ORIGINAL ARTICLE

PROGRAMMABLE CONTROLLER AND HUMAN-MACHINE INTERFACE RETROFIT FOR SHEET-METAL CUTTING CONTROL

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ABSTRACT

A 1995 Colgar sheet-metal cutting machine used in the Manufacturing Laboratory of Politeknik Negeri Manado experienced degraded cutting performance, a disabled automatic cycle, an unreliable safety function, and a non-functional blade-gap adjustment mechanism. This study aimed to retrofit the machine control system by integrating a programmable logic controller, a human-machine interface, limit sensors, a variable-frequency drive, and interlock-based emergency logic. The study used a research-and-development design combined with experimental validation. Data were collected through machine inspection, input-output mapping, ladder-diagram programming, HMI screen development, electrical installation, and functional testing with 2 mm and 6 mm steel plates. The retrofit restored manual and automatic blade movement, reactivated the worktable/blade-gap mechanism, enabled operator monitoring through HMI screens, and improved safety through upper and lower limit sensors, emergency stop logic, visual indicators, and audible alarms. Post-retrofit tests showed that the blade-gap setting operated normally, with a 0.35 mm gap for 2 mm steel plates and a 0.75 mm gap for 6 mm steel plates. The machine could perform a complete automatic down-and-up cycle through a single command while retaining full manual control. The findings indicate that PLC-HMI retrofitting is a practical modernization strategy for legacy sheet-metal machines because it improves functionality, operational accuracy, usability, and machine safety without replacing the main mechanical structure.

Keywords: Human-Machine Interface; Industrial Automation; Programmable Logic Controller; Safety Interlock; Sheet-Metal Cutting Machine.

INTRODUCTION

Sheet-metal cutting machines remain essential equipment in manufacturing workshops because they support sizing, preparation, and trimming of steel plates before welding, forming, and assembly operations. The cutting quality of a shear-type machine depends not only on the mechanical condition of the blade but also on the consistency of blade movement, the adjustment of blade clearance, the stability of the worktable, and the reliability of electrical control. In metalworking theory, inappropriate clearance may produce excessive burr, bending instead of shearing, accelerated tool wear, and unsafe load conditions on the machine structure (Groover, 2019; Kalpakjian & Schmid, 2014). Therefore, a machine that still has a strong mechanical frame may become operationally ineffective when its control, sensing, and safety subsystems are no longer functioning.

The Colgar Model 01 20 sheet-metal cutting machine with serial number 9509/112/L101 has been used at Politeknik Negeri Manado since approximately 1995. Before the retrofit, several key functions had deteriorated: the upper and lower blade limit sensors were not reliable, the automatic mode was unavailable, the blade-to-worktable distance adjustment no longer operated properly, and the stopper mechanism was difficult to use. During pre-retrofit testing, thin steel plates were sometimes bent rather than cut, while thicker plates created excessive load, impact noise, and oil leakage. These symptoms indicate a gap between the intended operating condition of a cutting machine and the actual condition of a legacy machine that had lost part of its automatic control capability.

A practical solution for this type of problem is retrofit rather than full replacement. Retrofitting extends the useful life of industrial assets by replacing obsolete control elements while retaining the major mechanical structure, which is consistent with maintenance engineering and asset management principles that emphasize reliability, maintainability, and life-cycle value (Campbell et al., 2011;

Dhillon, 2002; Jardine & Tsang, 2013; Moubray, 1997). For educational manufacturing laboratories, retrofit is also pedagogically valuable because students and technicians can learn the integration of sensors, actuators, PLC programs, HMI displays, safety circuits, and commissioning procedures on a real machine rather than on a simulation platform alone.

