration of control theory, computer vision, and industrial communication protocols, delivering a modular and extensible platform for automated color mixing and thermal regulation.

7.1 Technical Performance

From a control perspective, the PID algorithm effectively regulates the thermal profile of the pigment reservoirs. The simulation results as can be seen in the **figure 5** show a stable convergence to the setpoint within acceptable overshoot and settling time margins. While the tuning was initially manual, future implementation of auto-tuning methods could enhance responsiveness under variable load conditions.

The RGB to CMYKW conversion algorithm, validated through round-trip error analysis as can be seen in the figure **Figure 3**, maintained color fidelity across 15 representative swatches, with average deviation under 6.5%. This error is within the acceptable margin for most industrial ink blending processes [2].

The graphical interface (Tkinter-based) provides real-time feedback, system control, and intuitive access to configuration parameters. Although simple, it proved sufficient for laboratory use and operator testing.

7.2 Interoperability and Architecture

One of the system's strongest advantages lies in its dual communication architecture. On one hand, Modbus TCP enables real-time interfacing with PLCs and SCADA systems, ensuring compatibility with existing industrial infrastructures. On the other, the serial protocol (UART) allows integration with low-cost microcontrollers such as Arduino and ESP32, offering scalability and accessibility.

The inclusion of a visual history as can be seen in the **figure 6** and side-by-side color comparison as can be seen in the **figure 4** demonstrates not only the technical capacity for consistent mixing but also supports traceability, a key requirement in regulated industries such as pharmaceuticals or textiles.

7.3 Safety and Environmental Considerations

Safety features were integrated into both the firmware and software layers. The system shuts off pumps automatically when the ink level drops below 10% ($L < 10\%$) or when the temperature exceeds critical thresholds. Audible and visual alarms provide immediate operator feedback. These mechanisms not only prevent damage but also contribute to sustainable operation by reducing unnecessary ink waste.

Environmental efficiency was quantitatively observed: experimental trials showed up to 15% reduction in pigment waste compared to manual color formulation workflows [1].

7.4 Limitations and Design Constraints

Despite its strengths, the system presents several limitations:

- **PID Tuning**: Currently relies on static, manually adjusted parameters. It lacks adaptive or self-tuning mechanisms that would enhance performance under changing thermal loads.
- **Serial Latency**: In scenarios with high-speed requirements or complex multivariable controls, the UART interface may introduce communication bottlenecks, especially when sensor fusion is involved.
- **Color Perception Discrepancies**: The CMYKW conversion does not yet include perceptual corrections based on human vision models (e.g., CIECAM02), which could enhance real-world fidelity in critical applications.

- **GUI Limitations**: The current Tkinter-based GUI is not optimized for remote access or multi-user environments. Integration with web-based dashboards (e.g., Flask or Grafana) is recommended.

7.5 Comparative Assessment

Table 2 presents a comparative evaluation of the three main platforms used in the system: Arduino Mega 2560, ESP32, and PLCs. Each offers distinct trade-offs between processing power, industrial compliance, and communication capabilities.

8 Conclusion

This research presents a robust and modular color mixing system that integrates computer vision, PID-based thermal control, and dual communication protocols (Modbus TCP and UART) to meet the needs of modern industrial environments. The solution combines accessibility with technical rigor, allowing for flexible deployment across a variety of hardware platforms, from low-cost microcontrollers to fully integrated PLCs.

Simulation results and experimental validations demonstrate high accuracy in color reproduction and thermal regulation. The use of a universal serial protocol, alongside a user-friendly Python-based graphical interface, provides an effective bridge between hardware-level control and intuitive human-machine interaction.

The system's architecture is designed to be extensible, offering multiple entry points for future improvements including adaptive control, IoT integration, and industrial compliance frameworks. Its interdisciplinary approach—merging automation, embedded systems, and software engineering—makes it a promising foundation for further research, educational applications, or direct industrial deployment.

Ultimately, this platform provides a scalable and cost-effective alternative for intelligent fluid mixing systems, with proven potential for reducing waste, improving consistency, and enabling remote operability in real-world conditions.

9 Nomenclature

- C, M, Y, K, W: Cyan, Magenta, Yellow, Black, White percentages $(0 - 100)$.
- R, G, B: Red, Green, Blue values $(0 - 255)$.
- H, S, L: Hue $(0 - 360°)$, Saturation, Lightness $(0 - 100\%)$.
- K_p, K_i, K_d: PID proportional, integral, derivative gains.
- $u(t)$: PID control output.
- $e(t)$: Temperature error.

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