Industrial Grinding with Programmable Logic Control: A Case Study

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ABSTRACT The advancement of machinery during the industrial revolution has led to the development of new production methods, which in turn has increased the need for precision machining technologies. To address the issue of precision processing, various solution methods have been developed, including the use of Programmable Logic Controllers (PLCs) and microprocessor technologies. This study focuses on the use of PLCs and grinding machines in a production line, using Mitsubishi PLCs and GTWorks-3 programs for programming and the MODBUS protocol for communication between devices. The results of the study showed that the use of PLCs in the production process resulted in a 33% time saving and improved surface smoothness of the processed materials. Additionally, the PLC programming was able to quickly detect and address faults in the machine.

KEYWORDS Axis drives, Controller, CNC, Grinding Machines, PLC.

1. INTRODUCTION

Today, technology is beyond being a part of our lives; it has become our life itself. From the first industrial revolution, which started with the use of steam systems at the end of the 18th century to the 4th industrial revolution, not only a single production line has been controlled, but also the digital operation of the entire company has started to control and observe [1,2].

As production technologies have advanced, there has been a growing need for precision in the manufacturing process. However, irregular surface curvatures can pose a challenge for industrial applications and increase processing time. To address this, there has been increased research and development of universal machines, numerical control machines, and Computer Numerical Control (CNC) machines, which offer high precision and fast processing capabilities. The use of simulation programs has also become widespread to improve quality, reduce costs, and increase efficiency. CNC machines have been particularly popular due to their ability to reduce processing time by up to 80-85%. As a result, they have become widely used in various manufacturing sectors, including machining, aviation, automobiles, medicine, and cutting tools. To meet the demand for CNC machines that can work on more than 2-axis, there has been a growing need for 3, 4, and 5-axis machines. In this study, a 3-axis CNC machine was developed to meet these demands [3-7].

In contemporary times, automation systems are increasingly being used to accomplish tasks without human intervention. This has several benefits such as reduced labor costs, time savings, and minimization of errors. Programmable Logic Controllers (PLCs) are one such controller developed for this purpose. PLCs are microprocessor-based devices that serve as an alternative to conventional control elements in industrial automation circuits. They can be used not only to control individual machines but also to manage all factory automation systems. The first PLC, the Modicon, was introduced in 1968 by General Motors engineers as a relay control system and was later produced and released by Bedford Associates [8]. It replaced the control structures that were designed using logic gates at the time [9-10]. Currently, there are several manufacturers in the market producing PLCs with different brands and features, but their operational logic remains the same. Compared to relay systems, PLCs offer several advantages, which include [11]:

- Designing a control circuit with a PLC is simpler than designing a circuit with a relay.
- In any system change, the control part must be completely changed in the relay system, while only a software change will be sufficient in the PLC.
- PLC systems take up less space and fail less than relay systems.

- PLC systems are less affected by bad environmental conditions than relay systems.
- In PLC systems, the status of inputs and outputs can be monitored.

In this study, a surface grinding machine was examined. The surface grinding machine has innovative aspects such as fast, self-running, and high precision. As a result of this research, the parameters that are required in machine tools or will be required during operation have been determined. Along with these parameters, end-user evaluations and requests were also taken into consideration.

The objective of this study was to develop an automated industrial grinding machine using a PLC and to design the automatic operation of a surface grinding machine with three axes, which was electrically examined at all stages. The proposed system is intended to facilitate a faster and more efficient grinding process on an automatic working bench. Mitsubishi PLC and GTWorks-3 programs were utilized for the design, while communication between devices was established via the MODBUS protocol. In addition to communication, 16 inputs and 14 outputs were incorporated into the PLC, with two analog inputs and one analog output available on the spindle driver. Axis drivers were operated through communication with the PLC using encoders and Modbus. Sensors were also installed on the machine to display information about the machine and the surrounding environment.