The programmable logic controller (PLC) is widely used for machine automation because it is robust, deterministic, modular, and suitable for sequence control. PLCs implement logic, timing, counting, arithmetic, and interlocking functions through input-output modules and a cyclic scan process (Bolton, 2015; Dunning, 2005; Petruzella, 2017). IEC 61131-3 standardizes programming languages such as ladder diagram, function block diagram, structured text, sequential function chart, and instruction list, thereby making PLC-based control more portable and maintainable across industrial environments (International Electrotechnical Commission [IEC], 2013; John & Tiegelkamp, 2010). Ladder diagram is especially appropriate for retrofit projects because it resembles relay logic and can be understood by maintenance personnel who are already familiar with electromechanical circuits (Jack, 2010).

The human-machine interface (HMI) strengthens this control architecture by giving operators a visual control and monitoring layer. A well-designed HMI reduces reliance on hidden electrical panels, supports situation awareness, and helps operators understand the state of the machine before executing commands (Endsley, 1995; International Society of Automation [ISA], 2015). In a retrofit context, the HMI must not merely duplicate buttons; it should communicate operating mode, command status, actuator movement, alarm state, and emergency conditions in a form that is easy to interpret. Human interaction with automation is most effective when the system clearly separates manual control, automatic control, safety functions, and feedback signals (Parasuraman et al., 2000).

Machine retrofit must also address safety systematically. ISO 12100 places risk assessment and risk reduction at the center of machinery design, while IEC 60204-1 provides requirements for electrical equipment of machines, including emergency stop, control circuits, and operator interfaces (IEC, 2016; International Organization for Standardization [ISO], 2010). For safety-related parts of control systems, ISO 13849-1 and IEC 62061 provide principles for designing and validating safety functions such as interlocks, limit monitoring, and safe stopping (IEC, 2021; ISO, 2023). Although the present project is implemented in a laboratory context rather than a certified production line, these standards provide a rational basis for integrating an emergency stop, limit sensors, visual-audible alarms, and interlock logic into the upgraded system.

Previous studies and technical developments show that PLC, HMI, VFD, and sensor-based control can improve the precision and efficiency of industrial equipment. HMI modules based on Omron PLCs have been used to make control processes more visible in training environments (Depto Maniar et al., 2021), while VFD-based drives enable motor speed and acceleration control by varying frequency and voltage (Bose, 2002; Hughes & Drury, 2019; Nugrahanto et al., 2022). PLC-based safety simulations also demonstrate that programmable control can coordinate input signals, output devices, and alarm responses in transportation and machine contexts (Kawulur et al., 2022). However, the specific gap in the present study is the absence of an integrated retrofit model for an aging Colgar sheet-metal cutting machine that simultaneously restores blade up-and-down control, blade-gap adjustment, stopper movement, automatic cycling, HMI-based operation, and safety interlock logic.

The novelty of this study lies in the practical integration of an Omron CP1H PLC, Omron HMI, VFD, solenoid control, upper and lower limit sensors, emergency stop logic, and selector-based operating modes into one retrofit system for a legacy sheet-metal cutting machine. The objective of the study is to design, implement, and validate a PLC-HMI-based control retrofit that restores the machine functionality, improves blade movement control, reactivates blade-gap and stopper mechanisms, and strengthens operational safety.

