# DEVELOPMENT OF A PLC-BASED CONTROL SYSTEM FOR DEMONSTRATING A SCALABLE INDUSTRIAL PROCESS IN A LAB ENVIRONMENT


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# Development of a laboratory-scale sheet stamping machine based on a PLC-Based Control System

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by

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# ABSTRACT

A significant gap often exists between the theoretical knowledge of industrial automation taught in universities and the practical skills required in the field. To address this challenge, this thesis presents the complete development of a Programmable Logic Controller (PLC) based control system designed to demonstrate a scalable industrial process within a laboratory environment.

The project's core is a lab-scale sheet stamping machine, realized through the integration of a Siemens S7-1200 PLC, a KTP700 Human-Machine Interface (HMI), a DC geared motor, a solenoid actuator and an industrial incremental rotary encoder with a resolution of 600 Pulses Per Revolution (PPR) coupled with a measurement wheel, having a circumference of 250 mm. This measurement setting provides a linear resolution of approximately 0.42mm/pulse that was determined to be sufficient for the project’s final goal. The validation for the final system was done using a probabilistic uncertainty analysis. A combined uncertainty of 0.37 mm was achieved and systematic errors were removed. The system automates the process of feeding a paper sheet and stamping it at user-defined intervals. The operator uses the HMI that serves as a monitoring and control panel for this automated system. Its intuitive touch interface design allows the user to monitor real-time process data, fault alarms and to set process parameters defined by the desired length of interval that must be passed between each consecutive stamp and the desired number of total stamps that must be made before the automated cycle ends.

The PLC utilizes these set points to execute its control logic, while tracking the sheet’s linear travel by processing the encoder's pulse count. This thesis documents the complete engineering workflow, from defining the system requirements and selecting components, to the mechanical design in SolidWorks, configuration of the UltiMaker Cura Software for converting the designed model into a 3D-printer compatible G-Codes, which were optimized for quality and time consumption and the resulting mechanical 3D printed fabrication, electrical connections, PLC and HMI software development in TIA Portal, and final system testing and performance calibration.

The control program, implemented in Ladder Logic, features position tracking using the PLC's high-speed counter, synchronized motor and actuator control, and the implementation of fault detection algorithms for feed roller and stamp actuator, based on the encoder data and the current feedback of the solenoid stamp actuator, respectively.

The resulting platform functions as a successful proof-of-concept for an industrial automated stamping system and serves as a valuable and flexible educational tool. It provides students with a hands-on opportunity to engage with industrial hardware and immediately observe the impact of their changes. A set of guided lab assignments could be developed for students that could include different tasks, such as implementing a new fault detection routine, designing a more intuitive HMI display with alarm history, optimizing the control logic for higher throughput, effectively bridging the gap between academic theory and practical engineering applications.

# ACKNOWLEDGEMENT

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# NOMENCLATURES

## Acronyms

1. **AC** - Alternating Current
2. **ADC** - Analog-to-Digital Converter
3. **CAD** - Computer-Aided Design
4. **CPU** - Central Processing Unit
5. **CTU** - Counter Up
6. **DC** - Direct Current
7. **FDM** - Fused Deposition Modeling
8. **HMI** - Human-Machine Interface
9. **HSC** - High-Speed Counter
10. **I/O** - Input/Output
11. **IEC** - International Electrotechnical Commission
12. **LAD** - Ladder Diagram
13. **PLC** - Programmable Logic Controller
14. **PPR** - Pulses Per Revolution
15. **PROFINET** - Process Field Network
16. **TIA** - Totally Integrated Automation
17. **TON** - Timer On-Delay

## Symbols

1. **Dactual** - Actual Measured Distance
2. **Ddesired** - Desired Distance
3. **I** - Current
4. **Pavg** - Average Power
5. **Ppeak** - Peak Power
6. **R** - Resistance
7. **Req** - Equivalent Resistance
8. **tcycle** - Total Cycle Time

9. **A** - Ampere
10. **mA** - Milli Amperes
11. **ton** - Actuation Time (On-Time)
12. **V** - Volts
13. **δ** - Symbol representing Absolute Uncertainty
14. $\Omega$ - Ohms
15. $W$ - Watts

# Chapter 1: INTRODUCTION

## 1.1 Overview

This project is about the design of a small-scale proof of concept of a sheet stamping machine and its simulation in a lab environment. The project uses principles of automation as the basis of development.

Stamping machines serve as an important invention in industrial manufacturing because they have made it easier to stamp accurately, be it sheets of paper, newspaper, metal etc. This project makes this process of stamping paper sheets possible to be demonstrated in a lab environment to students. A programmable logic controller (PLC) and Human Machine Interface (HMI) are used to program and work with.

This thesis goes through the attempt to design a PLC based variable length system by taking input of a desired interval for the stamping from the human through an HMI screen and stamps the moving paper sheet with accurately separated intervals.

## 1.2 Motivation

Modern industrial automation continues to revolutionize production systems by enhancing process efficiency, precision, and operational safety. However, many engineering students lack practical exposure to real-world industrial automation systems, limiting their ability to bridge the gap between theoretical knowledge and industry demands [1]. The aim of the project is to design and implement a PLC-controlled industrial machine. Students will gain hands-on experience in industrial automation through this interactive lab project.

The motivation to do this project is to improve hands-on learning experiences in industrial automation courses by designing and implementing a lab-based PLC-controlled industrial sheet stamping machine. This research will also contribute to the goal of modernizing educational strategies in engineering programs.

## 1.3 Problem Statement and Solution

Precision cutting and stamping of materials are crucial processes in industrial manufacturing, especially in the packaging industry. Conventional, manual or semi-automated stamping methods may adversely affect quality and throughput and may also pose potential safety risks.

This project solves those issues with a PLC-controlled machine designed for the lab. Real-time feedback and length calculation will be possible due to a rotary encoder. It also features a custom HMI, allowing users to input specific lengths and quantities on the fly.

The result is a practical educational tool. It extends textbook theory, allowing students to experiment with real industrial automation hardware and techniques, like PLC programming or sensor integration.

## 1.4 Objectives

The main objectives of this thesis are as follows:

1. Crafting a sheet stamping machine in a lab scaled environment
2. Creating a reliable control system with a Siemens S7-1200 PLC and industrial-style sensors and actuators, such as a solenoid and an AB phase rotary encoder.
3. Implementing an interactive HMI that lets users alter process parameters and see the results instantly.
4. Developing a system that completes a task and acts as a teaching aid for industrial automation concepts.

## 1.5 Applications

The system architecture in this thesis can be directly used in industrial process as well as in an educational setting.

### *1.5.1 Educational and Training Applications*

This thesis is designed for an applied learning environment.

- PLC Programming and Logic Development: Students get familiar with the Siemens TIA Portal and learn to modify the ladder logic. They can change system behavior, for example modify the stamping sequence or add new functions.
- Integrating Sensor and Actuator: Calibration of industrial hardware, like the AB phase rotary encoder and the solenoid actuator on a PLC is a relevant skill to acquire for students.
- Designing the HMI: Students can design various types of interactive user interfaces that allow users the different parameters.
- Mechatronics and System Integration: The thesis captures core mechanical design concepts like SolidWorks, 3D printing, electrical wiring, and software control.

### *1.5.2 Industrial Process Simulation and Prototyping*

This lab scaled prototype emulates the automation techniques mostly used in industries like stamping, marking, and cutting.

- Packaging Industry: Stamps, labels or cutting packaging material (cardboard or plastic film) use automation.
- Textile and Leather Goods: Automatic stamping of patterns or logos on textiles is a direct application of the functions of the project.
- Printing and Paper Converting: Control is required in newspaper printing and paper goods manufacturing for cutting or marking continuous rolls of paper.
- Electronics Manufacturing: Requires marking or punching of components on printed circuits.

## 1.6 Scope and Limitations

The scope of this thesis is to create an entire educational demonstration system, including hardware design and software development.

### *1.6.1 Within Scope*

- System Design and Construction: using SolidWorks and 3D printing to design the system architecture and fabricate the whole structure
- Hardware Integration: creating a self-contained system by selecting, interfacing, and wiring of all core components, including the Siemens S7-1200 PLC, KTP700 HMI, DC motor, solenoid actuator, and rotary encoder.
- Software Development: The development of a complete control program in Ladder Logic and the design of an intuitive HMI application that allows users full operational control with parameter adjustment.

### *1.6.2 Limitations*

- The project does not incorporate industrial-grade safety features or undergo long-term reliability testing as it is designed for demonstration in a lab environment only.
- The scope does not include an analysis of different stamping materials or the development of an inking/marking system for the stamp head. The project focuses on control system and the process demonstration
- The control logic is limited to a stop and stamp process. More complex control strategies, such as stamping-on-the-fly, are considered outside the current scope.

## 1.7 Thesis Outline

This thesis is divided into six chapters. A brief description of each is given below:

- Chapter 1 introduces the project, motivation, objectives, applications, scope, and provides an overview of the thesis structure.
- Chapter 2 presents a review of existing work and theoretical concepts in industrial automation, focusing on PLCs, HMIs, rotary encoders, actuators, and motors.
- Chapter 3 explains the design of the system architecture, mechanical and electrical design, control system design, and software development.
- Chapter 4 outlines the assembly process, wiring, programming, testing, troubleshooting, and debugging.
- Chapter 5 provides the assessment of the performance of the system, reports conclusions about the results against the objectives and summarizes the challenges faces.
- Chapter 6 provides a conclusion, contributions, and provides recommendations on improvisations.

# Chapter 2: LITERATURE OVERVIEW

## 2.1 Industrial Automation

Automation is the adoption of technology in a process with a machine and with minimal human participation [2]. It entails the application of the control systems, which may include the computers or PLCs to operate and manage the industrial machinery and processes [2]. Automation is excessively used to enhance productivity, quality and consistency of products. It positively improves operational safety in dangerous areas as human activity is eliminated, and it also aids in reducing costs of labor.

## 2.1.2 Types of Automation

There are three types of automation, each of which is adapted to the nature of production volumes and product change [2]:

1. Fixed Automation is where the process flow of operations is defined by the equipment layout. The operations are simple in nature but cannot be easily modified. Its high costs and inflexibility make it suitable for mass production mostly.

2. Programmable Automation involves programming the sequence of operations based on the product configurations. It is used where flexibility is required in batch production. It is in this type of pf automation where PLCs are used.

3. Flexible Automation is rather an extension of programmable automation. In this multiple product variations can be produced without losing any production time in changeovers. Here there is possibility to create different combinations and arrangements of products rather than having to create batches of them.

## 2.2 Programmable Logic Controllers (PLCs)

### *2.2.1 Programmable Logic Controllers (PLCs)*

A Programmable Logic Controller is microprocessor-based controller that runs functions, sequences and logic by storing instructions and controlling machines and processes [3].

### *2.2.2 How PLCs Work: The Scan Cycle*

The PLC is operating based on the scan cycle which continuously repeats itself. It offers real time control by reading inputs, executing program, and updating outputs. The PLC runs by gathering the status of sensors that are connected and then executes the required task based on the information gathered and then carries the programmed control rules [3]. This cycle happens very quickly, in about a few milliseconds.

### *2.2.3 The Siemens SIMATIC S7-1200*

The controller used in this project is a S7-1200 CPU 1215C. It is a robust device with set of onboard digital and analog I/O, integrated High-Speed Counters (HSCs) that can process signals up to 100 kHz, and two integrated PROFINET ports for communication [4]. These features make it well-suited for a project like ours [3]. The programming is done using the TIA (Totally Integrated Automation) Portal and supports languages defined in IEC 61131-3, including Ladder Diagram (LAD) [5].

## 2.3 Human-Machine Interface (HMI)

A Human Machine Interface visualizes process variables and uses graphical displays to interact with automated systems. It translates complex data process into accessible visual information. An operator can use the HMI to control operations, monitor system status, and change any process parameters in real-time on the graphic display [6]. The Siemens KTP700 Basic PN is used in this project. It has an in-built touch-screen display and can communicate with the S7-1200 PLC through PROFINET.  Like S7-1200 PLC, the TIA Portal is used for configuration and operation processes, enabling quicker setup and simplified maintenance.

## 2.4 Rotary Encoders

### *2.4.1 Types of Encoders*

A Rotary encoder is an electro-mechanical sensor that can provide position and speed feedback by converting the position of a rotating wheel into an electrical [7]. The two main types occasionally used in the manufacturing industry are absolute encoders, which provide a unique code as position feedback, and incremental encoders, which generate pulses as position feedback. The incremental encoder is used in this project.

### *2.4.2 Working Principle of an Incremental Quadrature Encoder*

The project uses an industrial grade incremental AB phase encoder. It creates separate pulse trains, Channel A and Channel B. These are 90 degrees out of phase with each other. The PLC's HSC can compute the amount of rotation and the direction by monitoring the number of pulses and the phase relationship between the pulse trains. Motion control systems use this technique is used for accurate position tracking [8].

## 2.5 Actuators and Motors

Actuators help in converting electrical signals into physical motion. They are acting on the commands received from the PLC [9].

- DC Geared Motor: The DC geared runs the motor paper feed mechanism. The integrated gearbox reduces the motor's high speed while proportionally increasing its output torque. This high torque ensures to pull the paper smoothly from the source roll.
- Solenoid Actuator: The push-pull solenoid actuator runs the stamping action. A solenoid converts electrical energy into a linear push or pull motion. When current flows through its coil, a magnetic field is generated, which exerts a force on a ferromagnetic plunger. They have a quick response time and a simple ON/OFF control, making them suitable for rapid and repetitive actions.

