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Implementation of a PLC and HMI-Based Control System on a Prototype of Portable Plastic Injection Machine

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Abstract. The portable plastic injection machine is one of the technological innovations in plastic production, adapted from industrial-scale injection molding machines to support laboratory-scale production or learning programs. Previous research has produced a prototype of a horizontal-type portable plastic injection machine with dimensions of 672.5×308×308 mm and a weight of 19.12 kg. However, the machine still has several issues. One of the main issues is the control system, which is based on a microcontroller and considered less reliable for long term automated operation. Additionally, the lack of operational efficiency is due to the absence of a clamping distance adjustment function, which currently can only be modified by changing the arduino program. The control system was improved by replacing the microcontroller-based system with a PLC-based system and adding several necessary functions. The development process included a study of the existing control system, followed by programming planning, component assembly, and software programming. After programming, the improved systems were tested. The test results show that switching to a PLC and HMI-based control system makes machine operation easier and more efficient. Additionally, the electrical system of the machine becomes simpler compared to the previous microcontroller-based control system.

Keywords: Plastic Injection Machine, Control System, PLC, HMI

Introduction

Plastic injection is one of the most widely used manufacturing techniques for plastic products today The process utilizes a plastic injection machine that works by heating plastic material to its melting point [1]. The molten plastic is then injected into a mold and cooled until it solidifies [2]. Generally, existing plastic injection machines are large and designed for industrial-scale production [3]. However, research has led to the development of a small, laboratory-scale plastic injection machine that is relatively easy to transport as a portable plastic injection machine.

The previously developed prototype of portable plastic injection machine has dimensions of 672.5×308×308 mm, a weight of 19.12 kg, and a microcontroller-based control system to manage stepper motor movements, as shown in Figure 1. The machine is operated using five push buttons and a mini LCD for monitoring cycle counts. Its operational cycle is divided into two modes: automatic and manual. The automatic cycle has a significant limitation: the clamping distance cannot be adjusted and remains fixed. Changing the clamping distance requires re-uploading the microcontroller program. This limitation makes it difficult to use different molds that do not match the pre-programmed clamping distance. This issue arises from the functional limitations of the microcontroller. Therefore, an upgrade to the control system is necessary to simplify the operational process.

Fig. 1 Portable Plastic Injection Machine

In this study, development was carried out by modifying the microcontroller-based control system to be based Programmable Logic Controller (PLC)-based controller using a Mitsubishi FX3U CPU and an OP320-5A Human Machine Interface (HMI). While microcontrollers and PLCs share the same basic function of processing a program to control a device, a microcontroller is technically more challenging for applications requiring interaction. This is because microcontrollers necessitate the design of additional signal conditioning for their input/output ports, and their programming language, often assembler, is relatively complex [4]. The addition of an HMI supports the new function of adjusting clamping distance, which was previously unavailable, and aids in cycle monitoring. This development is expected to make the machine's control system more effective and user-friendly.

Theoretical Background

A plastic injection machine is a device used to mold raw plastic materials, a common practice in modern manufacturing. This machine integrates advanced microprocessor control technology with various auxiliary equipment to ensure process flexibility and efficiency [5]. The working principle of a plastic injection machine begins with feeding material into the machine. The material is then heated by a heater until it melts. The molten plastic is pushed by a screw or piston through a nozzle into a mold, where it is cooled until it hardens and forms the desired product [6]. Generally, a plastic injection machine consists of several main components are barrel, screw, nozzle, and plastic mold [6].

Programmable Logic Controller (PLC) is an electronic device designed for ease of use, providing control functions for various types of applications with varying levels of complexity [7]. A PLC operates by receiving input signals from the process being controlled, executing logical instructions based on a pre-written program stored in its memory, and finally producing output signals to operate actuators or other connected devices [8]. Based on their output type, PLCs are divided into two categories: transistor output and relay output. Transistor outputs have the advantage of a much faster response time compared to relays, allowing them to be used for high-speed pulse outputs, whereas relays cannot [9]. The PLC FX3U is a PLC manufactured by Mitsubishi with an FX3U type CPU. This PLC comes in various models depending on the number of inputs and outputs. It can be powered by either AC or DC electricity, with power consumption ranging from 30 to 65 Watts [10].