2. GRINDING MACHINES

In the manufacturing industry, machining operations play a crucial role in achieving the desired size, shape, and accuracy of products. Machining encompasses various processes, such as grinding, turning, welding, drilling, sawing, cutting and grooving, filing, milling, reaming, tapping, threading, and shaping, among others [12-14]. One of the oldest and most basic shaping methods is the grinding process, which has been used since ancient times for sharpening bones, swords, and cutting and piercing tools. Machining involves the removal of a layer of material from the surface of a workpiece, such as metal, wood, plastic, etc., using a tool and power to shape the material into the desired form, size, and surface finish. The material removed during the machining process is known as chips, and their shape and size depend on the cutting tool geometry, processing speed, and workpiece material. Figure 1 illustrates the basic structure of the grinding process.

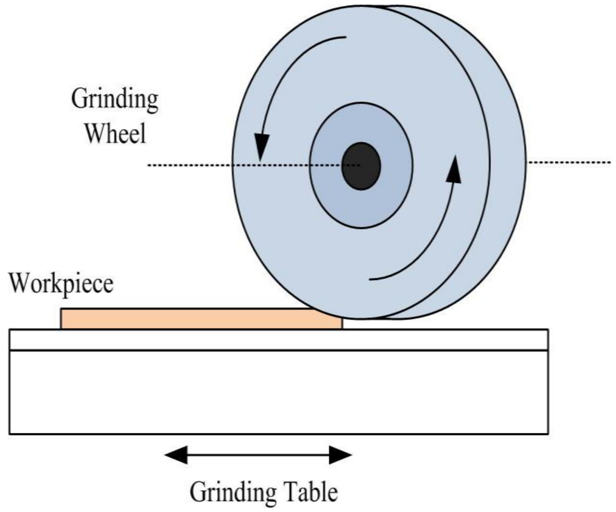


Figure 1. Image of the surface grinding process

The precision machining process is crucial for achieving desired size, shape, and accuracy in the manufacturing industry. Among various machining processes, grinding is a widely used method for cutting a piece from the workpiece surface using a tool and power to give a material the desired form, such as surface, shape, and size. The main advantages of the grinding process include achieving precise tolerance range, elimination of distortions after heat treatment, sawdust removal from hardened surfaces, and obtaining quality and bright surfaces, making it the preferred final step in manufacturing.

Grinding machines are widely used in industry and are available in various types such as universal machines, NC (Numerical Control) machines, and CNC machines. Universal machines are the most common and cost-effective, while NC machines are partially computerized refinements of universal machines and are operated with symbols such as numbers and letters. CNC machines, which have been increasingly used in recent years due to technological advancements, acceleration, and precision, are preferred for high-precision and intense production but are expensive, thus not preferred in smaller workshops [3].

3. PROGRAMMABLE LOGIC CONTROLLER

PLCs are similar in terms of structure, although the usage areas and purposes are varied. They consist of a power supply, a Central Processing Unit (CPU), memory, input (or sensing unit), and output (or control elements). A PLC consists of the parts shown in Figure 2.