# Chapter 3: SYSTEM DESIGN AND METHODOLOGY

## 3.1 System Requirements

Before starting the design, a set of requirements was in set in place to guide the development of the lab-scale stamping machine. These requirements are categorized into functional, metrological, physical, and operational.

### *3.1.1 Functional Requirements*

These define the basic actions the system must be able to perform:

- The system must automatically feed a continuous paper sheet from a source roll.
- It must provide a Human-Machine Interface for an operator to input two key parameters: the desired stamping interval (in millimeters) and the total number of stamps per cycle.
- The system must use the AB phase rotary encoder to track the linear distance the paper has moved.
- The solenoid actuator must stamp precisely at the specified interval.
- The system must stop the process once the user-defined total is reached by automatically counting the number of completed stamps.
- The system must run in a continuous operation mode if the user has not specified stamp count.

### *3.1.2 Metrological Requirements*

These requirements define the evaluation criteria and the desired system performance:

- Positional Uncertainty: An absolute uncertainty of 1cm is allowed.
- Standard Deviation: The deviation between stamp placements should not exceed ±5mm in a continuous cycle.
- Minimum Throughput: The system should be stamping at a speed of 25 stamps per minute at a 100 mm interval setting.

- HMI Response Time: HMI inputs should be registered, and screen data should be updated with less than a 200 ms delay.

### *3.1.3 Physical Requirements*

These are the requirements for the physical architecture and aspect of the machine:

- Dimensions: The machine exterior must be compact fitting within a 900mm x 900mm x 400mm (L x W x H) envelope.

- Weight: To ensure portability, the weight of the assembled machine and all devices should not be more 10 kg.

- Materials: Mechanical parts, customized according to the machine, must be designed using standard FDM 3D printing with PLA material.

- Power: The system should operate from a standard 230V, 50 Hz AC wall outlet and internally step down the power to 24V DC for all control components.

### *3.1.4 Operational Requirements*

These requirements outline the conditions for smooth system operation:

- User Interface: The HMI must be self-explanatory so users with basic technical knowledge can easily operate the machine.

- Operating Environment: The device should be designed for operating in a standard indoor laboratory environment.

- Modularity: The individual components like the encoder or motor should be easily replaced or upgraded for future experiments keeping the design modular.

## 3.2 System Architecture

The system architecture is based on a central Siemens S7-1200 PLC. The operational workflow is as follows:

1. User Input: The user selects the stamping interval and the number of stamps that are required into the Siemens KTP700 HMI. These parameters are transmitted to the PLC through PROFINET.
2. Actuation: The PLC receives parameters from HMI and transmits signal to the DC motor which will drive the feed roller. The sheet starts to pull from the roll.
3. Position Feedback: The high-friction measurement wheel starts rotating as the paper is moving. This AB phase rotary encoder is attached to the wheel which generates quadrature pulse signals corresponding to the linear distance traveled by the paper.
4. Control Logic: The PLC's HSC input receives the pulses from the encoder and simultaneously calculate the position of the paper. When the measured distance reaches the desired interval, the command to stop is sent to the motor.
5. Stamping Operation: As soon the stop command is sent, the PLC triggers a signal to the solenoid actuator to perform the stamping action.
6. Process Repetition: The internal position counter of the PLC is reset and restarts the motor to begin the next cycle. This process is repeated until the desired number of stamps is reached.

### *3.2.1 Block Diagram*

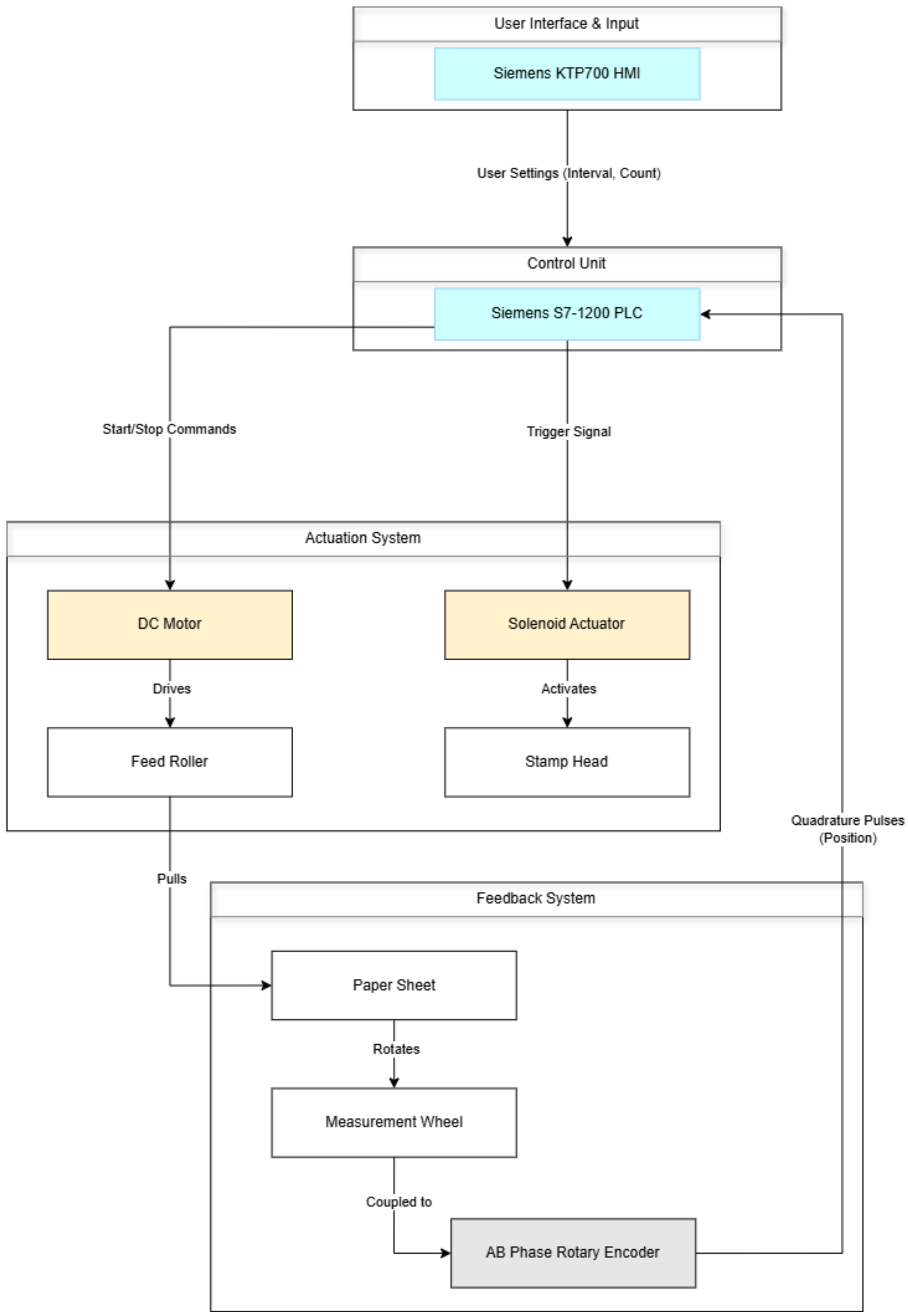


*Figure 1 System Architecture Block Diagram*

## 3.3 Mechanical Design

The mechanical design was envisioned to be compact and modular. The structure was designed in SolidWorks CAD software and most of the custom components were made using Fused Deposition Modeling 3D printing for rapid prototyping and easy assembly.

The initial concept, shown in Figure 3.1, outlines the basic layout of the system. A gantry-style frame holds the stamping mechanism over the paper path.

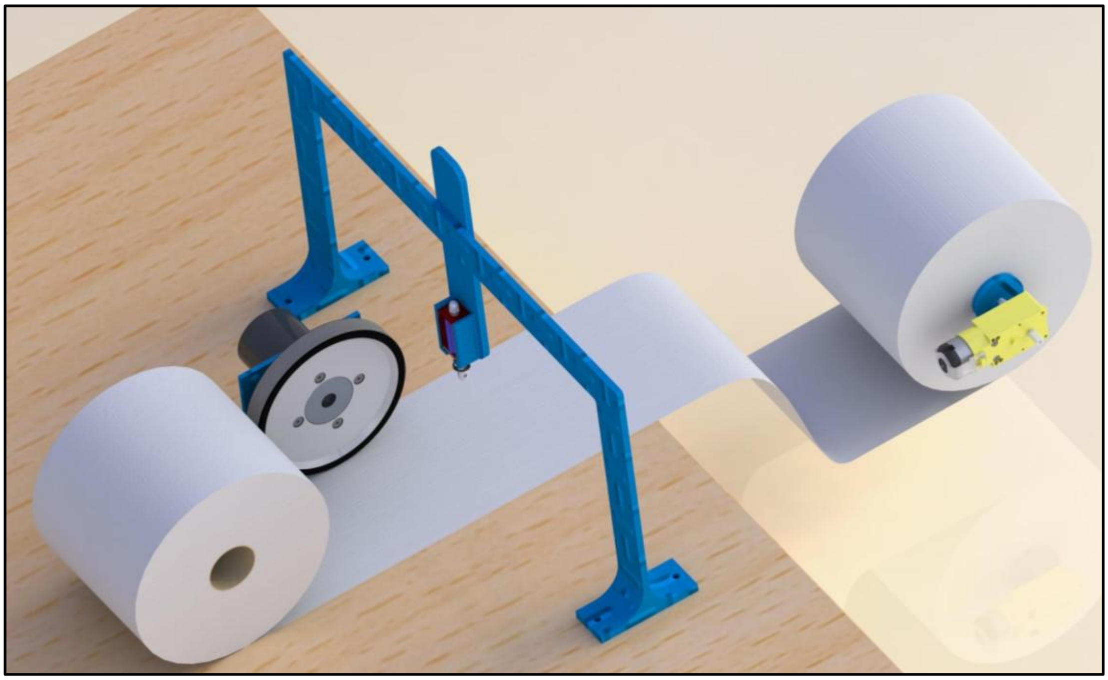

*Figure 2 Initial Concept Design*

The mechanical system is broken down into three key sub-assemblies:

### *3.3.1 Paper Feed Mechanism*

This consists of two rollers; the upper roll holds the source paper roll and moves freely. the lower motor-driven roller pulls the paper through the system. To connect the DC motor's shaft directly to this feed roller, a custom 3D-printed coupling was designed. This helped in ensuring an efficient torque transfer.

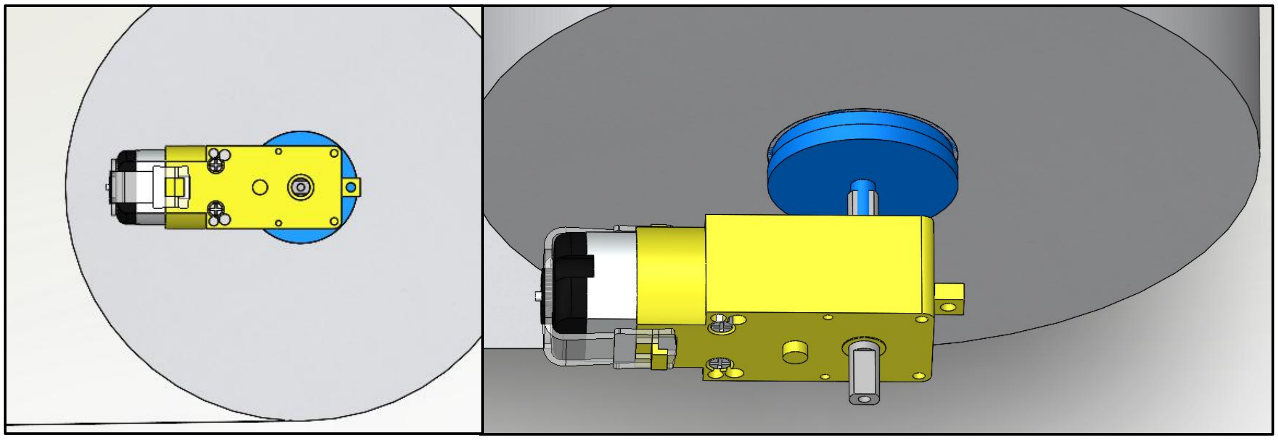

*Figure 3 Feed roller shaft design*

### *3.3.2 Stamping Gantry*

The stamping head assembly is held by a vertical blue frame at a fixed height above the paper. The electromagnetic solenoid actuator is mounted on it by a 3D-printed clamp. A

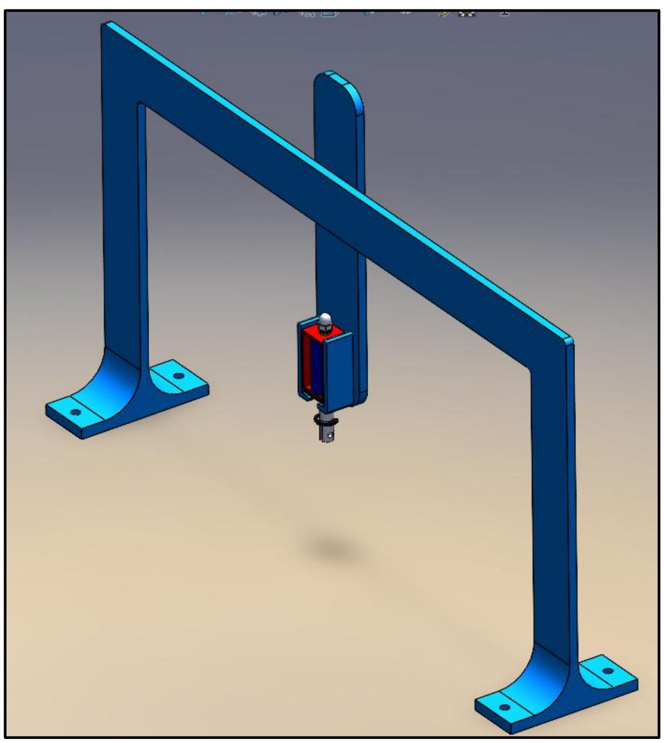

*Figure 4 Modular Stamp Gantry Assembly*

simple stamp head is attached to the actuator's plunger, which moves vertically to mark the paper.