Human-Machine Interface (HMI) is a device that serves as an interface between humans and machines [11]. An HMI facilitates communication between the operator and the machine. In practice, an HMI can take the form of a control panel with various buttons, a touchscreen, or software running on a computer [12]. The benefits of using an HMI include:
1. Minimizing the size of the control panel
2. Reducing wiring costs

3. Simplifying machine operation and monitoring
4. Reducing the number of input devices like push buttons

The HMI OP320-5A, manufactured by Xinje Electric, Co. Ltd, is a relatively small HMI equipped with operational buttons. It can connect to various PLC brands such as Mitsubishi FX, Omron C Series, Siemens S7 Series, Koyo SG Series, and others, using RS232 for communication [13]. Stepper motor is an electric motor that works by converting electrical pulses into discrete mechanical movements, with each pulse rotating the motor by a fixed angle [14]. The general working principle of a stepper motor is to create a sequentially rotating magnetic field, causing the rotor to follow the orientation of this field. By controlling the motor's input pulses, the angular position of the motor shaft can be controlled without feedback [14]. A stepper motor has a construction consisting of a rotor and a stator without a commutator, as it is a brushless motor. The rotor is made of magnetic material, typically ferromagnetic, and the stator consists of copper coils [15].

Methodology

The methodology used consists of several main stages: evaluation of the existing control system, component selection, program planning, component assembly, programming, and testing. These stages are outlined in the flowchart shown in Figure 2.

Evaluation of the existing control system was conducted to understand the machine's previous workflow. This process consisted of two stages: a review of the existing program and a review of the electrical components used. The program review involved examining the previous Arduino program to observe aspects such as the machine's work cycle and stepper motor parameters.

The results of the program analysis, shown in Figure 3, revealed that the machine has a production cycle consisting of clamping, injection, cooling, and unclamping. This production cycle can be operated in two modes: manual and automatic. The manual mode requires the operator to execute the production cycle steps manually, while the automatic mode allows the production cycle to run automatic continuously.