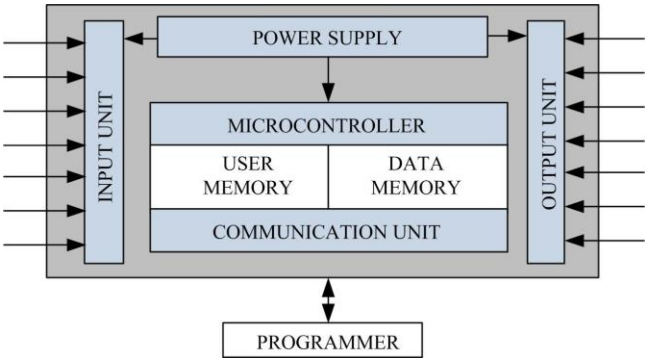


Figure 2. PLC block diagram

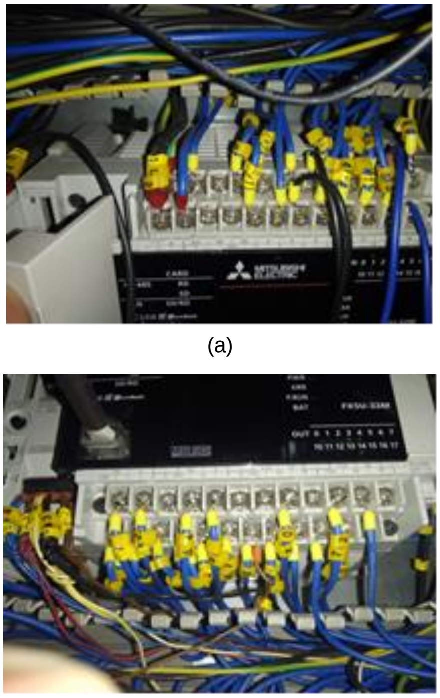
The CPU is responsible for performing all arithmetic and logical operations, as well as counting and timing functions in a PLC. The program is written in the CPU and then stored in the memory unit, which can be made of different types of interfaces such as EEPROM, EPROM, PROM, ROM, and RAM. Typically, EPROM memory units are used in PLCs. Inputs to PLCs can be digital signals from sensors and buttons, or analog information such as temperature, weight, current, voltage, and position. Each PLC model has its own input configurations, and additional input modules can be added if needed. Outputs from the PLC control the system, and can be both digital and analog signals. Contactors and relays are connected to the output of PLCs to receive signals. Additional output modules can also be added if necessary. PLC programmers can choose from six different programming languages, including IL, LD, ST, SFC, FBD, and CFC, all of which adhere to the IEC 61131-3 standards. [10,15-16].

The research utilized a set of machine components including the axis motors, drivers, spindle motor inverter, screen, and PLC. To design the interface program for the PLC, GT Designer3 Version 1.217B was employed. Furthermore, in this study, the ladder diagram was the programming language of choice.

3.1. PLC input – output

The PLC utilized in this study has 16 inputs and 16 outputs, with all inputs and 14 outputs being utilized. Inputs are established from signals derived from the HMI, sensors, and buttons, which are then processed within the PLC, and outputs are directed accordingly. Among the input signals, I0.0, I0.1, and I0.2 are designated as high-speed inputs and are intended for receiving signals of utmost importance. For instance, in the event of an emergency stop, these inputs are preferred in order to promptly halt the machine. All input signals can be organized as follows: I0.0 Emergency stop, I0.1 X-axis + direction, I0.2. X-axis – direction, I0.3. Handwheel Z-axis selection, I0.4. Handwheel Y-axis selection, I0.5. Handwheel 10μ feed, I0.6. Handwheel 100μ feed, I0.7. Stone cap sensor, I1.0. Operator door key-sensor, I1.1. Current relay signal, I1.2. Boron oil level sensor, I1.3. Motor protection thermal contacts, I1.4. Magnetic table cancel switch, I1.5. Skid oil level sensor, I1.6. Y-axis home completed, I1.7. Z-axis home completed.

The PLC outputs in this study were utilized to activate elements and initiate motor operation. In the machine, four motors were controlled by the PLC outputs while one motor was controlled by the inverter. A relay that is energized by the PLC output was used to provide the 220VAC voltage connected to the NO contact to the single-phase motor. For motors operating with 3*380VAC, the output of the relay contact was used to energize the contactor coil. The 3-phase 380VAC input of the contactor was transmitted to the motor when its coil was energized. The reason why the PLC output is not directly given to the contactor is due to insufficient output power to meet the contactor coil power. If we list the PLC outputs utilized in this study: Q0.0. Hydraulic motor, Q0.1. Coolant engine, Q0.2. Paper filter motor, Q0.3. Operator door locking, Q0.4. Warning lamp red, Q0.5. Program running lamp is green, Q0.6. X-axis + direction of movement, Q0.7. X-axis - direction of movement, Q1.1. Servo axis lubrication, Q1.2. Hydraulic axis lubrication, Q1.3. Hydraulic relief valve, Q1.4. Handwheel Y-axis selection relay, Q1.5. Handwheel Z-axis selection relay, Q1.7. Grinding completed lamp.