### *3.3.3 Sensor Mounting*

Although not present in the initial concept render, the final design incorporates a crucial mount for the rotary encoder. This custom 3D-printed fixture holds the encoder and its measurement wheel in firm contact with the paper surface to ensure accurate tracking of linear movement.

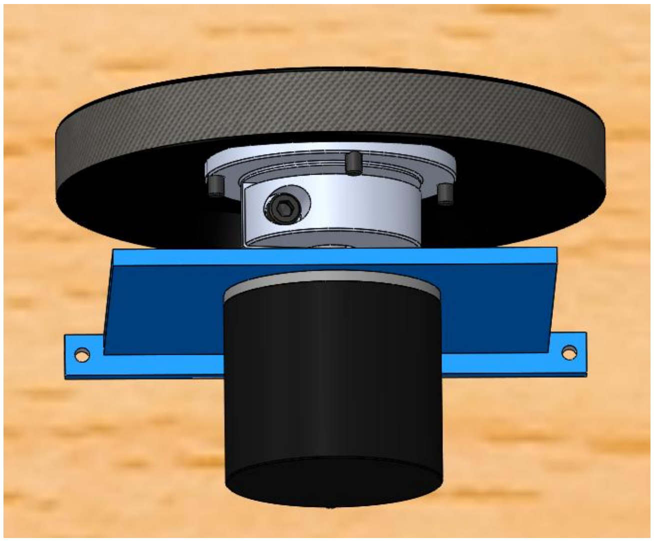

*Figure 5 Encoder Mount and Measurement Wheel (top view)*

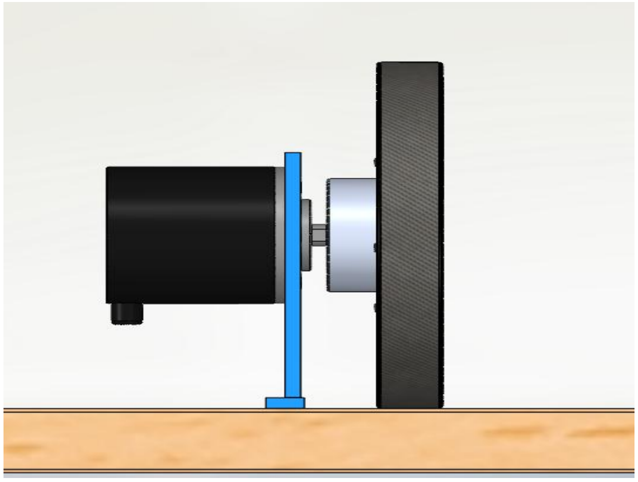

*Figure 6 Side View*

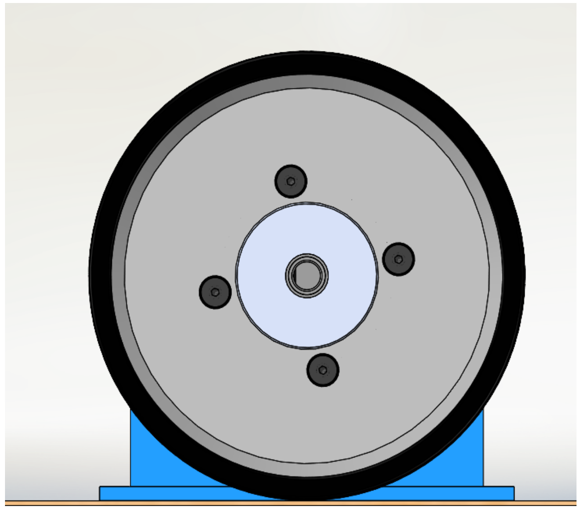

*Figure 7 Measurement wheel contact with paper*

### *3.3.4 Measurement Wheel EW-014*

This measurement wheel was used for the project. It is an Industrial Encoder Measurement Wheel. The outer nominal circumference of this measurement wheel is 250mm which is provided in the specification sheet from the manufacturer. It is made of aluminum alloy rubber which offers more friction when it is put in contact with a moving paper sheet.

*Figure 8 Measurement Wheel For Encoder*

## 3.4 Electrical and Electronic Design

The electrical design focuses on the selection and interfacing of components to create a reliable control system managed by the PLC.

The electrical design focused on ensuring proper interfacing and compatibility of all components within a reliable control system managed by the provided PLC and HMI. The Siemens PLC and HMI were the central control elements, and the remaining components were selected accordingly to achieve both industrial relevance and lab-scale feasibility

### *3.4.1 PLC – Siemens S7-1200 CPU 1215C AC/DC/RLY*

A Siemens S7-1200 series, CPU 1215C AC/DC/Rly (Article No. 6ES7 215-1BG40-0XB0) was provided as the central controller. Its robust performance integrated high-speed counters for encoder processing, and integration with the TIA Portal software environment made it the backbone of the control system [5].

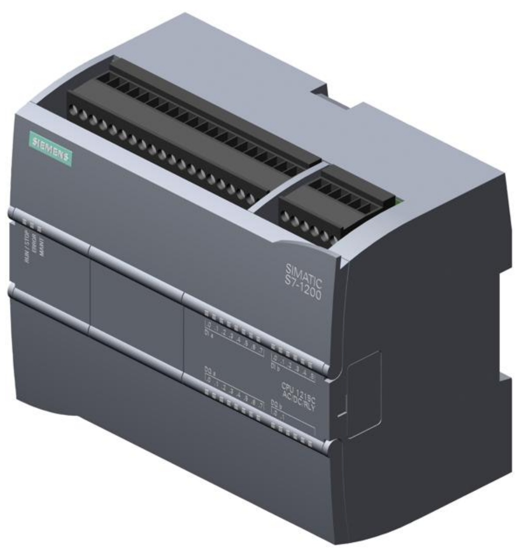

*Figure 9 Siemens S7 – 1215C AC/DC/RLY PLC*

The Siemens S7-1200 CPU 1215C AC/DC/RLY is a compact yet powerful PLC designed for industrial automation applications.

The following tables include the general specifications and features, power supply and sensor power of the S7-1200 CPU 1215C, sourced from the S7-1200 CPU System manual [4]:

| **Technical data** | **CPU 1215CAC/DC/Relay** |
|---|---|
| Product Number | 6ES7215-1BG40-0XB0 |
| Power dissipation | 14 W |
| Electrical current available (SM and CM bus) | 1600 mA max. (5 V DC) |
| Electrical current available (24 V DC) | 400 mA max. (sensor power) |
| Onboard digital I/O | 14 inputs/10 outputs |
| Onboard analog I/O | 2 inputs/2 outputs |
| Bit memory (M) | 8192 bytes |
| High-speed counters | Up to 6 configured to use any built-in or SB inputs.<br>100/80 kHz (Ia.0 to Ia.5)<br>30/[1]20 kHz (Ia.6 to Ib.5) |

Power supply and sensor power (CPU 1215C) [4]:

| **Technical data** | | **CPU 1215CAC/DC/Relay** |
|---|---|---|
| Voltage range | | 85 to 264 V AC |
| Input current (max. load) | CPU only | 100 mA at 120 V AC<br>50 mA at 240 V AC |
| | CPU with all expansion accessories | 300 mA at 120 V AC<br>150 mA at 240 V AC |
| Inrush current (max.) | | 20 A at 264 V AC |
| Voltage range | | 20.4 to 28.8 V DC |
| Max Output Current Rating | | 400 mA |
| Isolation between CPU Logic & Sensor Power | | Not isolated |

### 3.4.2 HMI - Siemens KTP700 Basic PN

A Siemens KTP700 Basic PN (Article No. 6AV2 123-2GB03-0AX0) was provided for user interaction. It's clear touch interface and native PROFINET communication with the S7-1200 ensured intuitive operation and efficient data exchange.

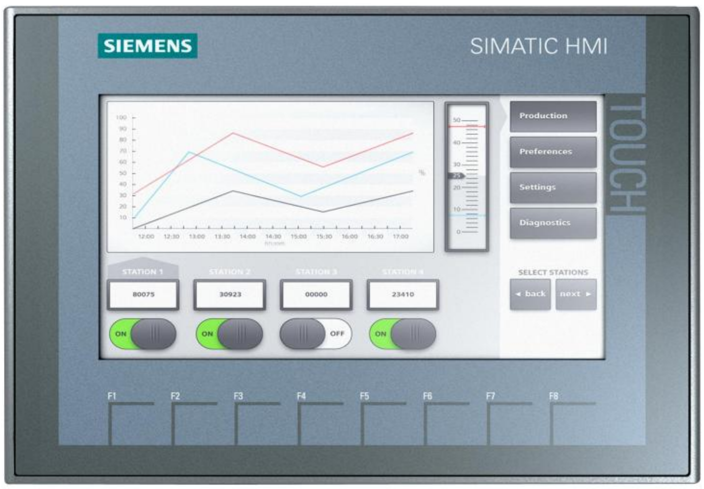


*Figure 10 Siemens KTP 700 Basic - HMI*

The following table contains technical information of the Siemens KTP700 Basic PN, sourced from the datasheet [10]:

| Technical data | Description |
|---|---|
| Display | 7-inch TFT, LED-backlit, 65,536 colors |
| Resolution | 800 × 480 pixels |
| Touch Type | Analog-resistive touchscreen |
| Function Keys | 8 function keys, onscreen numeric keyboard |
| Memory for User Data | 10 MB Flash memory |
| Interfaces | 1x PROFIBUS, 1x USB, 1x RS-485/RS-422 |
| Power Supply | 24V DC (19.2V - 28.8V range) |
| Current Consumption | 230mA @ 24V DC |

### *3.4.3 Position Sensor*

To complement the PLC which was provided, an industrial incremental AB phase rotary encoder with 600 PPR was selected. This encoder provided high-resolution position feedback, which was essential for achieving accurate sheet length measurement and stamping precision.
Some of the key feature of the Industrial Rotary Encoder are as follows:

- Measuring range: The photoelectric incremental rotary encoder is suitable for intelligent control of various displacement measurement, automatic fixed-length leather automatic guillotine machines, steel cut length control, civil measured height human scale, students racing robots
- Maximum mechanical speed: 5000 R / min, with shaft diameter 6 mm, voltage DC 5-24 V, the incremental rotary encoder is light weight and in small size, accounting a little space
- Purpose: The photoelectric incremental rotary encoder can be used to measure the rotational speed, angle and acceleration of the object and the length measurement
- Pulses: 600 p/r (Single-phase 600 pulses /R, two phase 4 frequency doubling to 2400 pulses)


*Figure 11 Industrial Rotary Encoder (600 PPR, Model E38S6G5-600B-G24N)*

### *3.4.4 Actuators*

1. For the paper feed mechanism, a simple DC motor was selected. Although the initial design considered a motor with an integrated encoder, a geared DC motor was chosen instead because the external industrial rotary encoder was already implemented to replicate industrial conditions and offered better compatibility with the PLC.

*Figure 12 DC Geared Motor*

2. For the stamping mechanism, a push-pull solenoid actuator was selected due to its fast response time and straightforward ON/OFF control, making it ideal for high-speed stamping operations.


*Figure 13 Push–pull Solenoid Actuator*

### *3.4.5 System Wiring*

All components are centrally connected to the PLC's I/O terminals. The rotary encoder's A, B phase outputs are wired to the PLC's dedicated high-speed inputs to ensure no pulses are missed. The roller feed motor and solenoid actuator are controlled via the PLC's relay outputs. The HMI is connected to the PLC's PROFINET port for both programming and data exchange. Power is supplied directly by AC mains as a 24V DC source is built-in in our PLC, which is a standard for industrial control systems.

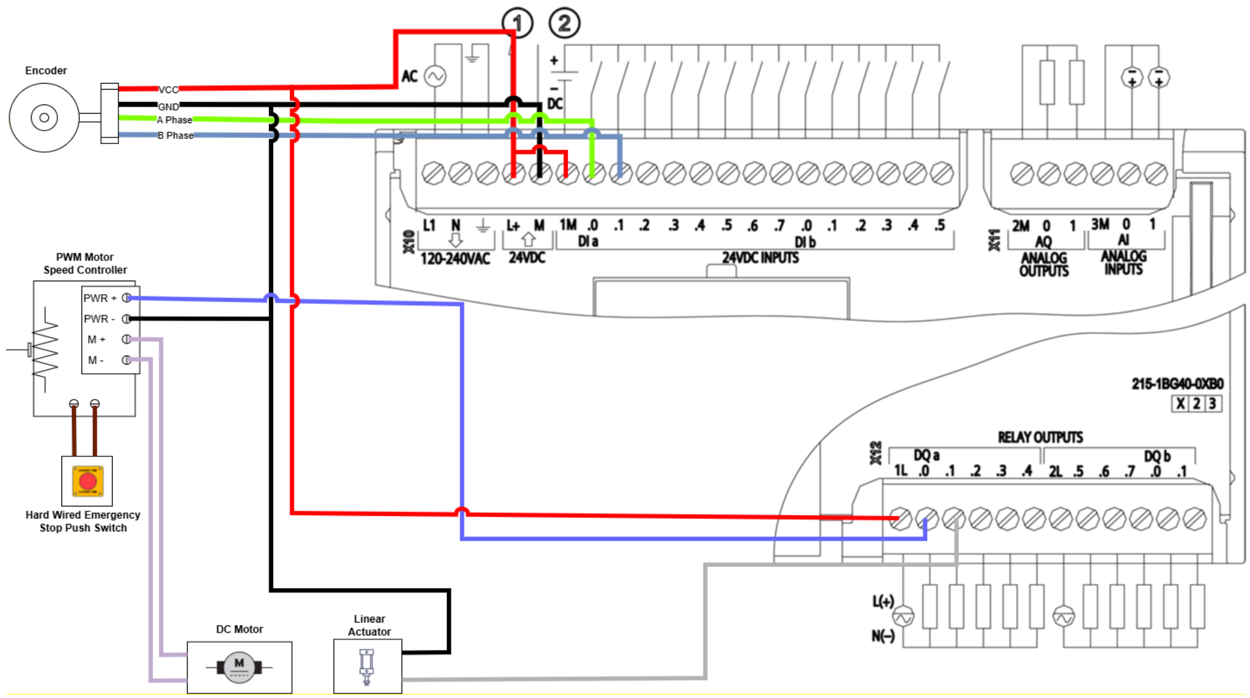


*Figure 14 Wiring diagram*

The wiring diagram in Figure 3.13 doesn't include a shunt resister. The shunt resistor was added later in series on the ground wire of the linear actuator. It was connected to the analog A0 port on the PLC for current feedback, later, as an additional fault detection feature.

