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DESIGN AND PERFORMANCE EVALUATION OF A PROGRAMMABLE LOGIC CONTROLLER BASED AUTOMATED THERMAL PAPER ROLLING SYSTEM

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ABSTRACT: *This study addresses the limitations of conventional semi-automatic thermal paper rolling machines, such as inaccurate roll length control, high material wastage, and operator dependency, by developing a fully automated PLC–HMI based control system. The proposed architecture employs a Siemens S7-1200 PLC, KTP-series HMI, incremental encoder, servo-driven slitting adjustment, and digitally controlled pneumatic actuators to achieve closed-loop roll length measurement and automated sequencing. Encoder feedback processed through PLC high-speed counters enables precise length control, while intelligent speed transition logic ensures smooth deceleration and accurate stopping. Experimental evaluation under identical operating conditions demonstrates significant improvements in roll length accuracy, production time, material utilization, repeatability, and paper quality. The results validate the effectiveness of PLC-based closed-loop automation as a practical and scalable solution for upgrading legacy thermal paper rolling machines*

Keywords: *Programmable Logic Controller and Human Machine automation; Special Purpose Machine; Closed-loop control; Encoder-based measurement; Industry 4.0*

I. INTRODUCTION

Industrial automation has become a fundamental enabler for modern manufacturing systems, driven by the increasing demand for higher productivity, improved product quality, reduced material wastage, and minimized human intervention. Programmable Logic Controllers (PLCs), Human–Machine Interfaces (HMIs), servo systems, and industrial communication networks form the backbone of contemporary automated production lines. These technologies are key components in the realization of Industry 4.0, where intelligent, flexible, and data-driven manufacturing systems are emphasized (Atieh et al., 2023; Ragai et al., 2022; Zhou et al., 2025).

Among various manufacturing domains, paper converting industries, particularly thermal paper processing, present unique automation challenges. Thermal paper rolls are extensively used in Automated Teller Machines (ATMs), point-of-sale (POS) terminals, ticketing systems, and billing applications. The quality and dimensional accuracy of these rolls—especially roll length, width, winding tension, and edge finish—directly influence printer performance and customer satisfaction. Consequently, even small deviations in roll length or winding quality can lead to significant economic losses and customer complaints.

Traditional thermal paper rolling machines typically employ semi-automatic control architectures, relying on AC motors, proximity sensors, mechanical counters, and pneumatic actuators. Such systems operate predominantly in an open-loop manner, where the final roll length is estimated based on rotational counts rather than real-time measurement of paper feed. While these systems are simple and low-cost, they suffer from inherent limitations such as inaccurate length control, dependency on operator skill, inconsistent product quality, excessive paper wastage, and low production efficiency. These limitations become more pronounced as production speed increases or when multiple roll sizes are required (Mahmood et al., 2017; Mo et al., 2023).

Recent research and industrial practices increasingly advocate the use of PLC-based closed-loop control systems combined with high-resolution encoders and servo drives to address these challenges. PLCs provide deterministic real-time control, robust industrial reliability, and seamless integration with sensors, actuators, and supervisory systems (Krupa et al., 2021; Su et al., 2019). When coupled with incremental encoders and high-speed counter (HSC) modules, PLCs enable precise measurement of linear displacement, making them well suited for length-critical applications such as paper slitting and rewinding. Furthermore, HMIs enhance system usability by allowing operators to configure machine parameters, monitor real-time process variables, and diagnose faults without direct interaction with control hardware (Seiger et al., 2022).

Several studies have demonstrated the effectiveness of PLC-based automation in improving manufacturing accuracy, flexibility, and productivity. Applications range from thermal process control and flexible manufacturing systems to advanced motion control and adaptive production lines (Stanković et al., 2024; Vogel-Heuser et al., 2017; Yang et al., 2025). Encoder-based feedback systems have been shown to significantly reduce dimensional errors and material waste by enabling speed modulation and precise stopping control near target setpoints (Klopot et al., 2021; Wang et al., 2024). However, despite these advancements, limited literature exists that documents practical industrial case studies focusing on the full automation of thermal paper rolling machines, especially in small- and medium-scale manufacturing environments.

This paper addresses this gap by presenting the design, implementation, and evaluation of a fully automated PLC–HMI based thermal paper slitting and rewinding machine. The proposed system replaces the conventional counter-based semi-automatic setup with a closed-loop control architecture using a Siemens S7-1200 PLC, KTP-series HMI, incremental encoder, servo motor, and digitally controlled pneumatic actuators. The automation strategy focuses on accurate roll length control, optimized speed profiles, reduced manual intervention, and enhanced production efficiency.

The key contributions of this work are summarized as follows:

1. Comprehensive analysis of an existing semi-automatic thermal paper rolling machine, highlighting its operational limitations and sources of inaccuracy.
2. Design of a PLC-based closed-loop control system using encoder feedback for precise roll length measurement and control.
3. Integration of servo-based slitting width adjustment and HMI-driven parameter configuration to improve flexibility and ease of operation.
4. Implementation of intelligent speed transition logic, enabling smooth deceleration near the target length and eliminating over-rolling errors.
5. Experimental validation and comparative analysis, demonstrating significant improvements in accuracy, productivity, and product quality.

The remainder of this paper is organized as follows. Section 2 reviews related work in PLC-based industrial automation and manufacturing systems. Section 3 describes the overall system architecture and machine specifications. Section 4 explains the existing semi-automatic control method and its drawbacks. Section 5 presents the proposed PLC–HMI based automation strategy in detail. Section 6 discusses hardware and software implementation aspects. Section 7 provides results and performance evaluation, followed by a comparative discussion. Finally, Section 8 concludes the paper and outlines directions for future work.