(a)

(b)

Figure 3. PLC (a) Input Port (b) Output Port

PLC I/O connections are shown in Figure 3 (a) and (b), respectively.

3.2. Communication in PLC

To communicate within the system, the Modbus protocol is utilized. The drivers and the PLC communicate via four specific channels, namely TXD+, TXD-, RXD+, and RXD-, as depicted in the electrical project shown in Figure 4. Encoders installed in the motors provide information to the PLC, which is then displayed on the operator's screen through an Ethernet connection. The Modbus protocol supports baud rates ranging between 1200 to 9600 and can be utilized for four different speeds.

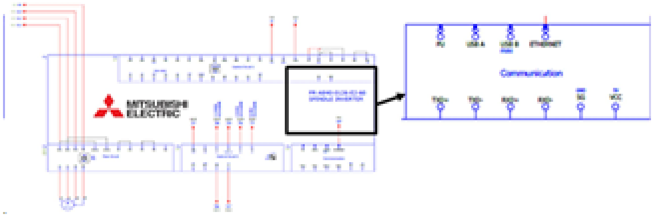


Figure 4. The spindle driver electrical project

Inverter, PLC, and display, which communicate with Ethernet, are connected by an Ethernet multiplexer. Ethernet multiplexer is selected as 5 inputs. The reason is that in addition to the 3 devices that will communicate with each other, a connection is added to download and read PLC software from the PC. PLC needs the energy to do all these operations. It provides this energy needed with 220VAC.

3.3. Human-machine interface (HMI)

The human-machine interface (HMI) is the component that establishes a link between the operator and the PLC, enabling the user to perform settings and control functions in an industrial setting. The user's actions on the HMI are transmitted to the PLC via communication protocols, providing the user with control over the machine. HMIs are available in various sizes and configurations, with a variety of features. Their physical appearance is similar to that of a computer screen. They employ different types of communication protocols and components, such as Modbus (RS485, RS232, RS422), Modbus TCP/IP, Ethernet, Profibus, among others [12]. In this study, the HMI screen is connected to the PLC via Ethernet cable and communicates and sends the data on it to the PLC. PLC receives this data and evaluates it and sends commands to motors or other output elements. The main screen of HMI has been shown in Figure 5.

The primary interface page, shown in Figure 5, displays essential information such as the current positions of the axes, the spindle rotation set value, working time, Manual-Auto mode selection, and control window. To ensure authorized access, the date and time in the upper right corner are encrypted, and the password can be entered by clicking the lock icon. The table speed adjustment section for models with a proportional valve is located on the right side of the screen, which is used exclusively for adjusting table speed on machines with proportional valve adjustment.

08/05/2020

PROCESS TIME 00:00:00

SET 0.00

Y Actual Position 0.000

Z Actual Position 0.000

SPEED 0.0

Figure 5. The main page of HMI in the manual status

The handwheel can be used for manual grinding, but it's important to ensure that the magnetic table holds the diamond properly before starting stone grinding. Failure to do so can result in serious work accidents. The handwheel is used to slowly lower the stone onto the diamond that's fixed on the magnetic table. If the stone comes closer to the diamond by more than 10mm, the handwheel should not be turned by more than 1µ. To position the diamond correctly, it should be placed about 4mm from the lowest part of the stone in the direction of rotation of the stone (to the left when looking from the front). Similarly, the stone should be centered with the diamond on the Y-axis using the handwheel. Once the diamond touches the stone, the Y-axis is selected via the handwheel, and it's moved on the diamond stone in the Y direction at the desired speed until the stone border ends. The Y-axis is then moved in the opposite direction until it crosses the stone border. The Z-axis is selected on the handwheel and is lowered to the desired pass. Then the stone is sharpened by moving it back and forth along the Y-axis. This process is repeated until the desired amount of grinding is achieved.

The machine can be equipped with a head grinding apparatus, which is turned clockwise and brought closer to the stone in machines with this option. Once it reaches the wiper on the stone, the diamond is moved on the stone at a constant speed using a pull handle. However, obtaining a smooth surface with this method can be difficult due to the manual sharpening process. This process is safe as it takes place behind the stone cover.