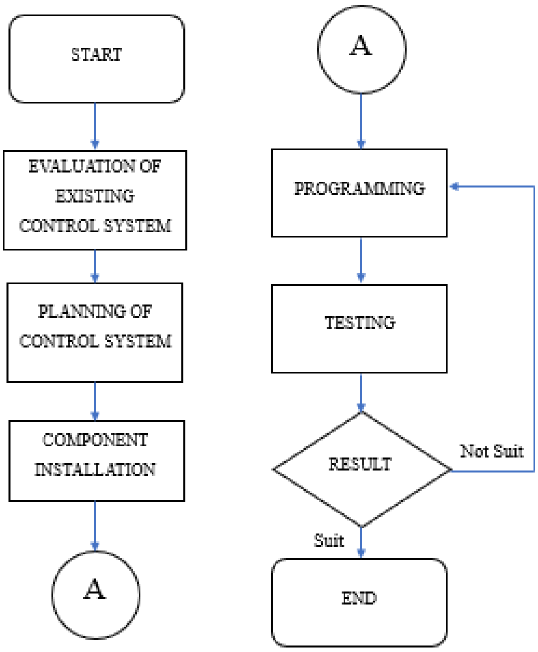


Fig. 2 Methodology Flowchart

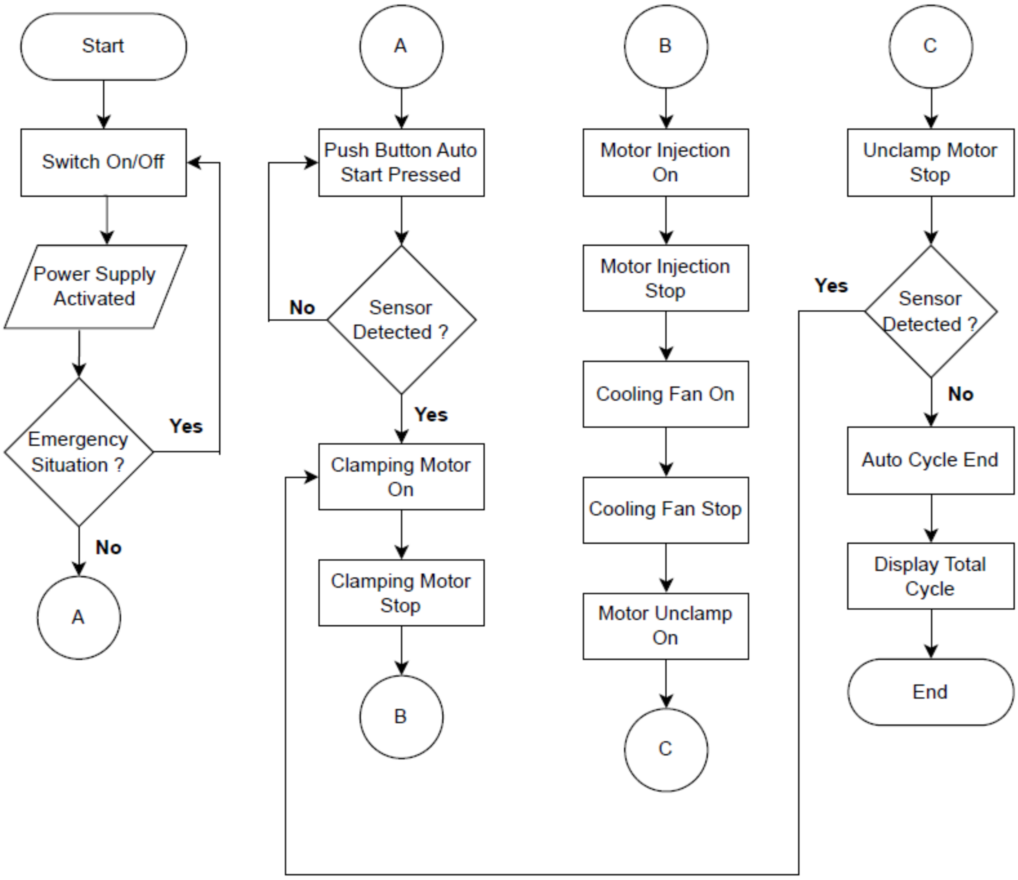


Fig. 3 Existing Programming Algorithm

The program analysis also yielded the stepper motor motion parameters, including motor rotation direction, number of pulses, and frequency. These parameters served as a reference for the subsequent PLC programming. Table 1 shows the stepper motor parameters from the previous system.

Table 1. Stepper Motor Parameters in the Existing Program

Parameter	Value
Clamp / Unclamp Pulse	18,000 *pulse*
Pulse Injection	16,000 *pulse*
Clamp – Injection Time Delay	400 ms
Delay Injection – Unclamp	2,500 ms
New Cycle Delay	1,000 ms
Rotation Direction Clamp Motor	*Clockwise* (CW)
Rotation Direction Unclamp Motor	*Counterclockwise* (CCW)
Rotation Direction Injection Motor	*Counterclockwise* (CCW)

The next step was an electrical review to identify the electrical components and their specifications. The results of this review were used for the subsequent planning phase, where it was determined which electrical components would be retained and which would be replaced. Table 2 shows the results of the electrical review.

Table 2. Existing Electrical Component

No	Electrical Component	Quantity	Specification/Type
1	PID Temperature Control	1	Rex C-100
2	Band Heater	2	220V 90 watt
3	Solid State Relay	1	SSR 25 DA
4	Temperature Sensor	1	*Thermocouple K*
5	Stepper Motor	2	NEMA 34
6	Microstep Driver	2	DM860H
7	Microcontroller	1	Arduino Atmega 2560
8	Power Supply	1	DC 24V
9	Relay 4 Channel	1	250 VAC 10A
10	Step Down Module	1	LM2596
11	Cooling Fan	1	DC 12V
12	Sensor	1	Induktif LJ12A3-4-Z/BX
13	Mini LCD	1	LCD 1602 + I2C DC 5V
14	Pilot Lamp	3	AD16-22S
15	Push Button Momentary	5	R13-507
16	Potensiometer	2	10K
17	Selector Switch	1	CRS252A1

After the existing control system review was complete, the process continued with planning the new control system. This planning was based on the results of the previous review and produced a programming algorithm to guide the PLC and HMI programming, as well as a wiring diagram to guide component assembly. The programming was performed after all components were installed on the machine. Programming was done using Mitsubishi GXWorks 2 software for the PLC and OP Editor for the HMI. The created program was then functionally tested.