II. LITERATURE REVIEW

The rapid evolution of industrial automation has significantly transformed manufacturing systems by enhancing flexibility, productivity, and operational intelligence. Central to this transformation is the widespread adoption of Programmable Logic Controllers (PLCs), which remain the dominant control platform in both discrete and continuous manufacturing environments due to their robustness, deterministic execution, and ease of integration with industrial devices. Modern PLCs support real-time control, industrial networking, and advanced diagnostics, making them suitable for complex automation tasks involving coordinated motion, sensing, and actuation. Recent literature emphasizes that PLC-based automation continues to play a critical role in the transition toward smart and intelligent manufacturing systems under the Industry 4.0 paradigm, particularly in small- and medium-scale industries seeking cost-effective modernization (Atieh et al., 2023; Ragai et al., 2022; Zhou et al., 2025).

2.1 PLC-Based Automation in Manufacturing Systems

PLCs have evolved from simple relay-replacement controllers into powerful real-time computing platforms capable of executing complex control algorithms, motion control strategies, and networked communication protocols. Advances in PLC hardware and software have enabled deterministic execution of sequential logic, closed-loop control, and data exchange with supervisory systems. Vogel-Heuser et al. analyzed the modularity and architectural patterns of PLC-based software in industrial environments, highlighting that well-structured and modular PLC programs significantly improve maintainability, scalability, and long-term system evolution (Su et al., 2019; Yang et al., 2022). These findings are particularly relevant for machines such as slitting and rewinding systems, where modular control of unwinding, slitting, rewinding, and tension control units is essential to accommodate varying product specifications.

Several studies have demonstrated the application of PLCs in diverse manufacturing contexts. Su et al. reported the successful implementation of Siemens PLCs in thermal control systems, showing improved process stability, robustness, and operational reliability under varying load conditions (Yao et al., 2025). Similarly, Klopot et al. implemented advanced control strategies such as adaptive dynamic matrix control within PLC platforms, demonstrating that PLCs are capable of executing computationally intensive algorithms while maintaining real-time performance (Zhang et al., 2023). Krupa et al. further confirmed that modern PLCs can execute model predictive control (MPC) algorithms, enabling precise control of industrial processes traditionally managed by dedicated controllers (Zhao et al., 2025).

In flexible manufacturing systems (FMS), PLCs serve as the primary coordination unit for machines, conveyors, and auxiliary equipment. Mahmood et al. analyzed the performance of FMS environments and concluded that PLC-based coordination significantly enhances throughput, reduces idle time, and improves overall equipment utilization when compared to manual or decentralized control approaches (Mahmood et al., 2017). These insights directly support the relevance of PLC-driven centralized control in improving productivity and consistency in paper converting and web-handling machines.

2.2 Encoder-Based Feedback and Motion Control

Accurate position and length measurement is a critical requirement in many manufacturing processes, particularly in applications involving cutting, slitting, and winding operations. Incremental encoders are widely used for this purpose due to their high resolution, reliability, and ease of integration with PLC high-speed counter modules. Jaswal et al. demonstrated precise motor position control using PLC-embedded control algorithms, highlighting the importance of encoder feedback in achieving accurate and repeatable motion profiles in industrial automation systems (Jaswal et al., 2025).

Encoder-based closed-loop systems offer substantial advantages over traditional open-loop counting methods. In conventional systems, mechanical counters or proximity sensors estimate length based on roller rotation, which introduces cumulative errors due to variations in roller diameter, mechanical slippage, and wear. By contrast, encoder feedback enables real-time monitoring of actual shaft rotation and allows dynamic speed adjustment as the process approaches target setpoints. Such closed-loop approaches have been shown to significantly reduce overshoot, material wastage, and dimensional inaccuracies in length-critical applications (Wang et al., 2024; Yang et al., 2025).

The use of high-speed counters (HSCs) within PLCs enables reliable processing of high-frequency encoder pulses without compromising control performance. Mao et al. discussed advanced PLC monitoring and control applications beyond conventional logic control, emphasizing that modern PLC architectures can efficiently handle event-driven and pulse-based inputs for precision motion and measurement tasks (Mao et al., 2022). These capabilities are particularly relevant for rewinding systems, where accurate length measurement must be maintained even at higher operating speeds.

2.3 Human–Machine Interface (HMI) and Operator Interaction

Human–Machine Interfaces (HMIs) play a vital role in modern industrial automation by bridging the gap between complex control systems and human operators. HMIs provide intuitive graphical interfaces for real-time visualization of machine states, parameter configuration, fault diagnostics, and manual override functions. Mo et al. highlighted that effective PLC–HMI orchestration significantly enhances human–machine integration, leading to reduced operator errors, improved situational awareness, and greater system adaptability in dynamic manufacturing environments (Mo et al., 2023).

In small- and medium-scale manufacturing environments, HMIs are particularly important because they simplify machine operation and reduce dependency on highly skilled operators. Seiger et al. proposed integrated architectures combining process management and event processing, demonstrating that HMI-driven supervisory control improves decision-making, operational transparency, and responsiveness in smart factories (Schwung et al., 2023). These findings underline the relevance of HMI integration in the proposed thermal paper rolling machine, where ease of operation and consistent parameter setting are essential for quality production.

2.4 Automation, Productivity, and Industry 4.0

Industry 4.0 emphasizes intelligent, interconnected, and autonomous manufacturing systems capable of self-optimization and data-driven decision-making. Atieh et al. analyzed the adoption of intelligent manufacturing systems by small and medium enterprises, concluding that automation using PLCs and digital interfaces is a key enabler for competitiveness, particularly in developing economies with limited access to high-end automation solutions (Atieh et al., 2023). Wang et al. further demonstrated that data- and knowledge-driven automation architectures significantly improve production efficiency, system responsiveness, and adaptability in intelligent factories (Yang et al., 2022).

Automation has also been shown to enhance quality control and reduce material waste. Stanković et al. presented a manufacturing optimization framework for real-time quality control, highlighting that closed-loop automation is essential for maintaining consistent product quality under varying operating conditions (Seiger et al., 2022). These results are directly applicable to thermal paper processing, where consistent roll length, uniform winding tension, and minimal paper damage are critical quality parameters.