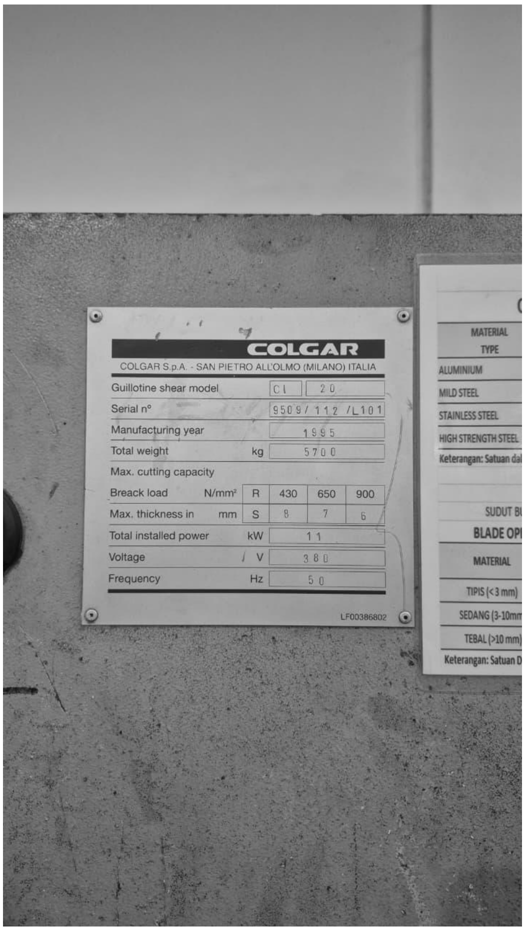

Figure 1. Cutting machine specifications

The specification plate shown in Figure 1 confirms the identity and basic capacity of the Colgar machine used as the retrofit object. This information was used to limit the scope of the retrofit to control modernization rather than mechanical capacity enlargement.

METHOD

This study used a research-and-development approach combined with experimental validation. The development component was used to design and build the new control architecture, while the experimental component was used to test whether the upgraded control system could perform the intended blade movement, blade-gap adjustment, stopper movement, safety response, and cutting operations. This design is appropriate for engineering-based studies because the main output is not only a description of a phenomenon but also a working product that can be evaluated through functional tests.

The research object was a Colgar Model 01 20 sheet-metal cutting machine located in the Manufacturing Laboratory of Politeknik Negeri Manado. The machine had remained mechanically useful but showed critical control problems: the automatic mode could not be used, the blade movement limit system was unreliable, the blade-gap adjustment did not function normally, and the stopper mechanism had degraded. The retrofit did not change the main frame, blade assembly, or hydraulic structure; instead, it focused on the control, sensing, interface, and safety subsystems.

The main instruments and materials included an Omron CP1H programmable logic controller, an Omron HMI panel, CX-Programmer software, NB-Designer software, a VFD, relays, panel buttons, a selector switch, an emergency stop button, indicator lamps, a buzzer, upper and lower limit sensors, solenoid control wiring, and a feeler gauge for blade-gap measurement. The use of PLC and HMI devices was selected because the system required deterministic sequence control and direct operator interaction. The VFD was included to support motor control and improve operational stability, while the sensors and emergency components were included to reduce the risk of uncontrolled blade movement.

The development procedure consisted of problem identification, input-output mapping, control design, HMI design, electrical installation, program downloading, commissioning, and validation. During problem identification, the research team inspected the solenoids, motor stopper, existing cable routes, control panel, and mechanical blade-gap mechanism. During input-output mapping, each actuator and sensor was assigned to the PLC input or output address. The ladder program was then developed to implement emergency stop logic, buzzer activation, manual mode, automatic mode, upper limit protection, lower limit protection, table movement, and motor stopper control. The HMI screens were developed to provide virtual commands and visual feedback for blade, table, and stopper operation.

Data collection was conducted through direct observation, documentation of components, functional testing of each PLC output, HMI command testing, safety response testing, and cutting tests using 2 mm and 6 mm steel plates. The 2 mm plate represented thin material that previously tended to bend, while the 6 mm plate represented a thicker material that previously caused performance degradation and oil leakage. The main measured data were blade-gap values after adjustment, while the main qualitative data were mode operation, sensor response, stopper response, alarm response, and cutting feasibility.

Data analysis used a functional validation matrix and descriptive comparison before and after retrofit. A function was considered successful when the command was executed consistently, the actuator stopped at the correct limit condition, the emergency stop interrupted operation, and the HMI command matched the corresponding panel command. The validation did not claim statistical generalization because the research object was one machine; instead, it focused on whether the retrofit product met the predetermined engineering requirements for functionality, practicality, and operational safety.