Wiring Diagram

The wiring diagram was designed based on the selected electrical components and served as a guide for the wiring process. Table 3 shows the PLC input and output addressing. There are three input components: two push buttons for starting and stopping the automatic mode, and a proximity sensor for position initiation. The PLC output section is mainly for the motor's micro-step driver input signals, which consist of pulse, enable, and direction. This addressing table was the basis for creating the wiring diagram, especially for the connections between the PLC and other components.

Table 3. PLC Input and Output Addressing

Type	PLC Address	Component
Input	X0	Push Button Auto Start
	X1	Push Button Auto Stop
	X2	Proximity Sensor
Output	Y0	Pulse Clamp / Unclamp
	Y1	Pulse Injection
	Y2	Enable Clamp / Unclamp
	Y3	Enable Injection

	Y4	Direction Clamp / Unclamp
	Y5	Direction Injection
	Y6	Auto Cycle Start Lamp
	Y7	Idle Lamp
	Y10	Cooling Fan

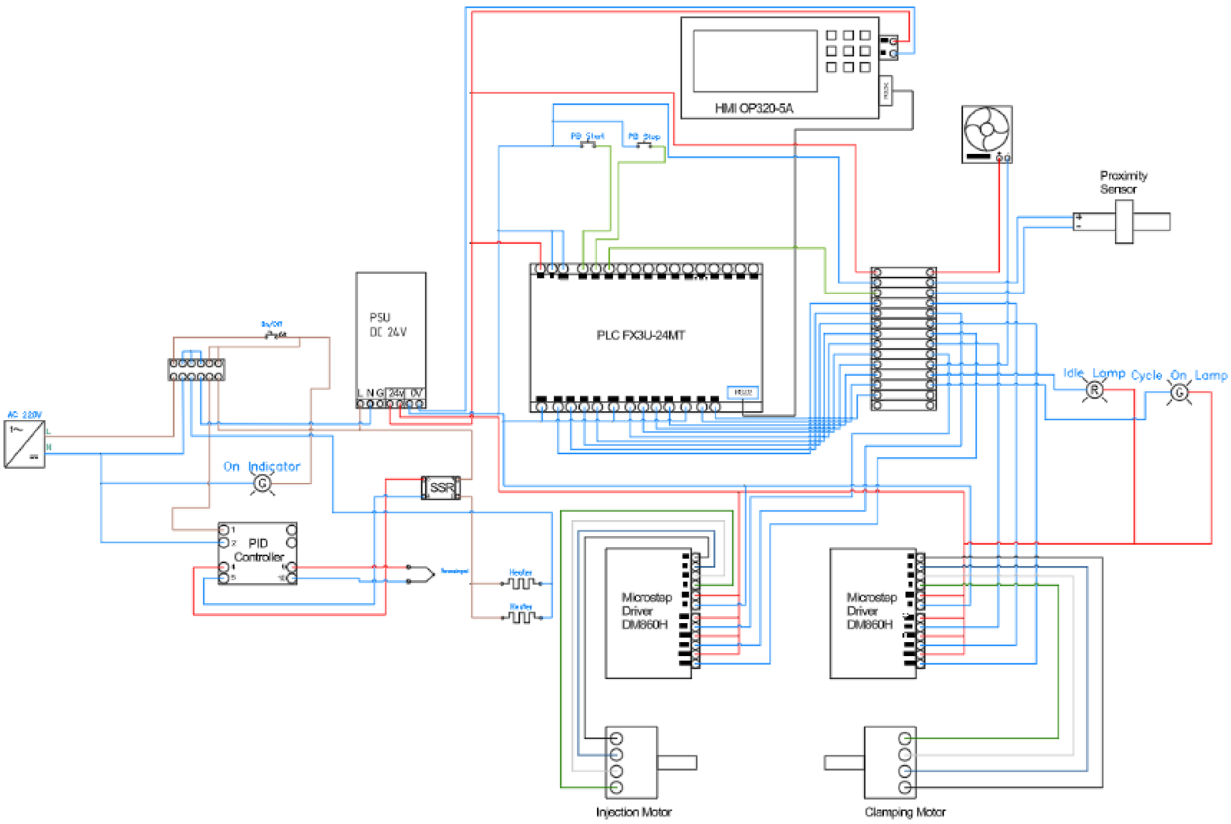


Fig. 4 Recent Wiring Diagram

Generally, the electrical components used operate on direct current (DC), with only one component, the barrel heater, using alternating current (AC). A DC power supply is used to convert AC to 24-volt DC. An additional electrical component, a terminal block, was used to organize the PLC inputs and outputs. Figure 4 shows the wiring diagram. Different colored lines are used for the wires to easily distinguish between positive and negative current paths. The red line indicates positive DC current, while the blue line indicates negative DC current or neutral for AC. Other colors used include brown for the phase in AC, while green represents the PLC input signal. For the motor, the wire colors match their actual wiring.