2.5 Research Gaps and Motivation

Although extensive research exists on PLC-based automation, motion control, and intelligent manufacturing systems, relatively few studies focus on practical, industrial-scale automation of paper slitting and rewinding machines, particularly thermal paper rolling machines used in commercial applications. Existing literature often addresses high-level manufacturing optimization or advanced control algorithms without detailing real-world implementation challenges such as pneumatic sequencing, encoder-based length calibration, and speed transition logic near stopping points.

Furthermore, many traditional paper converting machines in small- and medium-scale industries still rely on semi-automatic, counter-based systems that suffer from low accuracy, high material wastage, and strong operator dependency. There is a clear need for documented industrial case studies that demonstrate how modern PLC–HMI architectures can be applied to upgrade such legacy machines in a cost-effective, scalable, and reliable manner.

Motivated by these gaps, the present work focuses on the end-to-end automation of a thermal paper rolling machine, emphasizing practical control logic, hardware integration, and experimentally measurable performance improvements. By combining encoder-based feedback, servo-driven adjustments, and HMI-enabled supervision, the proposed system aims to bridge the gap between academic research and industrial practice.

III. SYSTEM OVERVIEW AND MACHINE SPECIFICATIONS

3.1 Overall System Overview

The thermal paper slitting and rewinding machine considered in this study is designed for producing narrow-width thermal paper rolls used in applications such as ATM receipts, point-of-sale (POS) terminals, ticketing systems, and billing printers. The machine performs a sequence of operations including unwinding of a jumbo roll, slitting into multiple narrow widths, controlled rewinding onto small cores, and optional finishing processes such as edge trimming and tail gluing.

From an automation standpoint, the system represents a hybrid discrete–continuous manufacturing process, where continuous paper motion is combined with discrete control actions such as pneumatic actuation, motor speed transitions, and length-based stopping. Such systems are widely encountered in flexible manufacturing environments and require coordinated control to ensure consistent product quality and productivity (Mahmood et al., 2017). PLC-based centralized control is well suited for managing these hybrid processes due to its deterministic execution and real-time response capability (Su et al., 2019).

The machine operates in two configurations:

1. Existing semi-automatic configuration, employing open-loop control using proximity sensors, counters, and manually operated pneumatic valves.
2. Proposed fully automated configuration, utilizing a PLC–HMI–encoder–servo architecture for closed-loop length control and automated sequencing.

This section presents the physical system layout and machine specifications, which form the basis for both control strategies.

3.2 Process Flow Description

The thermal paper rolling process begins with loading a jumbo (parent) roll onto the unwind section. The paper web then passes through multiple rollers that maintain tension and alignment before entering the slitting section. Proper web handling is essential to prevent wrinkles, stretching, and lateral misalignment that can degrade product quality (Seiger et al., 2022).

In the slitting section, rotary circular knives divide the wide paper web into narrow strips of predefined widths. Slitting accuracy directly influences final roll dimensions and printing performance. After slitting, the paper strips are guided toward the rewinding unit, where they are wound onto small paper cores under controlled tension. Uniform rewinding is necessary to ensure consistent roll density and smooth feeding in end-use applications such as printers and POS machines (Stanković et al., 2024).

Optional downstream operations such as edge trimming, tail cutting, tail gluing, and packaging may be included depending on machine configuration. While these features improve product readiness, they increase control complexity and synchronization requirements (Atieh et al., 2023).

3.3 Mechanical Configuration

The mechanical structure of the machine is designed for stable operation at moderate production speeds while maintaining dimensional accuracy. The major mechanical subsystems include:

- Unwind Unit: A shaftless unwind stand capable of holding large jumbo rolls. Tension during unwinding is regulated mechanically and, in the automated system, assisted by pneumatic control.
- Web Handling Rollers: Multiple guide and tension rollers ensure consistent paper tension and alignment. These rollers are mechanically linked to the main drive system.
- Slitting Unit: Rotary circular knives mounted on adjustable shafts. In the automated configuration, blade positioning is controlled by a servo motor for precise and repeatable width adjustment.
- Rewinding Unit: Rewind shafts with core holders for small-diameter cores. Controlled torque and speed ensure tight and uniform winding.

Mechanical robustness combined with intelligent control architecture has been shown to significantly enhance reliability and throughput in manufacturing systems (Ragai et al., 2022).

3.4 Electrical and Control Architecture

The electrical system includes motors, drives, sensors, pneumatic actuators, and control hardware. In the existing configuration, the rewinding unit is driven by an AC induction motor controlled through a variable frequency drive (VFD). Motor operation is initiated using manual pushbuttons and selector switches, while length measurement is performed using a proximity sensor and digital counter.

In the proposed automated system, the following components are integrated:

- Siemens S7-1200 PLC as the central controller
- KTP-series HMI for operator interaction
- Incremental rotary encoder mounted on the main shaft
- Servo motor for slitting blade positioning
- 24 V DC pneumatic solenoid valves

The PLC coordinates pneumatic sequencing, motor speed control, and length-based stopping logic. Encoder feedback is processed using the PLC's high-speed counter to accurately convert rotational pulses into linear paper length. Such PLC-based centralized control architectures significantly improve system integration and control accuracy (Krupa et al., 2021; Yang et al., 2022).

3.5 Physical Implementation of the Thermal Paper Rolling Machine

Plate 1(a) and Plate 1(b) show the actual industrial implementation of the thermal paper slitting and rewinding machine used in this study.

- Plate 1(a) illustrates the electrical control panel, which houses the variable frequency drive (VFD), control relays, terminal blocks, power supply units, and pneumatic solenoid valves. The compact arrangement minimizes wiring length, reduces electrical noise, and improves accessibility for maintenance.
- Plate 1(b) shows the mechanical structure of the machine, including the unwinding section, slitting rollers, rewinding shafts, and pneumatic cylinders used for paper insertion and tension control. The rigid frame and roller alignment ensure stable paper movement and consistent winding quality.