Table 1. Retrofit validation matrix

Subsystem	Validation criterion	Evidence used in the study
Blade up-and-down movement	Manual and automatic commands move the blade correctly and stop at the limit position.	Panel buttons, HMI commands, upper and lower limit sensor responses.
Blade-gap adjustment	Forward and reverse table movement adjusts the gap according to plate thickness.	Feeler gauge measurements and successful 2 mm and 6 mm cutting tests.
Stopper mechanism	Motor stopper moves forward and backward to support workpiece positioning.	Command response through ladder logic and HMI display.
Safety function	Emergency stop, buzzer, indicator, and limit sensors prevent unsafe blade movement.	Emergency stop test, alarm response, and sensor-triggered stopping.
Operator interface	HMI screens provide clear commands for blade, table, and stopper movement.	HMI operation test and comparison with panel-button commands.

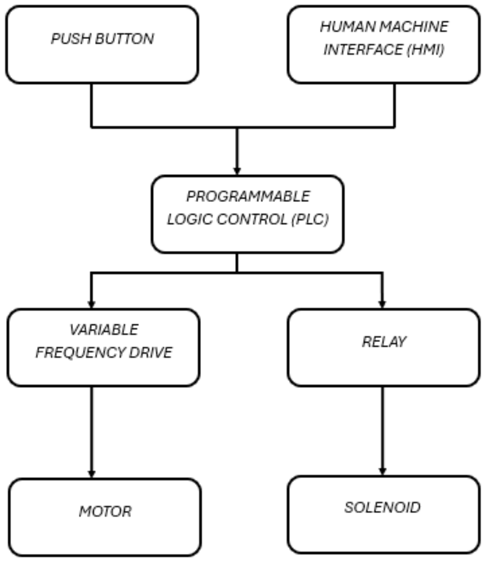

Figure 6. Block diagram of the retrofit control architecture

Figure 6 summarizes the retrofit architecture. The PLC receives signals from push buttons, the HMI, selector switch, emergency stop, and limit sensors; it then controls relays, solenoids, the VFD, and motor outputs according to the ladder logic.

RESULTS AND DISCUSSION

Pre-retrofit machine condition

The first stage of the retrofit was a baseline test to understand the actual machine condition. The test showed that the machine could no longer deliver stable cutting performance. A steel plate with a thickness of 6 mm caused a significant decline in performance and oil leakage, while a 1 mm steel plate could be bent rather than fully cut. In addition, the cutting blade frequently struck the body of the machine, producing a loud impact. This condition confirmed that the problem was not limited to ordinary wear; it involved a control failure because the blade could not be stopped and positioned precisely.

The baseline result is consistent with manufacturing theory that blade clearance and position control are essential to sheet-metal shearing quality (Groover, 2019; Kalpakjian & Schmid, 2014). If the lower position is uncontrolled, the blade may overload the machine body. If the upper position is uncontrolled, the cycle may become inefficient and unsafe. If the blade gap is not matched to the plate thickness, the machine may bend rather than shear the plate. Therefore, the retrofit target was formulated as a control-system recovery: the blade must move only when commanded, stop at upper and lower sensor limits, support automatic cycling, and allow blade-gap adjustment.

Figure 2. Pre-retrofit cutting condition on a 6 mm steel plate

Component identification and input-output mapping

Component identification showed that five solenoids were relevant to blade and table operation. Solenoids Y1 and Y2 were used to lower the blade, Y3 was used to raise the blade, while Y6 and Y7 were used to move the table forward and backward to determine the blade gap. This mapping was crucial because a PLC retrofit can only be reliable when each input and output is correctly related to the mechanical function it controls. Input-output mapping also reduced the possibility of cross-wiring between blade movement, table movement, and stopper movement.

The motor stopper was identified as the mechanism that limits workpiece positioning during cutting. Because the stopper has a direct effect on cutting repeatability and operator convenience, it was integrated into the new ladder program and HMI screen. The electrical panel was then inspected to determine which legacy components could be retained and which components should be removed or bypassed. This procedure follows maintenance engineering practice: replacement should be targeted at components that reduce reliability, while functional components may be retained to control cost (Campbell et al., 2011; Dhillon, 2002).