Programming Algorithm

The programming algorithm was divided into two parts: the PLC program algorithm and the HMI display algorithm. Figure 5 shows the PLC program algorithm, which was created based on the existing cycle with the addition of several necessary functions. These additions include setting the clamping distance for automatic mode, setting the injection and cooling times, and setting the injection speed in automatic mode. The clamping motion is limited by a proximity sensor at the minimum position, which serves as a marker or datum for the clamp's initial position. The sensor also functions to stop the clamping motor when it reaches the minimum position to prevent the clamp from hitting the back of the machine. Due to the limited number of buttons on the HMI, external push buttons are used to start and stop the automatic cycle

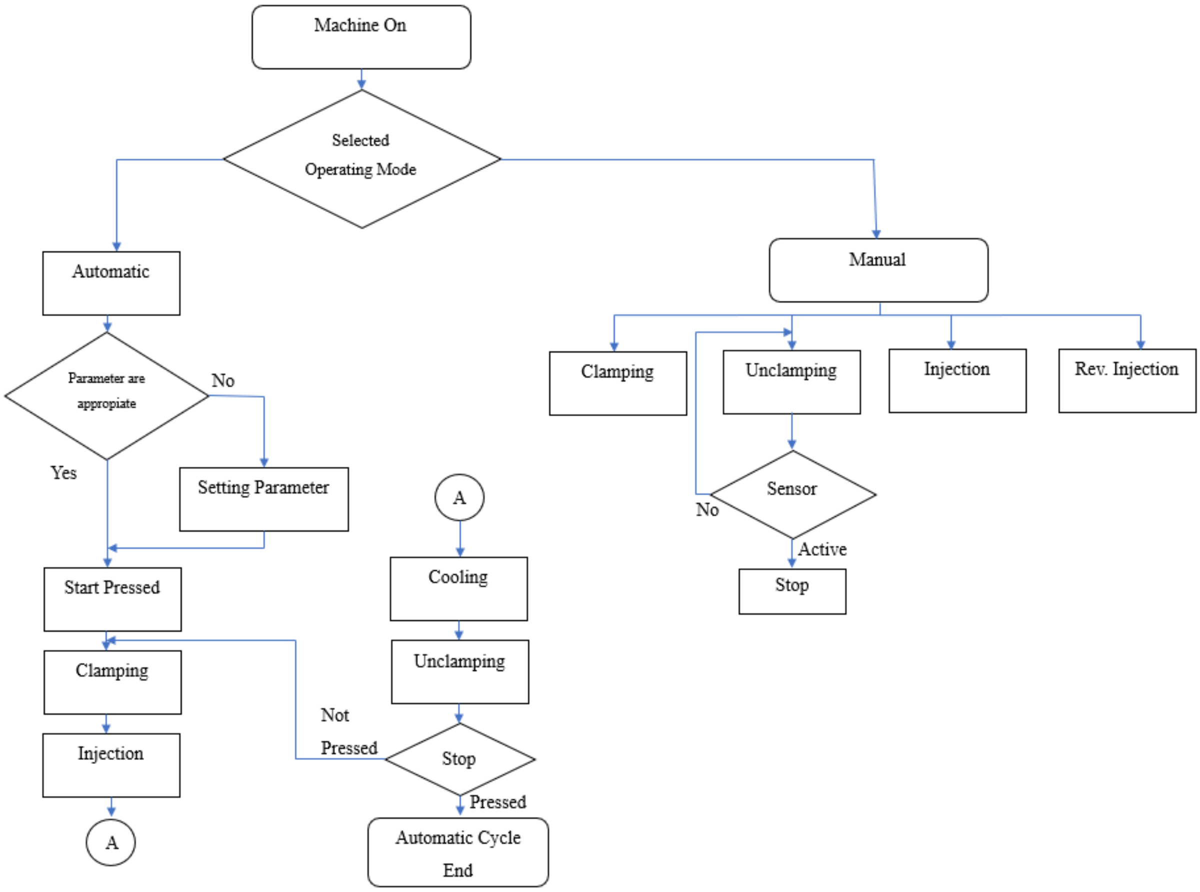


Fig. 5 PLC Programming Algorithm

The HMI display was designed based on the machine's existing work cycle. It offers a choice between manual and automatic modes. According to the previous problem of lacking parameter adjustment in automatic mode, a new screen was added to the automatic mode option for setting its parameters. These parameters include cooling time, injection time, and clamping distance. The designed HMI display algorithm can be seen in Figure 6.

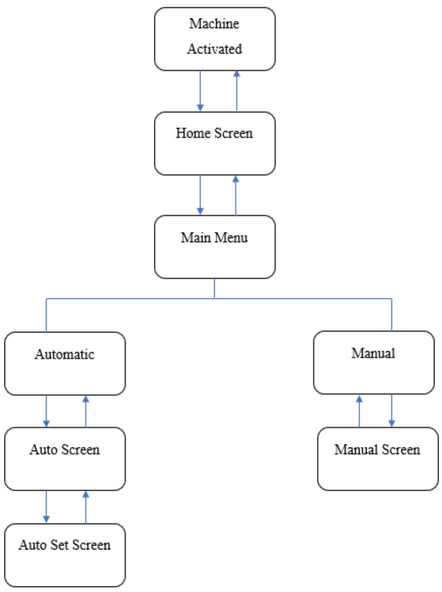
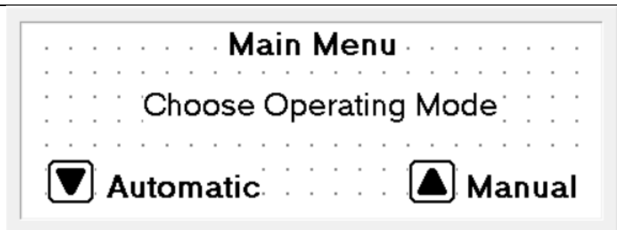
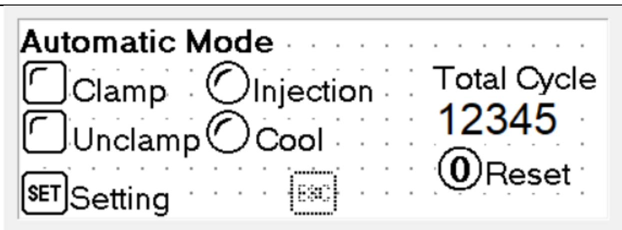
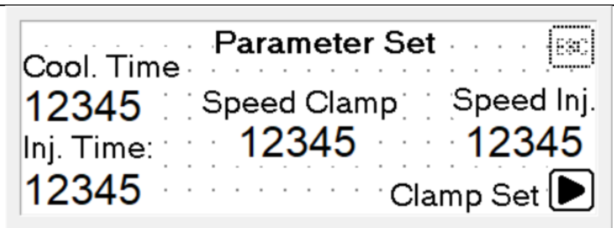
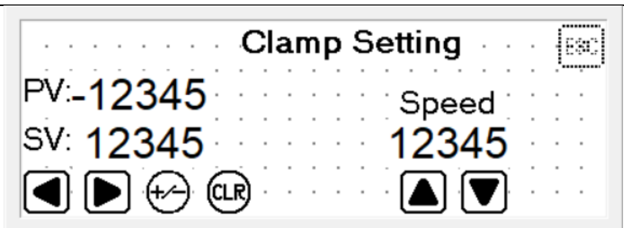
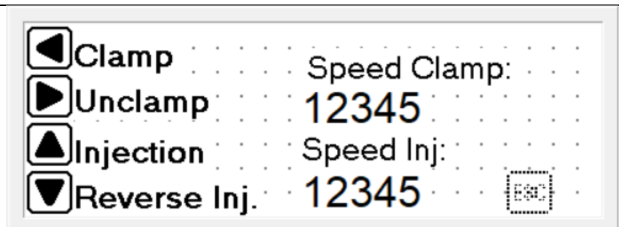