These physical layouts provide the practical foundation for implementing the PLC–HMI based automation strategy described in later sections.

(a) (b)

Plate 1. Physical implementation of the thermal paper slitting and rewinding machine
(a) Electrical control panel with VFD, relays, terminal blocks, and pneumatic solenoid valves;
(b) Mechanical structure showing unwinding, slitting, rewinding rollers, and pneumatic actuators.

3.6 Machine Specifications

The key technical specifications of the thermal paper rolling machine are summarized in Table 1. Maintaining accurate control within these limits is critical for consistent product quality. Automated control systems have been shown to significantly reduce quality variation and material wastage when operating within defined machine specifications (Alsabbagh and Langendoerfer, 2022; Athar et al., 2025).

Table 1. Machine Technical Specifications

Parameter	Specification
Maximum jumbo roll width	520 mm
Jumbo roll length	Up to 6500 m
Paper thickness range	35 GSM to 120 GSM
Finished roll width	25 mm to 82 mm (adjustable)
Maximum rewinding diameter	500 mm
Core inner diameter	14 mm, 18 mm, 24 mm
Production speed	One final roll in approximately 1.5 minutes
Power supply	230 V AC single-phase / 440 V AC three-phase
Main motor rating	1 HP, 440 V AC, 1440 RPM

3.7 Relevance to Automation Upgrade

The system overview reveals that the machine operates under varying conditions such as changes in roll diameter, paper thickness, and production speed. These variations introduce nonlinearity and uncertainty, making manual and open-loop control inadequate. PLC-based automation systems with encoder feedback and HMI supervision effectively address these challenges by enabling real-time measurement, adaptive speed control, and repeatable operation (Cook et al., 2023; Feng et al., 2024).

The detailed understanding of the physical layout and specifications presented in this section forms the foundation for analyzing the existing semi-automatic system and developing the proposed PLC–HMI based fully automated control strategy discussed in subsequent sections.

IV. EXISTING SEMI-AUTOMATIC CONTROL METHOD AND ITS LIMITATIONS

4.1 Overview of the Existing Semi-Automatic Control System

The existing thermal paper slitting and rewinding machine operates using a semi-automatic control architecture, commonly adopted in small- and medium-scale paper converting industries. The system relies on conventional electrical and pneumatic components without any centralized programmable controller. While this approach minimizes initial investment, it lacks the precision, intelligence, and repeatability required for consistent product quality.

The control setup consists of an AC induction motor with a variable frequency drive (VFD), a proximity sensor, a digital counter, pneumatic cylinders, and manually operated selector switches. No PLC or HMI is employed, and the operator is required to intervene at multiple stages of the production cycle. Similar decentralized and operator-dependent control strategies have been reported in traditional manufacturing systems (Su et al., 2019).

4.2 Hardware Configuration of the Semi-Automatic System

The main hardware elements of the semi-automatic system include a three-phase AC induction motor (1 HP, 1440 RPM) driven by a standalone VFD, which provides basic speed control without real-time process feedback. Length estimation is performed using a single inductive proximity sensor that detects the rotation of a metal dog mounted on a roller shaft. The sensor pulses are processed by a digital counter, which disconnects the motor contactor once a preset count is reached.

Pneumatic cylinders are used for paper insertion and pressure application to maintain winding tension. All pneumatic solenoid valves operate at 230 V AC and are actuated manually using selector switches. Pushbuttons and switches are also used for motor start/stop and auxiliary functions. Such manually coordinated systems are known to increase operator workload and reduce process repeatability (Klar et al., 2024).

4.3 Operating Principle of the Existing System

The operating sequence begins with manual mounting of the jumbo roll and threading of the paper web through tension rollers. After ensuring compressed air supply, the operator manually activates air feed, paper insertion, and pressure cylinders. The rewinding motor is then started using a pushbutton.

During operation, the proximity sensor detects each roller rotation and sends pulses to the digital counter, where one rotation corresponds to approximately 100 mm of paper length. When the preset count is reached, the counter output switches off the motor contactor. The finished roll is then manually removed and packed. This entire sequence is repeated for each roll, making the process highly operator-dependent and prone to variability (Comari et al., 2022).

4.4 Length Measurement Method

Roll length in the semi-automatic system is estimated using an open-loop rotation-based counting method. The digital counter assumes a constant paper length per roller revolution, ignoring changes in roll diameter, slippage, and tension variation. As rewinding progresses and the roll diameter increases, cumulative length errors occur. Such indirect measurement techniques have been widely identified as a major source of dimensional inaccuracies in traditional manufacturing processes (Schwung et al., 2023).

4.5 Limitations of the Semi-Automatic System

The semi-automatic control approach exhibits several critical limitations:

- Inaccurate roll length control, caused by open loop counting and diameter variation, leading to material loss or customer dissatisfaction (Wang et al., 2024).
- High manual intervention, increasing labour dependency and operator-induced variability (Ragai et al., 2022).
- Low productivity, due to manual sequencing and frequent stoppages, which limits achievable production rates (Mahmood et al., 2017).
- Paper damage during start and stop, resulting from sudden acceleration and deceleration without controlled speed transitions (Seiger et al., 2022).
- Over-rolling due to motor inertia, as the motor continues rotating during VFD deceleration after the counter trip signal (Klopot et al., 2021).

4.6 Semi-Automatic System Block Diagram

Figure 1. illustrates the block diagram of the existing semi-automatic thermal paper slitting and rewinding system without PLC control. The system operates through manual operator inputs, standalone motor speed control using a VFD, and open-loop length measurement based on a proximity sensor and digital counter. Pneumatic actuators for air feed, paper insertion, and pressure application are controlled via 230 V AC solenoid valves actuated by selector switches. Since no centralized controller or real-time feedback mechanism is employed, all sequencing and decision-making depend on operator intervention and preset counter values. This architecture highlights the inherent limitations of decentralized and open-loop control in achieving accurate length control and consistent production.