### *3.4.6 Control System Design*

The control logic is the core of the system, translating user inputs into mechanical actions. The strategy is to use the rotary encoder for closed-loop position control of an open-loop speed-controlled motor.

The operational sequence is governed by a state machine programmed in the PLC, which follows the logic outlined in the process flowchart. The two key software components are the position tracking and the actuation logic.

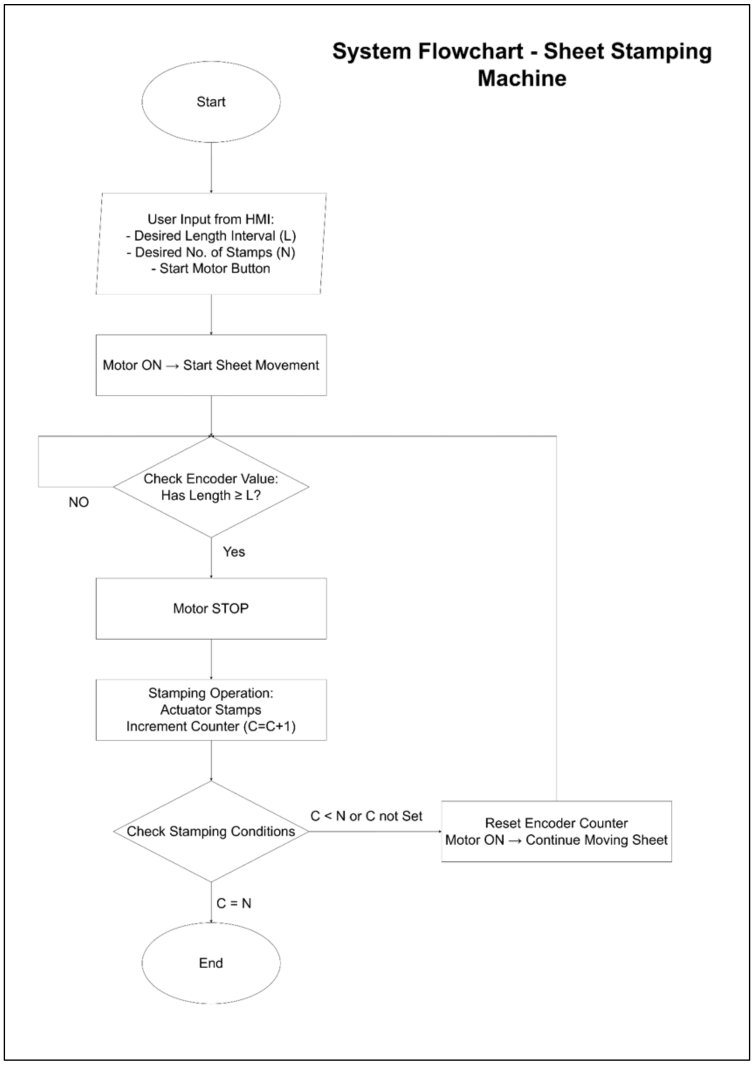


*Figure 15 System Flow Chart*

## 3.5 Calibration Function

The PLC's High-Speed Counter is configured in Quadrature mode to read the A and B signals from the encoder. This allows the counter to automatically increment or decrement based on the direction of paper travel, providing reliable position data [8]. This can be evaluated in the metrological analysis performed for the uncertainty analysis of the distance measurement system.

### *3.5.1 Uncertainty Analysis of the Distance Measurement System*

**Conceptual Framework:** The uncertainty analysis is carried out according to the Guide to the expression of Uncertainty in Measurement (GUM) using the Probabilistic Approach and involved an Indirect Measurement Method, where the measurand (Distance Travelled), is derived from the other directly measured quantities with a functional relationship [11].

The analysis was organized in 2 phases:

1. Data Extraction & Calibration Operation: In this we perform the initial measurements with the theoretical data and identify and correct the systematic error (bias) of our calibration parameter.
2. Uncertainty Propagation: In this phase we determine the uncertainty contributions of the input quantities through the calibration function and propagate them to calculate the combined standard uncertainty of the measurand.

### *3.5.2 Phase 1: Data Extraction & Calibration Operation*

Measurand (Distance Travelled) is a function of HSC and $C_{eff}$

$$D = f(HSC, C_{eff})$$

Our calibration function for the length measurement system is defined as:

$$D = \frac{HSC}{PPR} * C_{eff}$$

Where:

- D = Estimated Distance Travelled
- HSC = Pulse-Count value from High-Speed Counter
- C = Circumference
- PPR = Pulses Per Revolution = 600 (Constant)

The error sources showed that the systematic error is not a constant fixed error and it is proportional to the distance traveled.

The most dominant error is in the effective circumference of the measurement wheel, considering the compression of the rubber when the weight is added on it for better grip with the paper and the wobbling of the wheel itself due to the imperfect coupling with the encoder's shaft and the slippage of the paper. These factors result in an error that is assumed to scale linearly. For example, a 1% error of the circumference would result in a 1% error in the length of the distance that is measured regardless of the set point.

Therefore, an additive offset introduction such as Distance = Measured Distance + Offset would imply a constant mechanical lag (for example, stamp actuator latency) that adds a fixed length to every cut. However, experimental observations show that the error magnitude increases with length.to ensure linearity across the operating range, the suitable metrological approach is the correction of the value of the multiplicative input parameter, Effective Circumference ($C_{eff}$).

Experimental Procedure: For the measurement of the data in the table below, the system was initialized using theoretical values that are before any experimental correction. These values are:

1. Nominal Circumference ($C_{nominal} = 250\ mm$): This is the selected value based on the manufacturer's specifications for EW-014 measurement wheel. It is the theoretical wheel size before considering any of the rubber compression, wobble or manufacturing tolerances.
2. Nominal Pulses ($HSC_{nominal}$): This is the target value of the pulse count calculated by the PLC to reach the set point for the desired length (140mm) of paper displacement under ideal theoretical conditions.

| $(n)$ | $x(n)$ : Length Interval Between Stamps (mm) |
|---|---|
| 1 | 139.12 |
| 2 | 137.45 |
| 3 | 138.88 |
| 4 | 136.92 |
| 5 | 140.15 |
| 6 | 138.23 |
| 7 | 137.89 |
| 8 | 139.54 |
| 9 | 135.80 |
| 10 | 141.02 |
| 11 | 138.45 |
| 12 | 137.11 |
| 13 | 139.78 |
| 14 | 138.33 |
| 15 | 136.55 |
| 16 | 140.50 |
| 17 | 137.67 |
| 18 | 138.95 |
| 19 | 136.20 |
| 20 | 139.46 |

The Empirical Mean ($\overline{\boldsymbol{x}}$) is 138.4mm.

The Standard Deviation is $\boldsymbol{s}(\boldsymbol{x_1}) = \sqrt{\frac{1}{n-1}\sum_{k=1}^{n}(x_k - \overline{\boldsymbol{x}})^2} \approx 1.460\ mm.$

The PLC calculated 336 pulses for the target length of 140mm, with the effective circumference parameter set to its nominal value of 250mm. The stamping system provided the average output stamping interval of $\overline{\boldsymbol{x}} = 138.4\text{mm}$ which revealed a negative systematic bias of -1.6mm. The paper displaced less than expected for the given pulse count. This showed that the effective circumference is smaller than the nominal (250mm) configured in the PLC due to physical effects discussed before.

Now we calculate the combined uncertainty of the Effective Circumference. To determine the standard uncertainty of the effective circumference $u_c(C_{eff})$, we evaluate the uncertainty of input quantities using our calibration function for effective circumference.

$$C_{eff} = \frac{\overline{\boldsymbol{x}}_1 * PPR}{HSC}$$

It is composed of 2 sources, the random variation of the process that contributes as a Type A and the accuracy of the measurement tool that contributes as a Type B source of uncertainty.

1. Type A (Due to the experimental standard deviation of the mean): $$u_A(\overline{\boldsymbol{x}}_1) = \frac{s(x_1)}{\sqrt{n}} = \frac{1.46}{\sqrt{20}} \approx 0.327mm$$
2. Type B (Due to the reference instrument's inaccuracy):

   Although the resolution of the caliper is 0.01 mm, the manufacturer has explicitly stated the accuracy for Borletti CDJB15 which can be defined as the max permissible error (MPE =0.03mm). Assuming a rectangular distribution, we consider this value to evaluate the type B uncertainty.

$$u_B(caliper) = \frac{MPE}{\sqrt{3}} = 0.0173mm$$

The combined uncertainty of the mean using the root sum square method:

$$u_c(\overline{\boldsymbol{x}}_1) = \sqrt{\left(u_A(\overline{\boldsymbol{x}}_1)\right)^2 + \left(u_B(caliper)\right)^2}$$

$$u_c(\overline{\boldsymbol{x}}_1) = \sqrt{(0.327)^2 + (0.0173)^2} \approx 0.327mm$$

The partial derivative of the calibration function with respect to mean length is calculated at the current operating point values for HSC corresponding to 138.4mm, that is $HSC = 336\ pulses$.

$$\frac{\partial C_{eff}}{\partial \overline{\boldsymbol{x}}_1} = \frac{PPR}{HSC} = \frac{600}{336} \approx 1.786$$

Now we evaluate the Type B uncertainty due to the resolution of encoder $u_B(HSC)$. The encoder has a resolution of 1 pulse. Assuming rectangular distribution:

$$u_B(HSC) = \frac{Res}{\sqrt{12}} = \frac{1}{\sqrt{12}} \approx 0.289\,pulses$$

Similarly for the HSC, we obtain the sensitivity coefficients using partial derivative:

$$\frac{\partial C_{eff}}{\partial HSC} = -\frac{\overline{\boldsymbol{x}}_1 \times PPR}{(HSC)^2} = -\frac{138.4 \times 600}{(336)^2} \approx -0.736mm/pulse$$

Now, using the law of propagation of uncertainty:

$$u_c(C_{eff}) = \sqrt{\left(\frac{\partial C_{eff}}{\partial \overline{\boldsymbol{x}}_1}\right)^2 \times \left(u_c(\overline{\boldsymbol{x}}_1)\right)^2 + \left(\frac{\partial C_{eff}}{\partial HSC}\right)^2 \times \left(u_B(HSC)\right)^2}$$

$$u_c(C_{eff}) = \sqrt{(1.786)^2 \times (0.327)^2 + (-0.736)^2 \times (0.289)^2} \approx 0.621mm$$

This systematic error is corrected by applying a calibration operation. By characterizing the effective circumference that physically would have produced the 138.4mm length interval between each stamping operation with 336 pulses.

$$C_{eff} = \frac{\overline{\boldsymbol{x}}_1 * PPR}{HSC_{nom}} = \frac{138.4\,mm * 600}{336\,pulses} \approx 247.143\text{ mm}$$

The calibrated value of $C_{eff} = 247.143mm$ was updated in the PLC control logic.

#### *3.5.3 Phase 2: Uncertainty Propagation*

In this phase we to calculate the final uncertainty of our measurand (D) at the 140mm set point. We take another 20 samples after calibration and the measurement table is below

| $(n)$ | $x_2(n)$ : Length Interval Between Stamps (mm) |
|---|---|
| 1 | 140.25 |
| 2 | 138.80 |
| 3 | 140.55 |
| 4 | 138.10 |
| 5 | 141.35 |
| 6 | 139.15 |
| 7 | 138.65 |
| 8 | 140.75 |
| 9 | 137.95 |
| 10 | 141.45 |
| 11 | 140.88 |
| 12 | 138.40 |
| 13 | 141.05 |
| 14 | 139.20 |
| 15 | 137.80 |
| 16 | 141.10 |
| 17 | 139.30 |
| 18 | 140.10 |
| 19 | 138.25 |
| 20 | 140.65 |

The Empirical Mean $\overline{\boldsymbol{x}}_2 \approx 139.69mm$

The Standard Deviation: $\boldsymbol{s}(\boldsymbol{x_2}) = \sqrt{\frac{1}{n-1}\sum_{k=1}^{n}(x_k - \overline{\boldsymbol{x}})^2} \approx 1.250\ mm$

The random dispersion of resulting length measurements shows us the inherent mechanical repeatability.