Figure 6 shows the status of automatic mode selection. When this mode is selected, access to the manual page is closed, and manual page selection is disabled in the subpage navigator bar, preventing entry to the manual page. In this case, the start button on the screen becomes active, which is used to initiate automatic operation of the machine at specified positions. Once the start button is pressed, the "stop" and "pause" buttons appear on the screen, which can be used to halt and control the operation during automatic mode. The home screen displays axis actual positions in mm, where the right side of the decimal point is read as 1μm, 10μm, and 100μm.

Figure 6. The main page of HMI in automatic status

Automatic grinding refers to the process in which the machine automatically performs grinding operations. Once the necessary adjustments have been made, the machine can perform grinding at the desired speed, resulting in a high-quality cutting surface. While in automatic mode, the handwheel cannot be used for manual movements on the machine. However, it is permitted to use the handwheel for movements on the automatic grinding pages, allowing the user to adjust the axes.

To perform automatic stone grinding, the diamond must be affixed to the magnetic plate. It is essential to ensure that the magnetic table holds the diamond correctly before beginning the grinding process, as failure to do so could result in work accidents. Using the handwheel, the stone is slowly lowered onto the diamond attached to the table. If the stone comes closer to the diamond by more than 10mm, the handwheel should not be turned more than 1μ. The diamond should be positioned approximately 4mm from the lowest part of the stone in the direction of rotation (to the left when viewed from the front). Additionally, the stone should be centered with the diamond on the Y-axis using the handwheel. Once the machine is in the correct position, the user can begin automatic stone grinding by pressing the start button.

The rotational speed of the stone is measured and displayed in hertz (Hz) as the SP speed. In this investigation, the stone's speed will be set to the main frequency of 50 Hz, corresponding to a rotational speed of 1500 revolutions per minute (rpm). The run time denotes the duration for which the machine has been running in automatic mode, and it is reset upon starting a new run. The selected mode, whether manual or automatic, will be indicated on the screen with the corresponding mode name displayed. If the screen displays "manual," the manual mode is selected, and if "automatic" is displayed, the automatic mode is selected.

4. EXPERIMENTAL DESIGN

4.1. Electrical Project Design

When designing a machine or system, various factors such as material selection, software design of the PLC program, and identification of potential issues in the production process must be carefully considered in project design. The electrical project plays an important role in ensuring that the system operates smoothly and is free of errors. If mass production is anticipated, having an electrical project plan in place can be an invaluable resource for the implementation process.

In machine manufacturing, multi-contact high-speed relays are commonly used to ensure that the machine operations are halted quickly in the event of unsafe conditions or emergency situations, such as when the emergency stop button is pressed. These relays, known as safety relays, are integrated into the design of the machine and are used to inform the PLC of any emergency signals via 2 contacts.

In this study, a power supply with an output power of 24VDC and 10A was utilized as the power source for the machine, which runs on 220VAC. The selection of 24VDC as the operating voltage was made to ensure compatibility between the PLC inputs and outputs. Field elements, such as relays, sensors, contactor coil ends, and valves were chosen to operate with 24VDC and incorporated into the system. The choice of 10A was based on the fact that the total power requirements of the devices in the system did not exceed 10A.

When designing the machine, it was decided that it would have three axes, one of which is the X-axis. The X-axis is responsible for the movement of the machine and is controlled hydraulically. Typically, in grinding machines, the movement along the X-axis is not precise and moves continuously with the reciprocating principle, which is why it was chosen to be hydraulically controlled. This provides high power and a movement that doesn't require precision. The hydraulic axis speed can be adjusted by applying a voltage between +10VDC/-10VDC to a proportional valve unit. When a "+" voltage is applied, the axis moves in the positive direction, and when a "-" voltage is applied, it moves in the negative direction. The voltage amplitude determines the axis movement speed, which is achieved by pulling the valve coil with the required amount of thrust force.