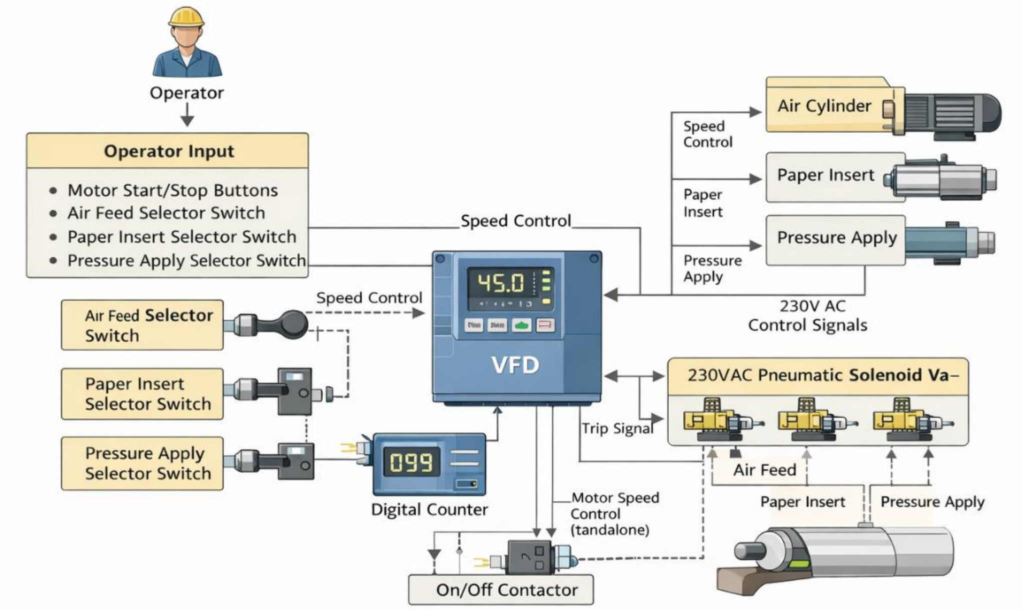

Figure 1. Block diagram of the existing semi-automatic thermal paper slitting and rewinding system without PLC

The existing semi-automatic thermal paper rolling machine represents a traditional open-loop control approach that is inadequate for modern manufacturing requirements. The absence of real-time feedback, centralized control, and intelligent sequencing results in inaccurate length control, low productivity, increased material wastage, and inconsistent product quality. These limitations clearly justify the transition to a fully automated PLC-based system with encoder feedback and HMI supervision, as presented in the subsequent section.

V. PROPOSED PLC–HMI BASED FULLY AUTOMATED CONTROL SYSTEM

5.1 System Architecture and Automation Concept

The limitations of the existing semi-automatic thermal paper rolling system—namely inaccurate roll length control, high manual intervention, and low productivity—necessitate a transition to a fully automated control architecture. In contemporary manufacturing environments, such limitations directly affect product quality, production efficiency, and scalability. Modern manufacturing systems increasingly rely on PLC-based centralized control with real-time feedback to ensure precision, repeatability, and operational robustness across varying production conditions (Buergin et al., 2017). In particular, encoder-based closed-loop control has been shown to significantly improve dimensional accuracy and reduce material wastage in length-critical web-handling and winding applications (Yılmaz, 2023).

To address these challenges, a PLC–HMI based fully automated control system is proposed for the thermal paper slitting and rewinding machine. The proposed system replaces manual sequencing, selector-switch operation, and counter-based length estimation with programmable logic control, encoder-based length measurement, servo-driven adjustments, and HMI-based supervision. This transition enables deterministic sequencing, real-time feedback processing, and consistent execution of control actions independent of operator skill.

The automation architecture is centered on a Siemens S7-1200 PLC, which coordinates all machine operations, including motion control, pneumatic sequencing, safety interlocking, and communication with field devices. Centralized PLC architectures are widely recognized for their deterministic execution, fault tolerance, and high reliability in complex industrial processes (Su et al., 2019). The proposed system integrates an HMI for operator interaction, an incremental encoder for real-time feedback, a VFD-driven AC motor for rewinding, a servo motor for slitting blade positioning, and 24 V DC pneumatic solenoid valves. This integrated architecture ensures seamless coordination between mechanical, electrical, and pneumatic subsystems, aligning with best practices in modern manufacturing automation (Ragai et al., 2022).

5.2 PLC–HMI Based Control Architecture

As shown in Figure 2, the PLC functions as the central controller, receiving process parameters such as target roll length, motor speed settings, batch count, and slitting width from the HMI via industrial Ethernet communication. The HMI serves as the supervisory interface, enabling parameter configuration, real-time monitoring, and manual intervention during setup or maintenance.

Encoder feedback from the main rewinding shaft is processed using the PLC's high-speed counter, enabling accurate real-time length calculation independent of the PLC scan cycle. Based on this feedback, the PLC dynamically regulates motor speed through the VFD and coordinates pneumatic actuators and servo positioning in a synchronized manner. This closed-loop control structure ensures precise length control, smooth operation, and reliable coordination between motion and actuation components.