We partially differentiate our calibration function for the length measurement with respect to $C_{eff}$ and $HSC$. By doing this, we obtain corresponding sensitivity coefficients and calculate them using operating point values $HSC$, now with pulses corresponding to new mean $\overline{\boldsymbol{x}}_2 \approx 139.69mm$, $HSC = 340$.

Calibration Function for length measurement:

$$D = \frac{HSC}{PPR} * C_{eff}$$

$$\frac{\partial D}{\partial C_{eff}} = \frac{HSC}{PPR} = \frac{340}{600} \approx 0.567$$

$$\frac{\partial D}{\partial HSC} = \frac{C_{eff}}{PPR} = \frac{247.143}{600} \approx 0.412mm/pulse$$

Now, we can obtain the final uncertainty of the measurement system at a set point of 140mm that is characterized by a combined uncertainty of $u_c(D)$

$$u_c(D) = \sqrt{\left(\frac{\partial D}{\partial C_{eff}}\right)^2 \times \left(u_c(C_{eff})\right)^2 + \left(\frac{\partial D}{\partial HSC}\right)^2 \times \left(u_B(HSC)\right)^2}$$

$$u_c(D) = \sqrt{(0.567)^2 \times (0.621)^2 + (0.412)^2 \times (0.289)^2} \approx 0.370mm$$

Confidence Level & Coverage Factor Evaluation: It can be stated that the dominant source of uncertainty comes from the measurement wheel's circumference $(C_{eff})$, while the contribution from the digital resolution of encoder is comparatively small but it is not negligible. Since the dominant part of the uncertainty contribution is derived from the mean value of the repetitive measurements, we can consider the Central Limit Theorem to Imply that the probability distribution of the measurand D can be approximated as a Normal (gaussian) distribution.

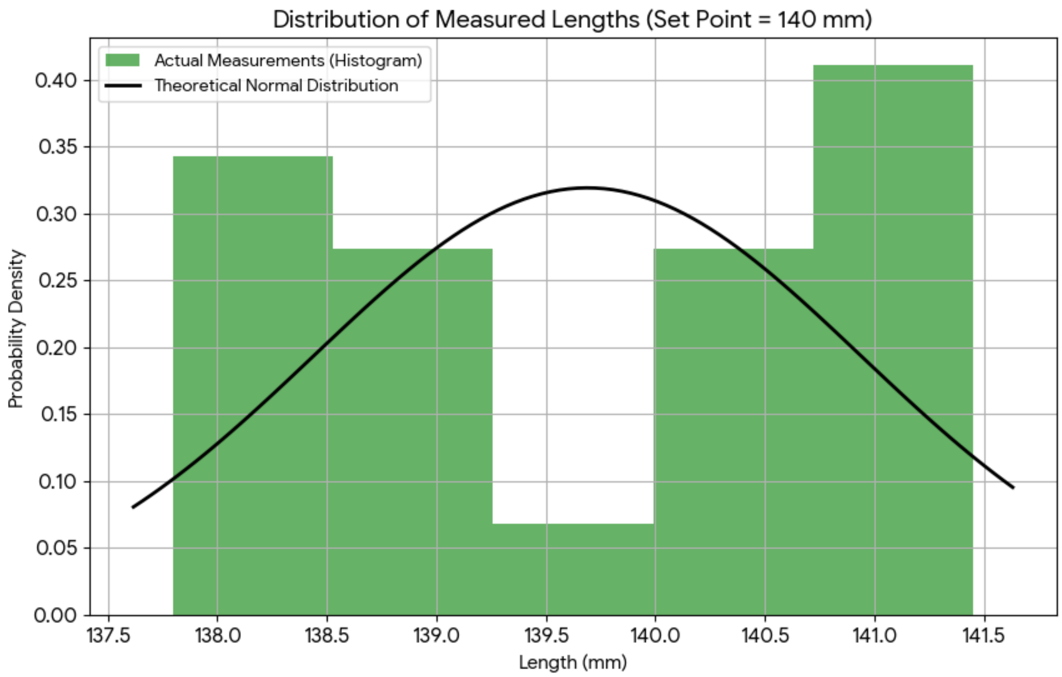


*Figure 16 Theoretical Normal Distribution*

Since we have absence of specific reliability data regarding the degree of freedom, for the Type B uncertainty components in manufacturer's specification, we cannot perform calculations for degree of freedom. Therefore, considering standard metrological practices for Normally Distributed Measurands, a coverage factor of 2 can be adopted which defines a confidence interval of approximately 95.45%.

In conclusion, we can say that the calibration successfully reduced the systematic error from (-1.6mm to 0.31mm), almost 81% error correction which now falls under the standard uncertainty limits of $u_c(D) = 0.370mm$.

### *3.5.4 Actuation and Process Logic*

The logic for stamping is simple. The PLC keeps comparing the calculated Distance with the stamping interval set value received from the HMI.

- When Distance is greater than or equal to the Stamping Interval, the PLC immediately halts the DC motor, the geared motor is beneficial for stopping the motor almost immediately, but the inherent lag is adjusted by characterizing the calibration parameter in the previous subchapter.
- It then commands the solenoid actuator's output for a predefined duration (e.g., 100 ms) to perform the stamp.
- The PLC resets the HSC's pulse count to zero after the stamp.
- It increments an internal stamp counter defined on a separate memory bit. If this counter is less than the Number of Stamps preset on the HMI, the PLC restarts the motor, beginning the next cycle.
- If the count is reached, the cycle loop breaks and the process stops.

## 3.6 System Design

The software was developed in the Siemens TIA Portal environment. The design includes both the PLC control program and the HMI user interface.

### *3.6.1 PLC Program Structure*

The control program was created using a Ladder Diagram. By taking a monolithic programming approach, all the logic resides within the main program cycle block (Main OB1). The code is segmented into a series of logical networks with each network responsible for a specific task.

- Network 1 Encoder Data Handling: This network deals with the built-in HSC technology block. It reads the raw pulse count from the rotary encoder and contains the logic to reset the counter's value to zero at the beginning of each stamping cycle.

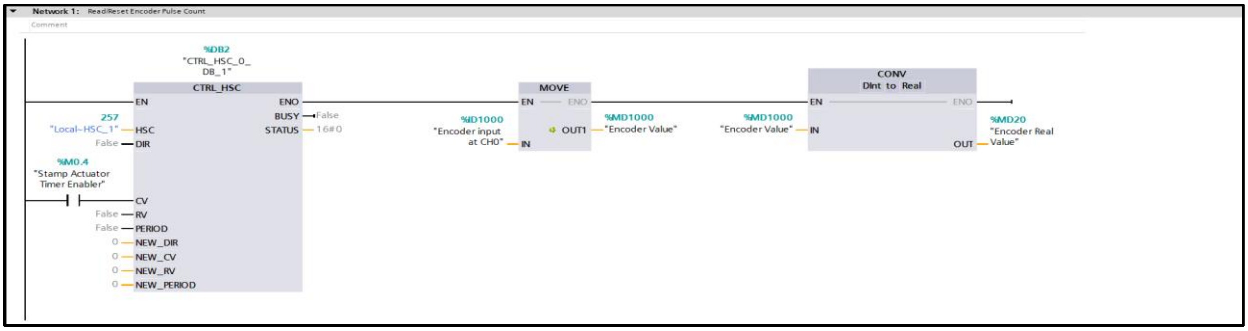


*Figure 17 PLC Network 1 — Read/reset encoder pulses*

- Network 2: Position Calculation: this network converts the raw pulse count obtained from Network 1 into a physical distance. The logic keeps using the formula $Distance\ (mm)\ = (\frac{247.143}{600}) \times Pulse\ Count$ to calculate the real-time linear travel of the paper sheet.

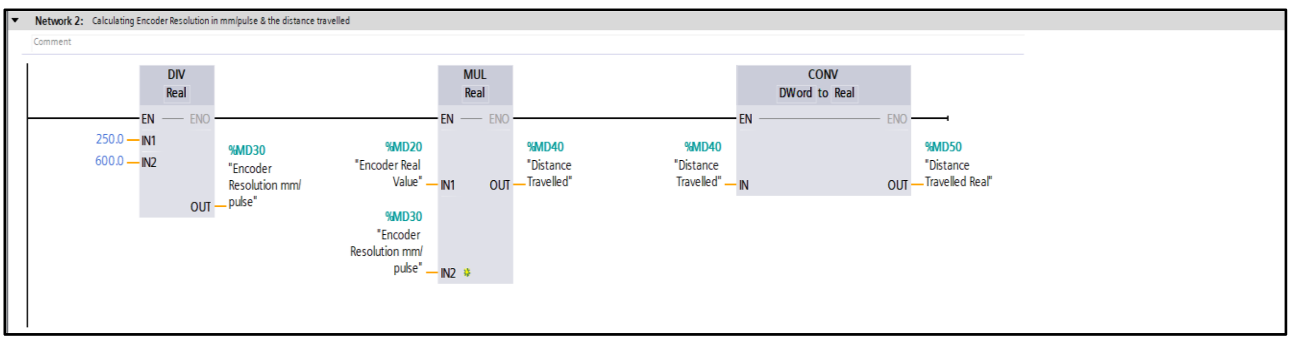


*Figure 18 PLC Network 2 — Distance calculation*

- Network 3 Motor Control Logic: This network is the central hub for controlling the paper feed motor. It has the primary Start/Stop logic linked to the HMI buttons. It also has several interlocks that will stop the motor when a stamping set point is reached, when the total desired stamp count is achieved, or as a safety measure while the stamping solenoid is active.

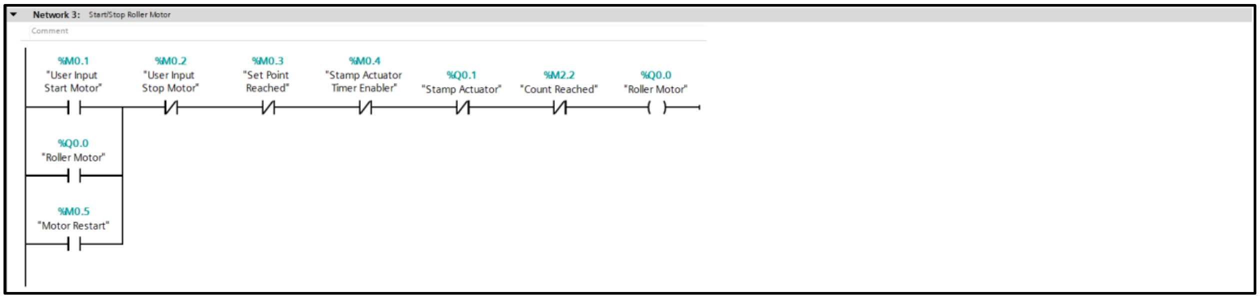


*Figure 19 PLC Network 3 — Feed motor control*

- Network 4: Set Point Comparison: This network is responsible for knowing the moment to stamp. It keeps comparing the calculated distance from Network 2 with the preset stamping interval from the HMI. A safety condition ensures that the interval value is greater than zero. When both of the conditions are met, a Set_Point_Reached memory bit is activated.

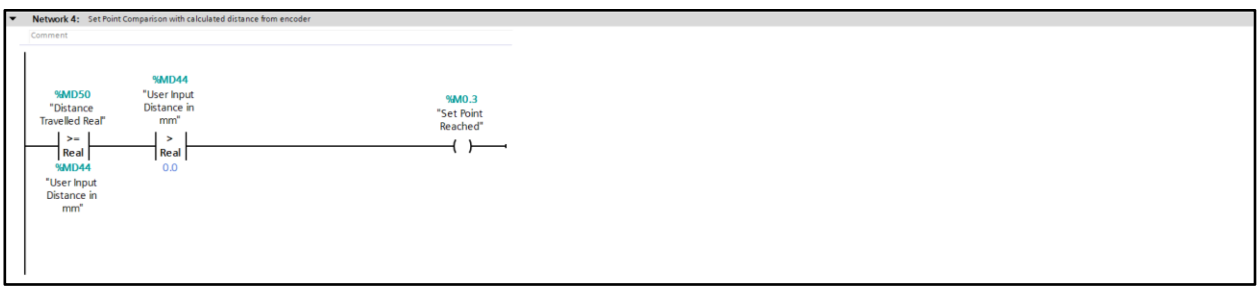


*Figure 20 PLC Network 4 — Encoder vs desired interval*

- Network 5: Stamping Sequence: Triggered by the Set_Point_Reached in network 4, this network runs the core stamping operation. It temporarily stops the motor, energizes the solenoid output for a few hundred milliseconds, and then automatically restarts the motor to feed the paper for the next cycle.