Fig. 6 HMI Programming Algorithm

The initial Home Screen on the HMI displays information about the machine, specifically the names of the research team who involved in its development. This is the initial screen when the machine is turned on and in an idle state. Pressing a button navigates the HMI to the Main Menu, which contains options for the operating mode. The Manual Screen contains commands to run the machine manually, along with speed adjustment settings. The Auto Screen displays information about the current cycle and the total number of cycles completed. It also includes a button to switch to the Auto Set Screen for adjusting automatic mode parameters

Table 4. HMI Screen

Name of Screen	Display
Home Screen	
Main Menu	
Auto Screen	
Auto Set Screen 1	
Auto Set Screen 2	
Manual Screen	

Programming

The PLC programming was done using GXWorks 2 with the ladder diagram programming language. The programming was carried out based on the algorithm and was done incrementally to avoid cascading errors. First, the manual mode was programmed. After the manual mode was successfully created, the automatic mode program was developed.

The PLC in this portable plastic injection machine is used to control the movement of stepper motors. As previously known, stepper motors use pulses for their movement, so the PLC program utilizes pulse output commands. There are various types of pulse output commands such as PLSY (Pulse Y Output), PLSR (Pulse Ramp), and DRVI (Drive to Increment). The PLSY command allows the Y output to emit a specified number of pulses at an instantaneous frequency; a limitation of this command is that the motor may not rotate if the input frequency is very high. The solution for high-frequency requirements is to use the PLSR command, which outputs pulses with a gradually increasing frequency, in other words, acceleration. The acceleration time can be set in this command in milliseconds. The DRVI command generally has the same function as the others but is typically used for positioning because it allows for reverse motor movement.

Different commands were used for the clamping and injection processes. The clamping process uses the PLSR command to enable fast movement, while the injection process uses the PLSY command because injection does not require rapid movement. These commands were paired with the required process inputs.

After PLC programming, the HMI was then programmed. The HMI programming was also based on the algorithm. The first step was to create the display and various buttons for the process, followed by linking each button to the PLC program. The buttons were matched to the internal relays in the PLC program. Therefore, during the initial HMI creation process, it was crucial to ensure that the selected PLC type matched the one being used. Once the button adjustments were complete, the HMI program was downloaded from the PC via RS232 communication.

Testing

The testing process was divided into two parts: testing the motor's movement accuracy and testing the injection characteristics of the PLC control system. The motor movement accuracy test was performed by setting the pulse in the program to move the motor by 4 mm. A dial indicator was mounted on the end of the clamp to measure any deviation, as shown in Figure 7.

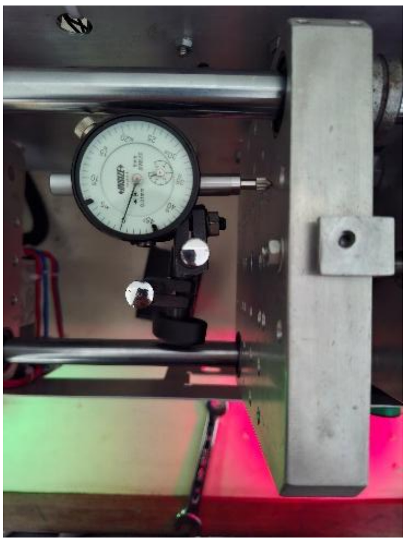


Fig. 7 Dial Installation for Testing

The injection characteristic test was an experiment on the effect of motor speed on the injection result. The test was conducted by rotating the motor for 100 revolutions at different speeds. The weight of the molten plastic output from the nozzle was measured and compared to see if there was a difference in weight when the injection motor speed was varied. Figure 8 shows the process of collecting the injected plastic.