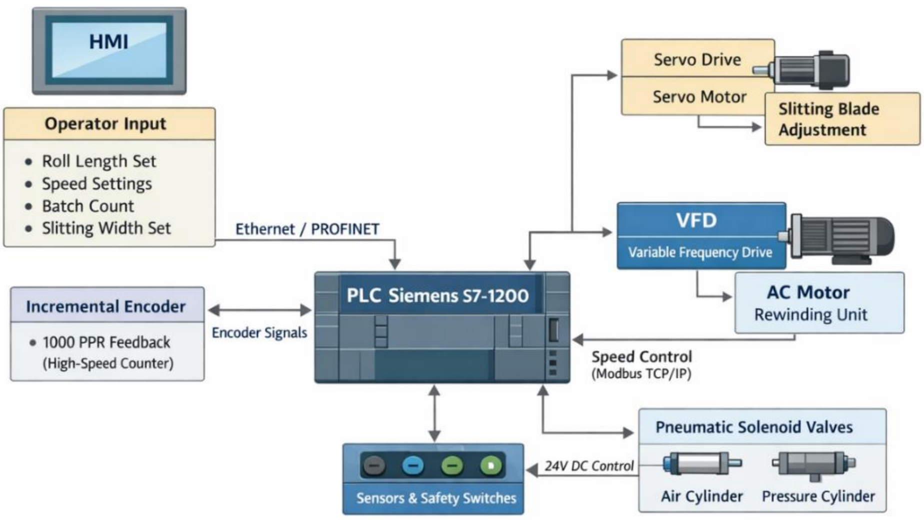

Figure 2. Block diagram of the PLC–HMI based fully automated thermal paper slitting and rewinding system

5.3 Sequential Control and Length Measurement

Unlike the selector-switch-based operation of the semi-automatic system, the proposed system employs PLC-based sequential control, where the entire operating cycle is initiated by a single start command. Upon receiving the start signal, the PLC automatically executes air feed activation, paper insertion, pressure application, and controlled motor start using predefined delays, interlocks, and confirmation signals. This deterministic sequencing eliminates operator-dependent timing variations and significantly improves process repeatability (Gaffurini et al., 2024).

Accurate length control is achieved using an incremental encoder with a resolution of 1000 pulses per revolution (PPR) mounted on the rewinding shaft. Encoder pulses are processed using the PLC's high-speed counter, and the accumulated pulse count is converted into linear paper length through arithmetic scaling based on roller circumference. This closed-loop measurement approach eliminates errors caused by roll diameter variation, slippage, and mechanical wear, which are inherent in proximity-sensor-based counting systems (Gaiardelli et al., 2024; Geng et al., 2024). As a result, the system maintains high accuracy even at elevated operating speeds.

5.4 Intelligent Speed Control and Actuation

One of the key enhancements of the proposed system is intelligent speed transition near the target roll length. The PLC continuously monitors the encoder-based length measurement, and when the remaining length reaches a predefined threshold, it commands the VFD to reduce motor speed from high speed to low speed. The final segment of winding is completed at low speed, after which the motor is stopped precisely at the target length. This strategy eliminates over-rolling caused by motor inertia and VFD deceleration delay.

Smooth speed transitions are essential for preventing material damage and ensuring dimensional accuracy in continuous manufacturing processes, particularly for thin and sensitive materials such as thermal paper (Seiger et al., 2022). In addition, slitting width adjustment is automated using a servo motor, which allows precise and repeatable positioning of the slitting blades through HMI-defined commands. Servo-based positioning significantly reduces setup time and improves width accuracy for different product variants (Jaswal et al., 2025).

All pneumatic actuators are controlled through 24 V DC solenoid valves, improving electrical safety, timing precision, and noise immunity. Centralized PLC control of pneumatic sequencing ensures synchronized operation with motor motion, thereby enhancing overall process coordination and reliability (Yang et al., 2022).

5.5 Hardware, Software, and Communication Integration

The hardware implementation integrates the PLC, HMI, encoder, VFD, servo drive, sensors, and pneumatic actuators into a unified automation platform designed for real-time industrial operation. The PLC program is developed using TIA Portal and organized into modular logic blocks corresponding to sequencing, encoder processing, speed control, and fault handling. Modular PLC software structures have been shown to improve maintainability, scalability, and long-term system evolution in industrial automation applications (Vogel-Heuser et al., 2017).

Communication between the PLC, HMI, and VFD is established using industrial Ethernet and Modbus TCP/IP, enabling reliable real-time data exchange and supervisory monitoring. Process variables such as current roll length, motor speed, actuator status, and alarm conditions are continuously updated and displayed on the HMI. This communication-enabled architecture improves transparency, diagnostics, and operational efficiency, which are fundamental requirements of intelligent manufacturing systems (Yılmaz, 2023).

The proposed PLC–HMI based fully automated control system integrates encoder feedback, intelligent speed control, servo-based positioning, and centralized PLC sequencing to overcome the limitations of the existing semi-automatic machine. The automation strategy delivers accurate roll length control, reduced material wastage, higher productivity, and consistent product quality. This integrated approach demonstrates the practical benefits of upgrading legacy paper converting machines using modern PLC-based automation and forms the foundation for the experimental evaluation presented in the subsequent section.

VI. RESULTS AND PERFORMANCE EVALUATION

6.1 Evaluation Methodology

The performance of the proposed PLC–HMI based automated thermal paper rolling system was evaluated through a comparative experimental analysis against the existing semi-automatic configuration. The evaluation focused on key performance indicators that directly influence product quality and production efficiency, including roll length accuracy, production time, material wastage, repeatability, paper quality, and operator dependency.

All experimental trials were conducted under identical operating conditions using the same paper grades, core diameters, winding tensions, and target roll lengths to ensure a fair and unbiased comparison. For each configuration, multiple production cycles were executed to assess consistency and repeatability. Final roll lengths were measured using calibrated measuring instruments to accurately quantify deviation from the set value. Such controlled comparative evaluation methodologies are widely adopted for validating the effectiveness of automation upgrades in manufacturing systems and for ensuring reproducibility of results across operating conditions.

6.2 Performance Improvement Analysis

6.2.1 Roll Length Accuracy and Material Wastage

In the existing semi-automatic system, roll length estimation was based on proximity sensor–driven rotation counting. This open-loop approach resulted in noticeable length deviations due to variations in roll diameter during winding, mechanical slippage between the paper and rollers, and delayed motor stopping caused by inertia. These factors cumulatively contributed to inconsistent roll length and excess paper consumption.