On the other hand, the Y and Z axes are responsible for precision machining and are controlled by servo motors. The motors communicate with the PLC, which detects motion via the RS232 socket or information received from the PLC. The motion-related information is then transmitted to the SDP, SDN, RDP, and RDN pins via the drivers.

The axes on the machine have sensor signals that determine their end limits, known as "HARD-LIMIT," and these signals are input directly to the drivers. Upon the initial startup of the machine, references are also obtained from these sensors. The MR-JE-70A drivers have an input that allows for the reading of handwheel signals, but since the handwheel signals are axis-specific, a double contact relay is used to allow the PLC to select the appropriate axis. The selected axis is then sent as a signal to the PLC, which chooses the relay and sends the A and B signals from the handwheel to the drivers.

The communication between the axis drivers and servo motors is accomplished through encoder cables, while power cables are routed from the drivers to the motors to ensure that they operate in accordance with the provided information. The connections for the servo axis drivers are nearly identical, with two key differences. First, a braked motor is used for the Z-axis. While the machine's axes use motor energy for their movements, they are inactive when no power is supplied or when the emergency stop button is pressed. As a result, the Z-axis, being vertical, would move downward due to gravity. To prevent the stone from falling and damaging the part, the operator, or the machine, the brake output of the driver cuts off the energy to the motor's brake using a relay, which locks the brake in place when power is lost. The electrical scheme for the y-axis is depicted in Figure 7.

The axis end limits, or HARD-LIMIT, are determined by sensor signals inputted to the drives. For instance, the Y and Z axis sensors are connected to pins 43 and 44 of the CN1 socket, as depicted in Fig. 7. The limit direction set by the sensor can be adjusted via the driver parameters. Additionally, the signals that report the reference points are short-circuited to pin 19, the "home" signal input.

According to the PLC software, the axis moves until it detects the home point and then moves 5mm in the opposite direction to eliminate the sensor. Unlike other axis drives, the Z-axis lacks a downstream limit sensor. This is because there is no criterion to determine the lower limit of the Z-axis when moving down, as the magnetic table can be removed to work on the machine. Also, as stone sizes decrease, the vertical axis must move down. Therefore, a lower limit sensor is not placed on the vertical axis due to unknown properties, such as the diameter of the stone.

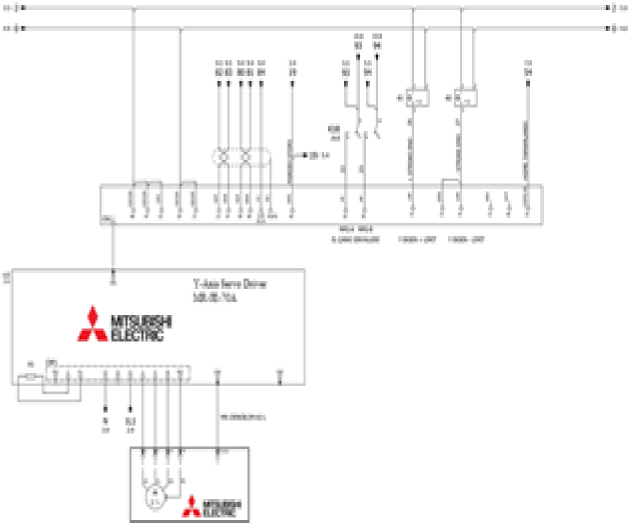


Figure 7. Y-axis electrical scheme

4.2. PLC Programming

The ladder diagram that corresponds to the grinding start command is depicted in Figure 8. Once the grinding command is issued, the 'grinding first run' and 'axes start' command lines are activated. The former command is used to position the axes before grinding begins. Once grinding is complete, the 'grinding completed' command line is reset to indicate that the previous grinding operation has been completed. Additionally, the position and track command lines are reset to prevent any unintended movement of the Z-axis.