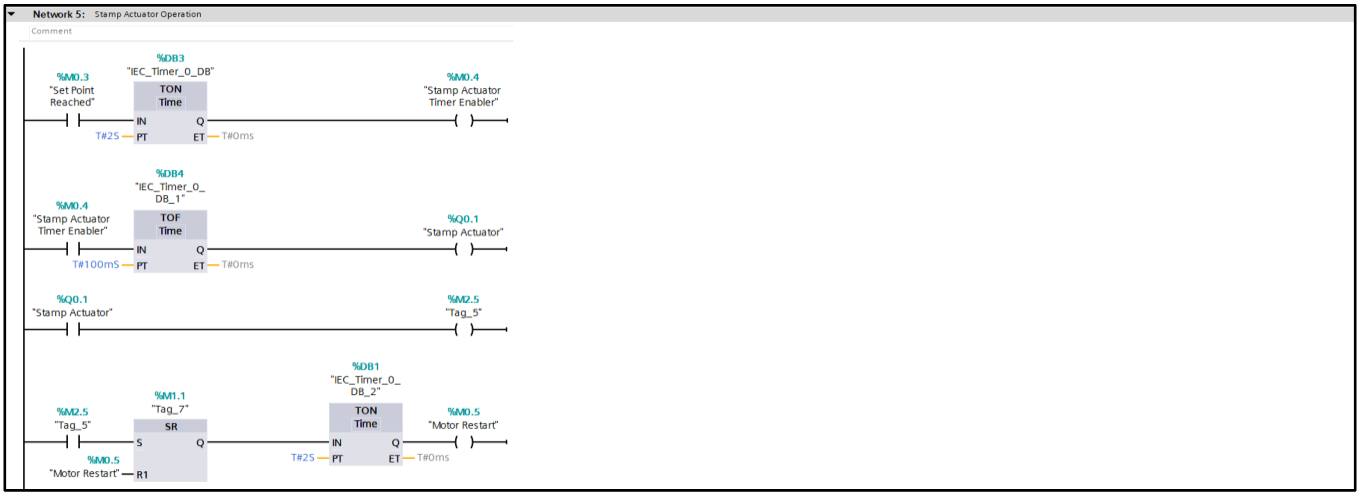


*Figure 21 PLC Network 5 — Actuation and cycle restart*

- Network 6: Stamp Counting: An up-counter (CTU) instruction is used in this network to track the number of completed stamps by monitoring the solenoid output bit. The counter's preset value is linked to the "desired number of stamps" input on the HMI. If the user enters a value greater than one, the counter will stop the entire process via the motor control network once the count is reached. If no value is set, the logic bypasses the counter, allowing for continuous, infinite operation.

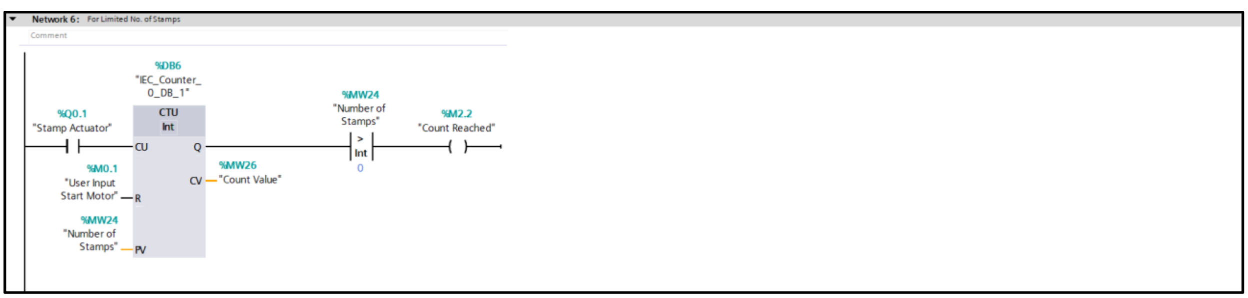


*Figure 22 PLC Network 6 — Cycle termination by stamp count*

- Network 7: Paper Feed Fault Detection: This network includes a fault detection routine designed to identify if there is a paper jam or sensor slippage. The logic operates by periodically taking a snapshot of the calculated paper travel distance. A 1 Hz clock memory bit triggers a MOVE instruction every second, which copies the current encoder value into a "Previous HSC Count" tag. An On-Delay Timer (TON) is then used to monitor for a fault. The timer starts its 1.5-second countdown only if two conditions are met simultaneously:

1. The "Roller Motor" (`%Q0.0`) is active.
2. The current "Encoder Real Value" is less than or equal to the "Previous HSC Count" snapshot.

Using a less than or equal to comparison makes the logic more robust, as it will correctly flag a fault if the paper is completely stalled or even if vibration causes the encoder to jitter backward slightly. If this fault condition persists for the full 1.5 seconds, the timer's output bit is energized, setting the Feed Fault Alarm bit. This alarm can then be used to stop the motor and trigger an alert on the HMI.

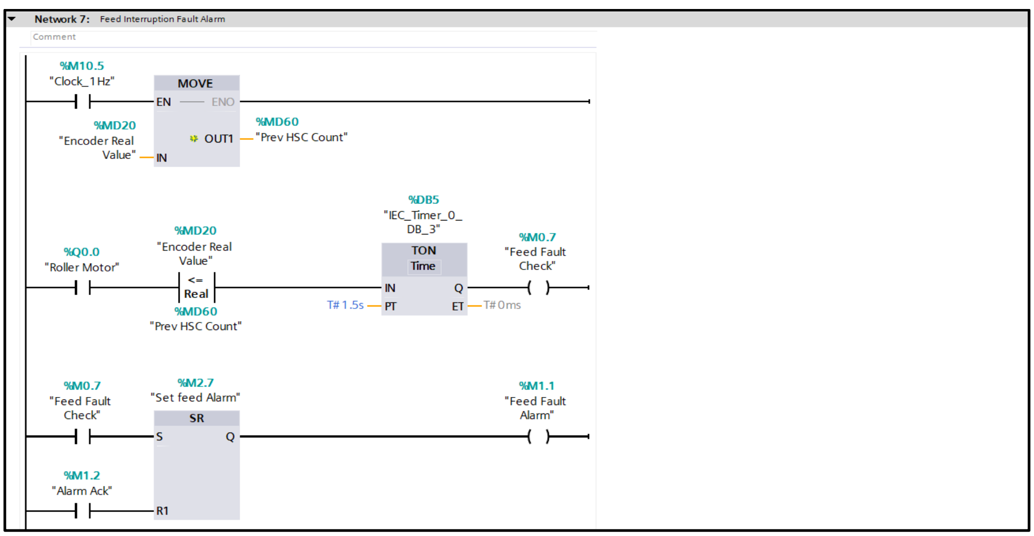


*Figure 23 PLC Network 7 — Feed fault detection*

- Network 8: Stamp Actuator Fault Detection: This network is designed to provide an advanced diagnostic check, confirming that the stamp actuator has correctly energized after receiving a command from the PLC. It works by reading the voltage from the shunt resistor circuit, which is proportional to the current being drawn by the solenoid. The logic operates as follows:

- When the command to activate the stamp actuator is given, an On-Delay Timer (TON) is initiated with a preset time of 400 ms. This delay allows a brief window for the solenoid's magnetic field to build and the current to stabilize.
- Once the timer completes, its output triggers a comparison check. The logic then reads the scaled voltage value from the designated analog input channel. If this voltage is still below a predefined threshold of 3.19V, the system concludes that the actuator has failed to draw sufficient current, indicating a potential wiring issue, coil failure, or power problem.
- If this fault condition is true, a "Stamp Actuator Fault Alarm" bit is set. This bit is then used to halt the machine cycle and display a specific fault message on the HMI, alerting the operator to the issue.

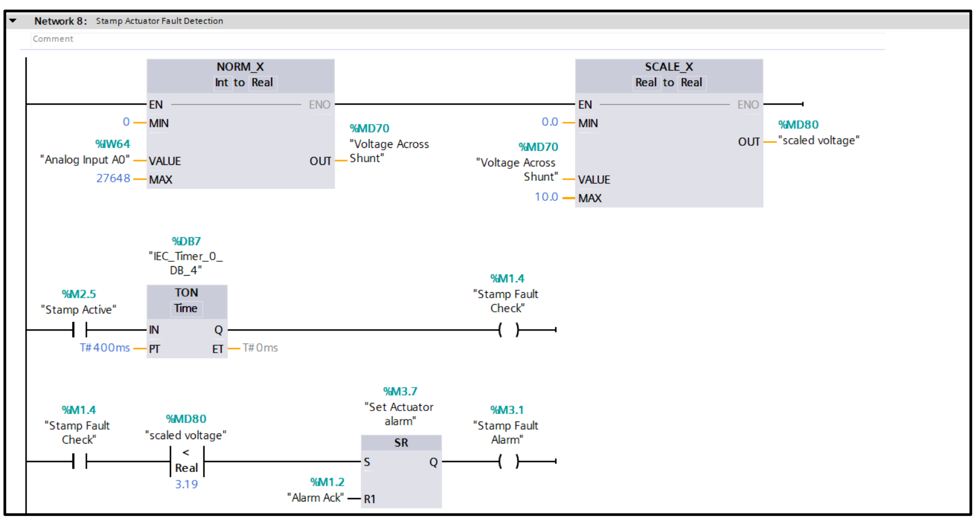


Figure 24 PLC Network 8 — Stamp fault detection

*3.6.2 HMI Screen Design*

The Siemens KTP700 HMI was programmed in the TIA Portal. It provides a simple interface for the operator. The design is on a main control screen that allows for full operation and monitoring.

The key elements of the HMI interface are:

- User Input Fields: The user enters desired Stamping Interval (in mm) and the Number of Stamps. These fields keep blinking if the interval is not set and turn green once the interval is set.
- Control Buttons: There are "Start Motor" and "Stop Motor" buttons on the screen and the “Acknowledge Alarm” button for the user to remove the active alarm flags.
- Data Displays: Two display fields show the Current Position of the paper and the current Stamp Count.
- Fault Alarms Indications: “Feed Interruption Alarm” and “Stamp Actuator Alarms” blinks red when anomaly is detected.

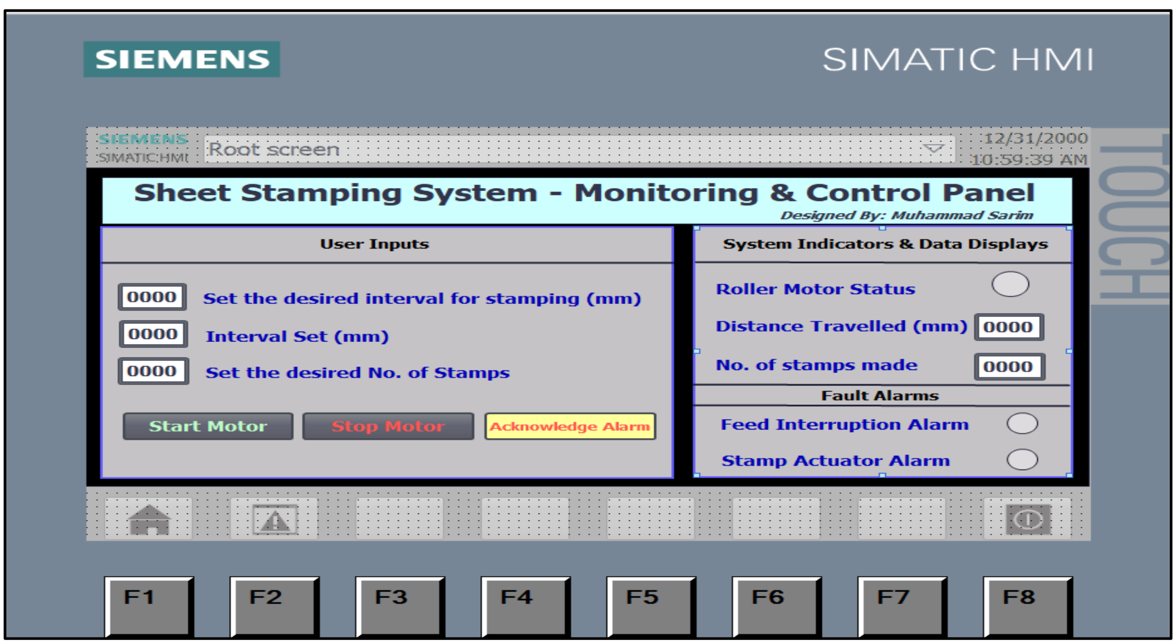


*Figure 25 Custom Designed Intuitive Monitoring & Control Panel*

## 3.7 Safety Design and Fault Alarms

Several fault detection mechanisms were designed. These features are important in industrial environments to reduce downtime and avoid material wastage. The logic for these checks is implemented directly within the PLC, with alarms displayed on the HMI.

### *3.7.1 Paper Feed Fault Detection*

It is possible for the material to jam, tear, or for a sensor to fail. This fault condition is designed to detect if the paper feed has stopped despite the motor being set active.

- Detection Logic: A supervisory timer is designed in the PLC. If the Motor Output tag is TRUE, the PLC keeps monitoring the HSC Pulse Count. If the pulse count doesn't change for a preset period of 1.5 seconds, the PLC detects a fault. This indicates the measurement wheel is not rotating even though the motor is commanded to run.
- Upon detection of this fault, the PLC will immediately:
    1. De-energize the Motor_Output, stopping the feed motor to prevent further damage or material waste.
    2. Activate a Paper Jam Alarm bit.
- HMI Indication: The Paper Jam Alarm bit will trigger a blinking alarm indicator on the HMI screen. The system remains in a halted state until the user physically resolves the issue and clicks on the "Acknowledge Alarm" button to reset the fault.

### *3.7.2 Actuator Fault Detection*

This feature ensures the correct actuation of the stamping solenoid once a command from the PLC has been received. It provides a confirmation that the electrical command resulted in physical action by monitoring the actuator's current draw.

- Hardware Requirement: This feature requires a current sensor wired in series with the solenoid actuator and connected to an analog input module on the S7-1200

PLC. A shunt resistor of 3.19 Ohm is used and the voltage across that resistor is read by the PLCs analog input channel A0.

- Detection Logic: When the Solenoid_Output bit is set to TRUE, the PLC starts a short timer (400 ms) and monitors the associated analog input channel. If the measured voltage does not rise above a minimum threshold (a value corresponding to 1 Amp) within that time frame, the PLC concludes that the solenoid has failed to actuate due to a wiring issue, coil failure, or power problem.
- System Response: If a fault is detected, the cycle is halted as the PLC sets an Actuator Fault Alarm bit.
- HMI Indication: The HMI displays a "STAMP ACTUATOR FAULT" alarm, alerting the operator.