In contrast, the proposed system employed encoder-based closed-loop length measurement, enabling continuous real-time monitoring of actual paper feed and precise stopping exactly at the target length (Mahmood et al., 2017).

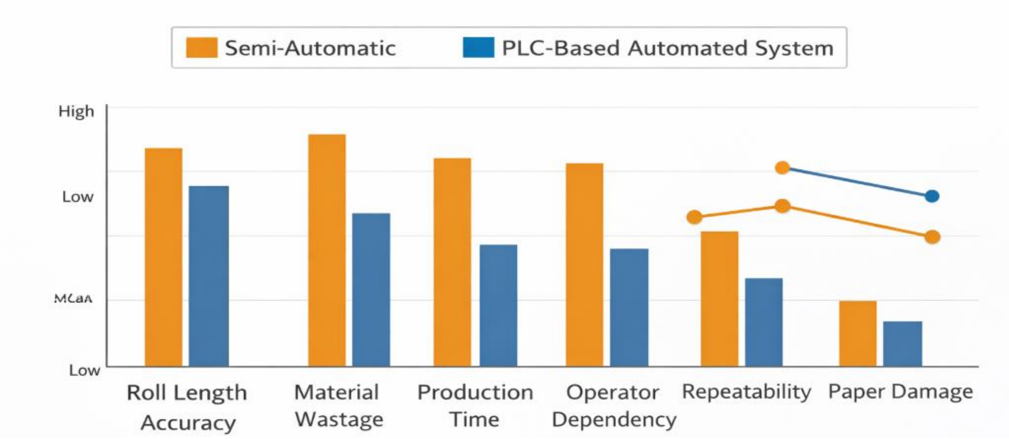

Figure 3. Performance comparison of semi-automatic and PLC-based thermal paper rolling systems.

As illustrated in Figure 3, the automated system achieved a substantial improvement in roll length accuracy, with deviation reduced to a negligible margin. Encoder feedback combined with intelligent speed transition logic ensured accurate length completion, confirming its effectiveness for precision paper converting applications (Jaswal et al., 2025; Seiger et al., 2022). In addition, controlled deceleration near the target length minimized excess winding caused by motor inertia, leading to a significant reduction in material wastage (Yang et al., 2022). This improvement directly translates into better utilization of jumbo rolls and reduced production losses.

6.2.2 Production Time, Repeatability, and Operator Dependency

The semi-automatic system required frequent manual intervention for pneumatic actuation, pressure application, and motor control, which increased cycle time and introduced operational variability between production cycles. Differences in operator response time and manual sequencing further contributed to inconsistent performance.

In contrast, the PLC-based system automated pneumatic sequencing and motor speed regulation, resulting in reduced production time and improved throughput. Once the cycle was initiated, all operations were executed automatically according to predefined logic without interruptions.

PLC-controlled sequencing ensured consistent execution of each operation with fixed timing and conditions, independent of operator skill. As shown in Figure 3, the automated system exhibited higher repeatability and significantly lower operator dependency. Reduced human involvement also improved operational safety and reliability, consistent with findings reported in PLC-based manufacturing studies (Mo et al., 2023; Su et al., 2019).

6.2.3 Paper Quality and System Reliability

Paper damage during start–stop operations was a recurring issue in the semi-automatic system due to abrupt acceleration and sudden stopping of the rewinding motor. These uncontrolled transitions often resulted in tearing, wrinkling, or uneven winding, particularly for thinner paper grades.

The proposed system employed smooth acceleration and intelligent speed transition near the target length, which prevented sudden mechanical stress on the paper web and significantly improved roll quality (Seiger et al., 2022). Uniform winding tension and controlled deceleration contributed to consistent roll density and improved end-use performance.

Furthermore, the centralized PLC architecture enabled stable and predictable control behavior during extended operation. Integrated sensors, interlocks, and fault handling routines allowed early detection of abnormal conditions, thereby enhancing system reliability and reducing unplanned downtime. Such centralized PLC-based control architectures are widely recognized for their robustness and suitability in industrial environments (Krupa et al., 2021; Yılmaz, 2023).

6.3 Comparative Performance Summary

A consolidated comparison of key performance parameters for both systems is presented in Table 2. The comparison clearly highlights improvements in roll length accuracy, reduction in material wastage, shorter production time, improved repeatability, reduced operator dependency, and enhanced paper quality achieved through the proposed automation strategy. Such comparative performance evaluations effectively demonstrate the tangible benefits of automation in manufacturing systems (Ragai et al., 2022).

Table 2. Comparative Performance Analysis

Parameter	Semi-Automatic System	PLC-Based Automated System
Roll length accuracy	Low	High
Material wastage	High	Minimal
Production time	Longer	Reduced
Operator dependency	High	Low
Repeatability	Inconsistent	Highly consistent
Paper damage	Frequent	Rare

Overall, the experimental results clearly indicate that the PLC–HMI based automation system significantly outperforms the semi-automatic configuration in terms of accuracy, productivity, material utilization, and operational consistency. The integration of encoder-based closed-loop control, automated sequencing, and intelligent speed regulation validates the suitability of PLC-based automation for thermal paper rolling and similar paper converting applications.

VII DISCUSSIONS

The experimental results demonstrate that the observed performance improvements are primarily attributable to the transition from open-loop to closed-loop control and the centralized PLC-based sequencing architecture. In the semi-automatic system, roll length accuracy was inherently limited by the assumption of constant roller circumference and fixed stopping behavior. As the rewinding diameter increased during operation, cumulative length errors became unavoidable. By contrast, the encoder-based closed-loop strategy continuously measured actual shaft rotation and converted it into real-time linear paper length, enabling precise compensation for diameter variation and mechanical slippage. This explains the substantial reduction in length deviation observed in the automated system and confirms the suitability of encoder feedback for length-critical paper converting applications (Jaswal et al., 2025).