When the 'grinding start' input is received, the positions of the Y and Z axes are saved to determine the starting point of the movements. Consequently, the actual positions of the Y and Z axes are assigned as the initial values using the DMOV instruction. The grinding amount is set to K0 in order to clear any default values. As per the stone grinding procedure, when the Y-axis is positioned at the center of the stone, it is retracted along the Y-axis by an amount equal to the thickness of the stone. To achieve this, the initial position is adjusted so that the Y starting position begins as far back as the stone thickness at the start of the sharpening process. Similarly, the Z-axis start position is assigned as the instantaneous position, and the end position is incremented by the value entered on the screen to determine the Z end position.

Figure 8. The ladder diagram of grinding starts in PLC software

To adjust the amount of grinding, the 'grinding start' signal is subtracted from the current position of the Z-axis, and the resulting value is recorded as the grinding amount. Once the Z-axis reaches this value, the grinding process is complete, and the 'grinding start' signal goes to a falling edge. At this point, the PLC compares the actual position of the Z-axis with the desired grinding position. If the actual position is less than or equal to the desired position, the starting position is subtracted from the actual position of the Z-axis and written as the remaining amount. When the actual position is equal to this remaining amount, the grinding process is complete and the axes stop moving.

After the axes have taken their positions, the comparisons are shown in Figure 9. As illustrated in the flowchart, the grinding process will be complete when the Z-axis reaches the value entered on the screen. The comparison between the desired position and the actual position of the Z-axis is made using the D>= or D= commands, just as in the case of the Y-axis.

The PLC ladder diagram in Figure 10 shows that the Z-axis end limit values are reset once grinding is completed. Additionally, the section that is connected to the "axes_start" command, which enables the axes to move, is also reset at the end of the grinding process.

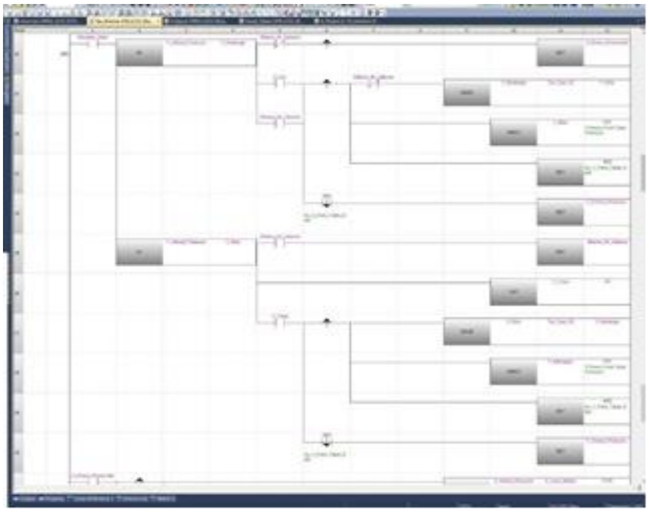


Figure 9. Axes command in PLC software

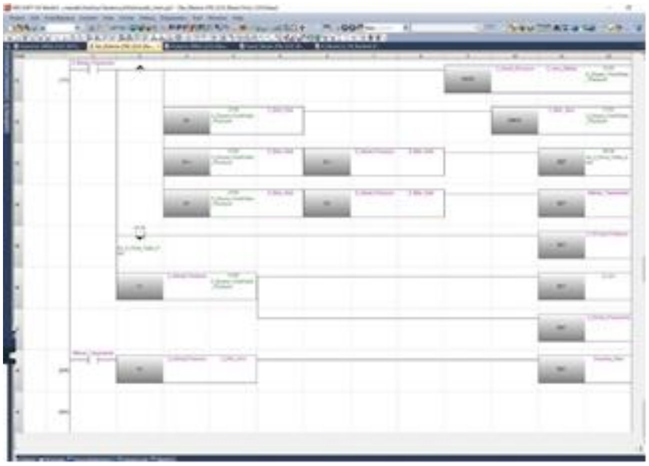


Figure 10. Grinding finish commands in PLC software

Once the grinding process is completed, the position of the workpiece needs to be adjusted to account for the amount of material removed from the stone during grinding. This is necessary because the stone thickness will decrease due to the grinding process. To address this, the grinding amount is added to the surface level after grinding is completed. This ensures that the shrinking stone piece will not affect the zero point. Operators do not need to manually adjust the value as the software automatically performs this operation.