### *3.7.3 Uncertainty and Power Calculations for Stamp Actuator Fault Detection System*

To ensure the reliability and accuracy of the actuator fault detection circuit, a detailed analysis of the shunt resistor's power dissipation and the overall measurement uncertainty was performed.

- **Power Dissipation Analysis:** The power dissipation in the shunt resistor network was analyzed to ensure it operates within safe thermal limits. The custom shunt was created using four 1W resistors configured in parallel: three 10Ω resistors and one 75Ω resistor.
  The total power rating of the network is the sum of the individual resistor ratings:

  $$P_{rating} = 4\ W$$

  The analysis considers the worst-case thermal scenario, which occurs at the shortest possible cycle time.

  - Peak Power ($P_{peak}$): The instantaneous power dissipated during actuation is. $P_{peak} = I^2 \times R_{eq} = \ 1.426^2 A \times 3.19\Omega \ \approx 6.48\ W$
  - Actuation Time ($t_{on}$): The solenoid is active for 0.4 s.

- Minimum Cycle Time ($t_{cycle, min}$): The shortest possible cycle time is 3.5 s.

The maximum duty cycle and resulting average power are:

$$Duty\ Cycle_{max} = \frac{t_{on}}{t_{cycle,min}} = \frac{0.4s}{3.5s} \approx 11.4\%$$

$$P_{avg,max} = P_{peak} * Duty\ Cycle_{max} = 6.48W \times 0.114 \approx 0.74W$$

Conclusion: The worst-case average power dissipation is 0.74 W, which is well below the 4 W continuous power rating of the parallel resistor network. This confirms the design is thermally safe for all operating conditions.

- **Uncertainty Calculation of Actuator Current Measurements**:

Considering the same framework utilized in subchapters of 3.5, we perform an indirect measurement method using Ohm's Law as calibration function to evaluate the measurement uncertainty of the current absorbed by the stamp actuator.

Our calibration function is given by: $I = f(\bar{V}_{shunt}, R_{eq}) = \frac{\bar{V}_{shunt}}{R_{eq}}$

1) **Step 1: Calculation of Equivalent Resistance Uncertainty ($u_c(R_{eq})$):**

The shunt network is composed of four parallel resistors: ($R1, R2, R3$ that are 10 Ω each), and (R4 that is 75 Ω).

$$1/R_{eq} = 1/R_1 + 1/R_2 + 1/R_3 + 1/R_4$$

$$1/R_{eq} = 1/10\,\Omega + 1/10\,\Omega + 1/10\,\Omega + 1/75\,\Omega$$

$$R_{eq} \approx 3.191\,\Omega$$

Calculating the Standard Uncertainty of Each Individual Resistor $u(R_i)$: The uncertainty evaluation for the resistor network was based on the component specifications identified physically. The resistors were identified as standard tolerance class (Gold (5%)).

However, as specific calibration data regarding the statistical distribution of these components was unavailable, we assumed the uncertainty using a Rectangular (Uniform) Distribution, treating any resistance value within the manufacturer's 5% limit as equally probable. We also treated the manufacturing errors of the distinct components as uncorrelated.

$$u(R_i) = \frac{a_i}{\sqrt{3}}$$

We can calculate half width of the interval as $a_i = R_{nominal} * Tolerance$

$$u(R_i) = \frac{R_{nominal} \times Tolerance}{\sqrt{3}}$$

For $R1, R2, R3$ $(10\ \Omega)$:

$$u\left(R_{1,2,3}\right) = 10\ \Omega \times \frac{0.05}{\sqrt{3}} \approx 0.289\ \Omega$$

For $R4$ $(75\ \Omega)$:

$$u(R_4) = 75\ \Omega \times \frac{0.05}{\sqrt{3}} \approx 2.165\ \Omega$$

Now we calculate the partial derivatives of our calibration function for equivalent resistance network:

$$R_{eq} = \frac{1}{1/R_1 + 1/R_2 + 1/R_3 + 1/R_4}$$

Which simplifies to: $\frac{\partial R_{eq}}{\partial R_1} = \frac{\partial R_{eq}}{\partial R_2} = \frac{\partial R_{eq}}{\partial R_3} = \left(\frac{R_{eq}}{Ri}\right)^2 = \left(\frac{3.191}{10}\right)^2 \approx 0.102$

$$\frac{\partial R_{eq}}{\partial R_4} = \left(\frac{3.191}{75}\right)^2 \approx 0.002$$

Now we propagate uncertainty using law of propagation:

$$u_c(R_{eq}) = \sqrt{\left(\frac{\partial R_{eq}}{\partial R_1}\right)^2 \left(u(R_1)\right)^2 + \left(\frac{\partial R_{eq}}{\partial R_2}\right)^2 \left(u(R_2)\right)^2 + \left(\frac{\partial R_{eq}}{\partial R_3}\right)^2 \left(u(R_3)\right)^2 + \left(\frac{\partial R_{eq}}{\partial R_4}\right)^2 \left(u(R_4)\right)^2}$$

This simplifies to $u_c(R_{eq}) = \sqrt{3 \times (0.102)^2(0.289)^2 + (0.002)^2(2.165)^2} \approx 0.051\Omega$

2) **Step 2: Evaluating the uncertainty of Input Voltage** $u_c(\bar{V}_{shunt})$

To characterize the input voltage, we operated the stamp actuator to collect 20 measurements of voltage readings using PLC which resulted in an empirical mean of $\bar{V} \approx 4.551V$ and experimental standard deviation of $\boldsymbol{s(V)} \approx 0.015V$

| Sample (n) | Voltage (V) |
|---|---|
| 1 | 4.54 |
| 2 | 4.55 |
| 3 | 4.57 |
| 4 | 4.55 |
| 5 | 4.53 |
| 6 | 4.56 |
| 7 | 4.52 |
| 8 | 4.55 |
| 9 | 4.54 |
| 10 | 4.56 |
| 11 | 4.53 |
| 12 | 4.58 |
| 13 | 4.55 |
| 14 | 4.54 |
| 15 | 4.57 |
| 16 | 4.55 |
| 17 | 4.54 |

| | |
|---|---|
| 18 | 4.56 |
| 19 | 4.55 |
| 20 | 4.53 |

Now we can calculate the uncertainty of the mean value which is a Type A contribution:

$$u_A(\bar{V}) = \frac{s(v)}{\sqrt{n}} = \frac{0.015}{\sqrt{20}} \approx 0.003V$$

And the Type B contribution in voltage measurement is due to the quantization of 10bit ADC present in the PLC.

Quantization step for 10bit and 0-10V range is 0.01V

$$u_B(V) = \frac{Resolution}{\sqrt{12}} = \frac{0.01}{\sqrt{12}} \approx 0.003V$$

The combined uncertainty $u_C(V) = \sqrt{\left(u_A(\bar{V})\right)^2 + \left(u_B(V)\right)^2} \approx 0.004$V

Now we partially derive the calibration function for current measurements to obtain sensitivity coefficients:

$$I = \mathrm{V} \times (\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4})$$

$$\frac{\partial I}{\partial V_{shunt}} = \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4}\right) = \frac{1}{R_{eq}} = \frac{1}{3.191} \approx 0.313A/V$$

The computations for partial derivatives with respect to resistances are simplified for one resistor as:

$$\frac{\partial I}{\partial Ri} = -\frac{V}{(Ri)^2}$$

$$\frac{\partial I}{\partial R_{1,2,3}} = -\frac{V}{(R_{10})^2} = \frac{4.55}{(10)^2} \approx -0.045A/\Omega$$

$$\frac{\partial I}{\partial R_4} = -\frac{V}{(R_{75})^2} = \frac{4.55}{(75)^2} \approx -0.0008A/\Omega$$

3) **Step 3: Evaluating the Combined Uncertainty of Measured Current $u_c(I)$**

$$u_c(I) = \sqrt{\left(\frac{\partial I}{\partial V_{shunt}}\right)^2 u^2(V_{shunt}) + \left(\frac{\partial I}{\partial R_{eq}}\right)^2 u^2(R_{eq})}$$

$$u_c(I) = \sqrt{(0.313)^2(0.004)^2 + 3(-0.045)^2(0.289)^2 + (-0.0008)^2(2.165)^2} \approx 0.023A$$

The final uncertainty of the current measurement system is characterized by a combined standard uncertainty of $u_c(I) \approx 0.023A$. Even though the dominant source of input uncertainty is from Resistances with a rectangular distribution but the combination of these resistances and voltage measurements allows the final distribution of the measurand $(I)$ to be approximated as Normal Distribution taking into consideration, the Central Limit Theorem.

# Chapter 4: IMPLEMENTATION AND TESTING

## 4.1 Mechanical Assembly and 3D Printing

This section discusses the physical construction of the stamping machine. It will cover the complete process from preparing the digital models for construction to the final assembly of the mechanical system.

### *4.1.1 From CAD Model to Printable File (Slicing)*

The mechanical components were designed in SolidWorks and were then exported as STL files for fabrication. The UltiMaker Cura slicing software was used. Key settings were chosen to balance fabrication speed and component strength. For a good surface finish the layer height was kept at 0.2 mm and for structural integrity of the component mounts, 30% infill was provided. The temperature of the build plate was kept at 58°C as this ensured good bed adhesion and prevented warping of the larger parts. These settings were processed by the software, and the G-Code file was generated for printing.

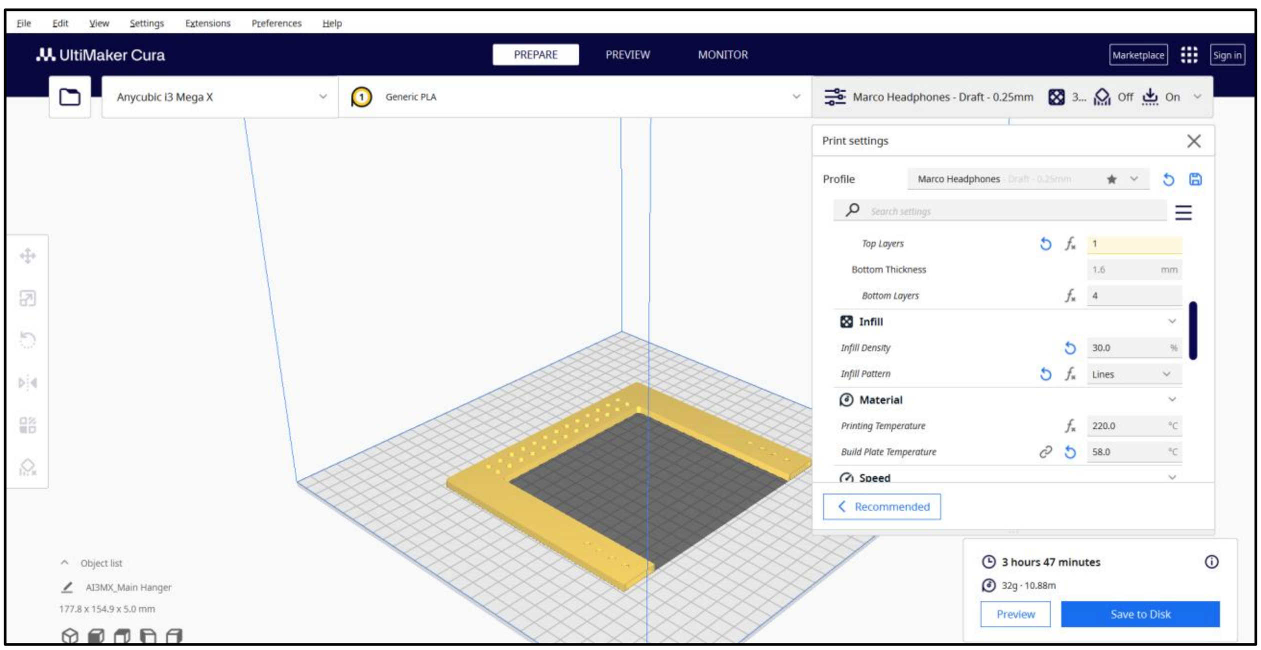


*Figure 26 Slicing 3D CAD model in Ultimaker Cura*

### *4.1.2 The 3D Printing Process*

Component printing was done on an Anycubic i3 Mega X printer and the material chosen was the PLA (Polylactic Acid) because it is easy to use and rigid. Once printing was completed, all the parts were post-processed. The support material was removed and through edges were sanded so they were clean for assembly.

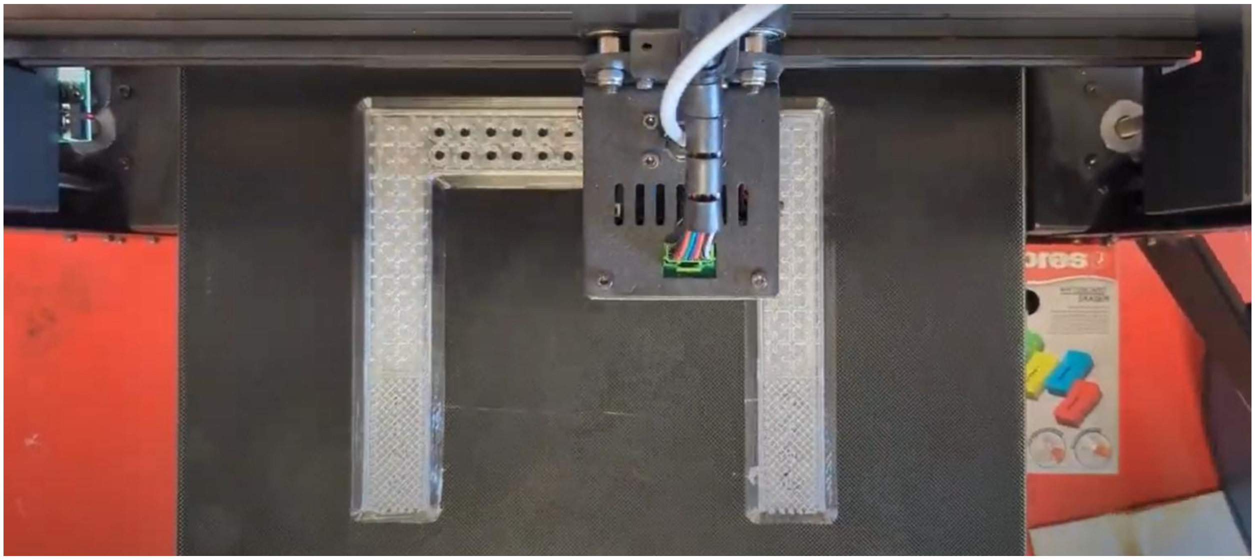

Figure 27 Anycubic i3 Mega X printing the stamp gantry

### 4.1.3 Mechanical Assembly Sequence

A modular approach was followed in the assembly process. The first step was to assemble the main gantry frame and attach it to the base platform. Once the structure was stable, the DC motor was mounted using its custom bracket and a 3D-printed coupling was attached to the roller. The solenoid actuator was fixed on the gantry. The last component was the rotary encoder. It was installed delicately so that the measurement wheel was pressed evenly on the paper.