The intelligent speed transition logic implemented in the proposed system played a critical role in minimizing material wastage and improving paper quality. Rather than relying on abrupt stopping based on a counter threshold, the PLC dynamically adjusted motor speed as the target length was approached. This controlled deceleration reduced inertial effects and eliminated over-rolling, which is a common limitation in conventional rewinding systems. Similar findings have been reported in manufacturing studies emphasizing smooth motion profiles for preventing material damage and improving dimensional consistency (Seiger et al., 2022; Yang et al., 2022). From an operational perspective, this approach directly contributes to improved utilization of jumbo rolls and lower cost per finished roll.

The reduction in production time and operator dependency highlights the broader productivity benefits of PLC–HMI based automation. Automated pneumatic sequencing and deterministic control logic eliminated variability associated with manual intervention, resulting in consistent cycle times across production runs. This repeatability is particularly important in small- and medium-scale paper converting industries, where production planning and workforce availability often constrain throughput. The results align with prior studies showing that PLC-controlled systems significantly enhance operational consistency and safety by reducing reliance on operator skill and reaction time (Mo et al., 2023; Su et al., 2019).

From an industrial implementation standpoint, the proposed automation strategy offers a practical and scalable upgrade path for legacy thermal paper rolling machines. The improvements achieved were realized without major mechanical redesign, demonstrating that substantial gains in accuracy and productivity can be obtained through control system modernization alone. This makes the solution economically attractive for manufacturers seeking incremental adoption of Industry 4.0 principles while maintaining existing equipment. The demonstrated reliability and performance stability further support the feasibility of deploying similar PLC-based automation architectures across a wide range of web-handling and paper converting applications (Krupa et al., 2021; Yılmaz, 2023).

CONCLUSION AND FUTURE SCOPE

This paper presented the design, implementation, and performance evaluation of a PLC–HMI based fully automated thermal paper slitting and rewinding machine, developed as an upgrade to a conventional semi-automatic system commonly used in small- and medium-scale paper converting industries. The study clearly demonstrated that traditional counter-based and manually operated systems are limited in terms of roll length accuracy, productivity, repeatability, and material utilization, making them unsuitable for modern quality-driven manufacturing environments.

The proposed automation architecture, centered on a Siemens S7-1200 PLC, integrated incremental encoder feedback, servo-based slitting blade positioning, HMI-driven parameterization, and communication-based motor control. The adoption of encoder-based closed-loop length measurement enabled accurate real-time monitoring of paper feed and eliminated errors caused by roller diameter variation, slippage, and motor inertia. This confirms the superiority of feedback-based control over open-loop methodologies for precision manufacturing applications (Jaswal et al., 2025).

The implementation of intelligent speed transition logic, in which the rewinding motor operates at high speed during most of the cycle and switches to low speed near the target length, proved effective in preventing over-rolling and paper damage. Controlled deceleration ensured exact stopping at the desired roll length—an issue that could not be resolved in the semi-automatic system. Similar benefits of smooth motion control for improved quality and reduced material waste have been reported in prior studies (Seiger et al., 2022).

The integration of an HMI significantly enhanced operator interaction by enabling centralized parameter setting, real-time monitoring, and fault visualization. Reducing operator involvement to a single start command minimized human dependency and improved operational consistency. These findings are consistent with research emphasizing the role of HMI-enabled automation in improving usability and efficiency in industrial systems (Mo et al., 2023).

Experimental results confirmed substantial improvements in roll length accuracy, reduction in material wastage, increased throughput, and enhanced repeatability when compared with the semi-automatic system. These outcomes validate the effectiveness of PLC-based centralized control architectures for hybrid discrete–continuous manufacturing processes (Su et al., 2019). Moreover, the results demonstrate that upgrading legacy machines with modern automation solutions can yield significant performance gains without requiring major mechanical redesign, supporting wider adoption in developing manufacturing sectors (Atieh et al., 2023). The proposed system also aligns with the principles of intelligent and flexible manufacturing under the Industry 4.0 framework (Yılmaz, 2023).

From an industrial perspective, the proposed automation strategy offers tangible economic and operational benefits, particularly for small- and medium-scale manufacturers. Improved length accuracy and reduced material wastage directly lower production costs, while enhanced repeatability and reduced operator dependency simplify workforce training and production planning. The ability to achieve these improvements through control system modernization—rather than extensive mechanical modification—makes the solution both scalable and cost-effective, thereby lowering barriers to automation adoption in resource-constrained manufacturing environments.

Despite the achieved improvements, several opportunities exist for further enhancement. Future work may focus on integrating advanced control algorithms, such as adaptive or model predictive control, to optimize winding tension and speed under varying paper grades and operating conditions (Klopot et al., 2021; Krupa et al., 2021). The incorporation of data-driven monitoring and analytics could enable predictive maintenance and continuous performance optimization, which are key features of intelligent manufacturing systems (Yang et al., 2022).

Additionally, the automation framework can be extended to support networked manufacturing and remote supervision, allowing integration with Manufacturing Execution Systems (MES) or cloud-based platforms for centralized monitoring and diagnostics (Schwung et al., 2023). The application of machine vision systems for defect detection, edge inspection, and roll alignment verification also presents a promising direction to further enhance quality assurance (Seiger et al., 2022). Finally, the proposed PLC-based automation concept can be generalized and applied to other web-handling and paper converting machines, such as film winding, foil slitting, and textile processing equipment, owing to its modular and scalable architecture (Vogel-Heuser et al., 2017).

DECLARATIONS

Conflict of Interest

The authors declare that they have no conflict of interest related to the publication of this work.

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This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Ethical Approval

This study does not involve human participants or animals and therefore does not require ethical approval.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Consent to Participate / Publish

Not applicable.

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