In Figure 11, the designed system has been shown. The operator can control the grinding machine by using an HMI screen in which automatic mode or manual mode can be selected. By adding an HMI touching screen to the structure of the designed machine, it was aimed at creating a healthier processing environment by providing visual support and monitoring the work. PLC connections and other connectors are shown in Fig. 12.

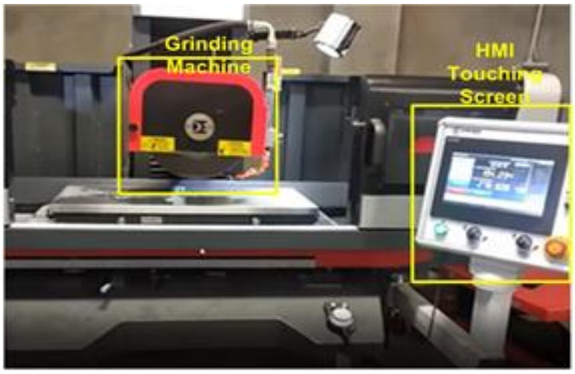


Figure 11. Designed grinding machine with HMI interface

Figure 12. PLC and other connections for control of the designed grinding machine

The final grinding process has been shown in Fig. 13. As can be seen, a smoother surface is obtained at the end of the grinding process.

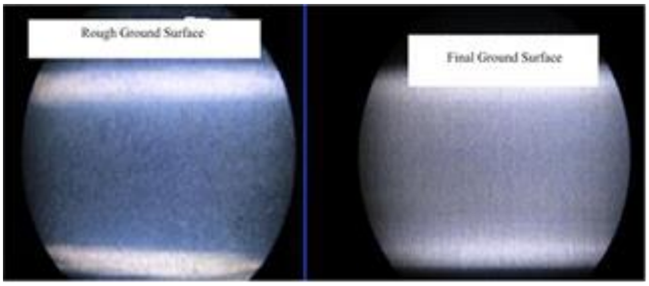


Figure 13. Results of grinding process

5. CONCLUSION

Automation is the use of various control systems to operate equipment with minimal or reduced human intervention. Automated machines or systems for automating machines are spreading rapidly today. Industries such as aviation, military industry, and defense now use automation in many areas. In this context, many computer-controlled machines and developments on these machines have been made and continue to be made. In this way, by minimizing personal errors, the system is enabled to act according to the inputs and the transactions can be made automatically. Automatic systems started with the use of the first transistor and continued with the help of relay-coil and motor. These systems, which were established with the help of relays in the past, have now turned into systems that can make faster and mathematical interpretations by being smart with the help of industrial PLCs. In this study, an example of an automation system was developed by adapting it to industrial grinding machines.

In the 3-axis system, since the times missed by the operator in the machining times on the machine are continued instantly with the help of automation, the working time is shortened from these places and an acceleration in processing by 10% is foreseen. In the 3-axis system, it can be estimated that the machining time will be accelerated by 10% by shortening the working time from these areas since the missed times by the operator in the machining times are maintained instantly with the help of automation. However, since the operator's effect on these times is higher in stone grinding, it was planned to save up to 30% with the designed system and it was observed that it saved up 33% by using the designed system.

In addition to saving time by using the automation system, the automatic operation of the system will reduce the number of personnel and direct the person to different jobs. Repair or maintenance of the machines will be both simpler and more regular with an alarm system that activates in case of a malfunction of the system or an alarm informing that it is time for maintenance. In addition, while automatic grinding enables the surface quality to increase and the abrasive to be used for a longer time, operator errors will not be observed in the system.

Potential future research studies can be listed as follows. Each AC motor's operation can be controlled and faults can be detected by installing a phase sequencing-protection relay on each motor. Compensation can be applied to axes to eliminate perpendicularity issues. Machine malfunctions that may occur can be evaluated using artificial intelligence, enabling faster problem resolution. Prior to implementation, a simulation can be created on the screen to enhance visual representation of the task at hand.

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