Fig. 8 Collecting Injected Plastic

Result and Discussion

The developed portable injection machine, as seen in Figure 9, is now equipped with an HMI, allowing machine operation and parameter settings to be done directly through the interface. The operational process has also become easier. The motor movement accuracy test results showed that the motor provides sufficiently precise motion. Table 5 shows that the average deviation was 0.02 mm. The largest deviation of 0.04 mm occurred at a frequency of 1,000 Hz, which was due to the significant vibrations produced by the motor at this frequency. Because the 1,000 Hz frequency generates high vibrations, it is recommended to avoid using this frequency in the automatic program. The test was conducted only up to a frequency of 20,000 Hz because above this value, the motor experienced slippage or failed to rotate

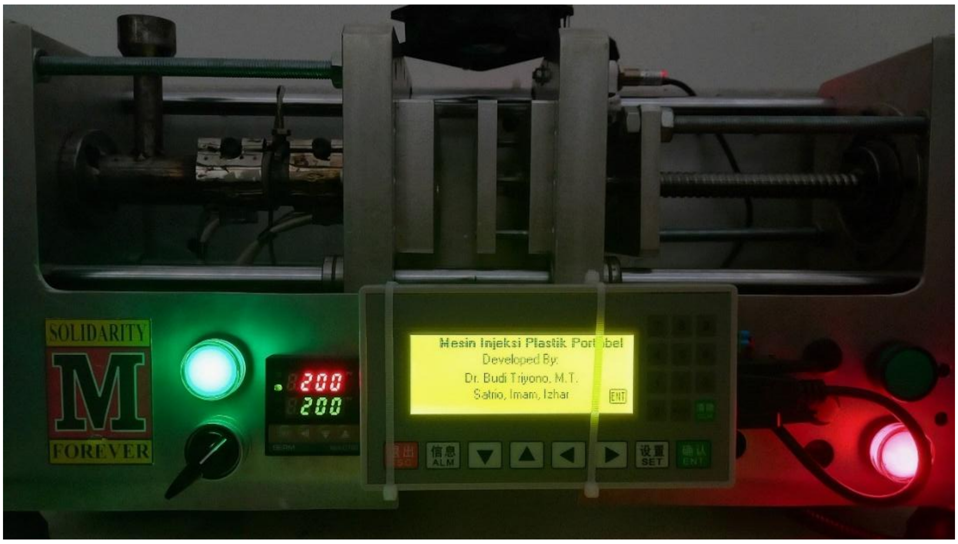


Fig. 9 The Developed Machine

Table 5. Motor Movement Accuracy Test Results

Test No.	Motor Pulse Count	Frequency (Hz)	Theoritical Displacement (mm)	Nominal Actual Displacement (mm)	Deviation (mm)
1	3,143	500	4	4.02	0.02
2	3,143	1,000	4	4.04	0.04
3	3,143	2,000	4	4.02	0.02
4	3,143	4,000	4	4.02	0.02
5	3,143	6,000	4	4.02	0.02
6	3,143	8,000	4	4.02	0.02
7	3,143	10,000	4	4.02	0.02
8	3,143	15,000	4	4.02	0.02
9	3,143	20,000	4	4.03	0.03

The injection characteristic test revealed the relationship between motor speed and injection performance. Table 6 shows that the weight of the injected plastic decreased as the motor speed increased. This can occur because when the injection screw rotates too quickly, the plastic pellets do not have enough time to fill the empty spaces in the screw flights, resulting in a smaller amount of melted plastic and thus a lower injection weight. It was also found that the motor could only rotate up to a frequency of 8000 Hz (300 rpm). Above 8000 Hz, the motor slipped because its torque was insufficient to turn the injection screw.

Table 6. Result of Testing Characteristic of Injection System

Test No.	Motor Speed (rpm)	Frequency (Hz)	Resulting Weight (Gram)
1	112.5	3,000	1.34
2	150.0	4,000	1.28
3	187.5	5,000	1.24
4	225.0	6,000	1.07
5	262.5	7,000	0.66
6	300.0	8,000	0.99

Conclusion

From the overall activities conducted, it can be concluded that the implementation of a PLC and HMI-based control system simplifies the machine's electrical installation, which it makes the operation, maintenance, and troubleshooting is easier. Furthermore, the addition of several functions has improved the effectiveness of the machine operation, as adjustments can now be made directly via the HMI. The motor motion generated by the PLC is sufficiently precise to control the stepper motor-driven clamping mechanism, with a maximum speed of 20,000 Hz (600 rpm) and a movement precision of up to 0.02 mm. For the injection mechanism, the motor's maximum speed is 8,000 Hz (300 rpm). The combination of a Mitsubishi FX3U CPU PLC and an OP320-5A HMI has proven to be an effective alternative for an interactive, practical, and economical sequential motion control system, especially for application on the portable plastic injection machine

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