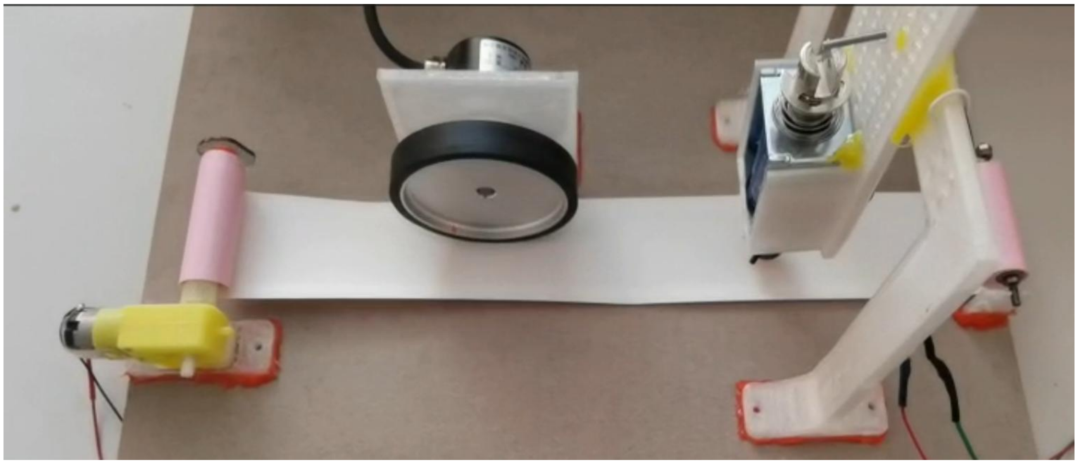

*Figure 28 Final prototype assembly in DET, Politecnico di Torino*

#### *4.1.4 Mechanical Fine-Tuning and Stabilization*

Inconsistent mechanical contact and motion at the measurement wheel was causing a wobble in the measurement wheel and slippage against the paper. The mechanical stability and reliability of the sensor system needed to be improved. Three adjustments were made:

1. Reduction of Wheel Wobble: The misalignment between the shaft's center and the wheel's center was there because the set screws securing the wheel to the encoder shaft were only on one side. The solution to this was to design a custom 3D-printed coupler and install it to align both centers to reduce wobble.

2. Improving Wheel Contact: A thin paper padding was added so that the surface height under the measurement wheel rose. This ensured the pressure was firm and consistent.

3. Enhancing Fixture Stability: To make the assemble parallel to the paper's path, the 3D-printed encoder mount was redesigned with more precise dimensions.

## 4.2 PLC and HMI Programming

The workflow started by creating a new TIA Portal project and matching the exact PLC and HMI models (PLC: 6ES7 215-1BG40-0XB0, HMI: 6AV2 123-2GB03-0AX0) and their firmware versions. This is an important step to avoid communication issues later. For fault detection logic, the PLC’s configuration was adjusted to enable the clock memory byte (MB10). The PG/PC interface was setup in TIA Portal define the rules of communication between the programming computer and the PLC. The PROFINET/Ethernet protocol was chosen.

After the hardware configuration, the control logic explained in Chapter 3 was placed in the ladder diagram inside the main organisation block. The HMI screens were designed and linked to the relevant PLC tags.

The full configurations were downloaded to the PLC and HMI in the final commissioning page. To observe tag values in real time, TIA Portal's online monitoring tools were used during initial tests. It was done to debug the logic and verify the communication between the HMI and PLC in real-time.

## 4.3 System Testing and Commissioning

Once the mechanical parts were assembled and software was deployed, a two-stage testing process was conducted to validate the system. In the first stage, multiple unit tests were performed for verifying whether each component is working correctly. Secondly, to see the entire system’s performance, integration tests were conducted.

### *4.3.1 Unit Tests*

The purpose of conducting unit tests is to individually verify each component’s functionality before attempting a full system run.

- Solenoid Actuator Test: this test confirmed whether the solenoid actuator is producing a proper stamp on the paper. The Fluke multimeter measured the current draw, and it was approximately 1426 mA when actuation happened. During integration testing, the system operated fine without tripping a fault despite initially thinking that an external power supply would be required as the current exceeds the PLC’s 24V supply's continuous rating of 400 mA. The power supply's ability to bear high peak currents for short durations made this possible. The PLC’s internal protection circuits weren’t triggered as the overload current was not drawn long enough due to the short actuation time. Hence, no external power supply was required.

- Rotary Encoder Test: The encoder test was performed by manually turning the measurement wheel in one complete rotation and checking the live value of the HSC in the TIA Portal. The result showed that one complete rotation gave a count of 600. Since the encoder has a specified 600 PPR resolution, it means that encoder was in correct alignment with the PLC.
- Motor Feed Test: the DC motor was turned on and we checked if there was sufficient torque to pull the paper smoothly from the source roll without pausing or changing the speed of the paper being pulled.

### *4.3.2 Integration Tests*

The integration tests were conducted after the unit tests to assess the performance of the system as a complete machine against the requirements defined in Chapter 3. The main objective was to see whether the machine's stamping accurately. It was done by setting a 200 mm stamping interval on the HMI and running 10 cycles consecutively. Then the distance between each stamp was measured. The detailed quantitative results of these tests are further discussed Chapter 5 (Results and Discussion).

## 4.4 Troubleshooting and Debugging

### *4.4.1 System Bias Diagnosis*

Positioning tests were conducted where there was a consistent discrepancy between the set point and the actual cut length.

At a setpoint of 140 mm, there was a systematic positioning error. The mean of the measured intervals was 138.40 mm resulting in a negative bias of -1.6 mm. The error was repeatable which means it is a Systematic Error. The bias is because the effective circumference of the wheel. It is different from the nominal manufacturer specification

(250 mm) due to the compression of the rubber tire against the paper. Rather than making any more mechanical adjustments, a probabilistic calibration was done which is discussed in detail in chapter 3.

# CHAPTER 5: RESULTS AND DISCUSSION

## 5.1 Performance and Metrological Validation

The main goal of this thesis was to develop a system which would perform automated stamping with a positional accuracy of ±10 mm. The results, after rigorous testing and research, show that this project meets the goals defined in Chapter 1.

| Metric | Requirement | Achieved Result | Met? |
| --- | --- | --- | --- |
| Positional Accuracy | ±10 mm | ±0.74 mm (approx. s95% Confidence Level) | Yes |
| Standard Deviation | 5 mm | 1.250 mm | Yes |
| Throughput | 25 stamps/min | 27 stamps/min | Yes |

*Table 5.1 Comparison of the Required vs Achieved Performance Metrics.*

### *5.1.1 Positioning Accuracy*

A detailed uncertainty evaluation was performed, as discussed in the Chapter 3. The system has a final combined standard uncertainty of 0.37 mm. This significant result proves that high precision can be achieved with low cost, 3D printed components and a software calibration. The systematic bias which was caused by mechanical slippage was successfully eliminated.

### *5.1.2 Reliability and Throughput*

At a 100 mm interval, the system consistently maintained a throughput of 27 stamps per minute during operation trails, that are dependent on the timing intervals set in the machine considering safety and reduced vibrations, which can be further improved if the actuating mechanism is designed with an “on the go” continuous moving roller design. There was no thermal degradation over repeating cycles, proving that the correct DC geared motor was chosen and correct relay control logic was applied.

## 5.2 System Integration and Logic Design

The project integrated digital logic, analog sensing, and mechanical parts in one control system.

### *5.2.1 Sensor Integration*

The PLC successfully handled the different signals:

- Digital Integration: The HSC worked properly with the incremental encoder. With high resolution, it was able to process rapid pulses to track position with sub-millimeter resolution.
- Analog Integration: A current sensing circuit was used for the stamp actuator. The PLC read the voltage drop across the shunt resistor. This allowed the system to tell the difference between a good stamp and a coil failure.

### *5.2.2 Advanced Logic Implementation*

The control program used advanced features of the S7-1200 PLC:

- State Machine Architecture: We managed the process with a state machine. This ensured that feeding, stopping, and stamping happened in the correct order.
- Timer Memory Utilization: In the fault detection logic, we used specific memory bits of IEC Timers. The logic monitored the encoder's duration of inactivity. This identified paper jams that simple switches might miss.

## 5.3 Challenges and Limitations

The following technical challenges were faced during the project and were resolved:

- Mechanical Design and Fabrication: No pre-existing template was used to design the mechanical structure of the stamping machine. It was an iterative design process in SolidWorks. To ensure structural integrity all components, from the main gantry to the sensor mounts, had to be optimized for the constraints of FDM 3D printing.

- Positioning Accuracy and Calibration: As detailed in Section 3.7, the most significant technical challenge was to overcome the initial positioning errors caused by mechanical instabilities. The wheel wobble and paper slippage required more attention and were resolved by mechanical redesign and software-based calibration.
- Component Sourcing and Circuit Design: There was no single high-power resistor present for the actuator fault detection circuit. This was resolved by designing a custom shunt resistor. The solution was creating a parallel network of four lower power 1W resistors. To ensure a functional design careful calculation of both the final equivalent resistance and the combined power handling capability was done.
- Power Budgeting: The high peak current of the solenoid (~1.4A) was greater than the PLC's integrated power supply's continuous rating (400 mA). For this a thorough analysis of peak vs. continuous loads was done to confirm that the short actuation time would not trigger the PLC's overload protection.
- Prototype Limitations: As stated earlier, this project is a lab-scale project. It does not have an inking system present for the stamp. It also lacks industrial-grade safety features like an emergency stop circuit or physical guarding. These aspects are acknowledged as limitations of the current implementation.

# CHAPTER 6: CONCLUSION AND FUTURE WORK

## 6.1 Summary of Work

This thesis presented the development of a PLC-based sheet stamping system for a lab environment. The project bridges the gap between theoretical automation knowledge and practical engineering skills.

The first step was to set the functional and performance requirements. The Siemens S7-1200 PLC and a KTP700 HMI were used in this project, and they were integrated with an industrial rotary encoder, a DC motor, and a solenoid actuator. Once that was done, a full mechanical system was designed from scratch in SolidWorks and custom components were constructed using a 3D printer.

The control logic was programmed in a Ladder Diagram in the TIA Portal environment. The position tracking was carried out by the PLC's High-Speed Counter. The HMI was designed to allow users to set process parameters and monitor the system. Its interface was kept intuitive for ease of use.

In the implementation phase the physical assembly was done and the software was commissioned. There was rigorous a testing stage where all individual components were tested and then the whole system's performance. During the testing phase a consistent positioning error caused by mechanical slippage was highlighted. It was resolved through a combination of mechanical adjustments and a software adjustment of the calibration constant. The final system successfully demonstrated the automated stamping process as per the initial requirements that were set.

## 6.2 Contributions

The main contributions of this thesis are as follows:

- Design and development of a mechatronic system: The project demonstrates a successful design, fabrication, integration, and validation of a complete mechatronic system from the scratch. It provides a practical example of applying industrial automation techniques to create a functional prototype.

- Creation of a Flexible Educational Platform: The final prototype is a flexible educational tool which can be used by students to modify Ladder Logic, design HMI screens, and learn sensor calibration and system troubleshooting.
- Real-World Troubleshooting and Engineering analysis: The project includes the diagnosis of a positioning error, the evaluation of actuator power requirements, and the development of diagnostic logic for detecting common system faults. These are real engineering problems which can contribute to the educational value of the prototype.

## 6.3 Recommendations for Future Work

The following improvements can be made to extend the system and increase its value in a laboratory environment:

- Development of a Professional Test Bench: A dedicated test bench can be constructed for a professional finish. The PLC and HMI could be mounted onto a panel with wired I/O terminals. The students can connect sensors and actuators safely and without accessing the PLC's direct terminals.
- Development of Structured Lab Exercises: Formal lab assignments can be created from this project like physically implementing and testing the designed actuator fault detection circuit or expanding the system's diagnostics by adding an HMI alarm history screen, implementation of calibration with-in the designed logic and interface can be a valuable expansion to this project.
- Integration of Advanced Safety Features: Industry-standard safety components can be added to the system like hardware-based emergency stop circuit and physical guarding.
- Modular End-Effector Development: The stamping tool can be swapped by any other tool designed for automated tasks, such as labeling, adhesive dispensing, or vision-based quality inspection using the same core PLC control architecture.

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