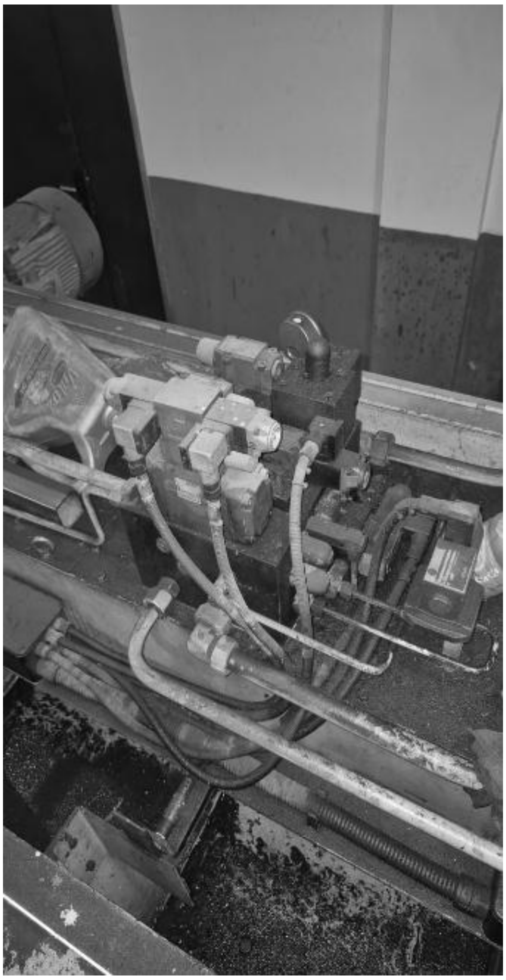

Figure 3. Solenoid components identified during troubleshooting

Figure 4. Motor stopper used as the workpiece guide limiter

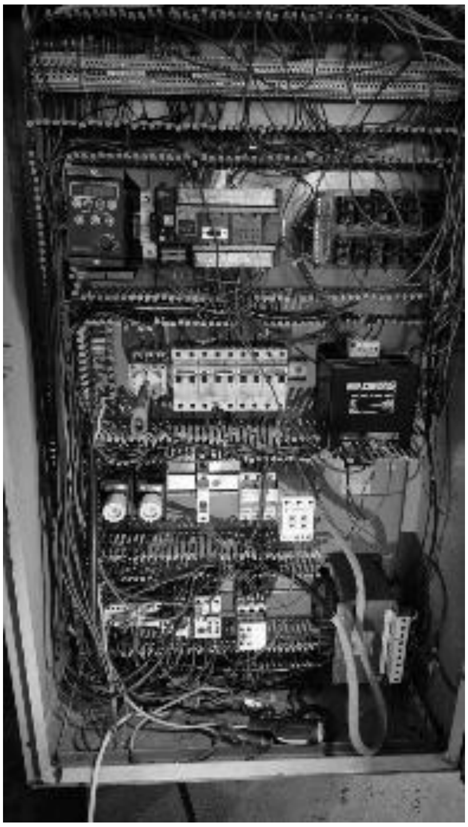

Figure 5. Electrical panel and cable installation before retrofit

PLC ladder logic and safety interlock design

The control program was developed in CX-Programmer using ladder diagram. This programming language was selected because it is suitable for sequential machine control and is understandable for technicians who previously worked with relay circuits (Bolton, 2015; Jack, 2010; John & Tiegelkamp, 2010). The ladder program began with emergency stop and buzzer logic. The emergency stop was designed to interrupt operation under abnormal conditions, while the buzzer and indicator lamps provided immediate feedback to the operator. Although this retrofit does not claim formal certification, the inclusion of emergency stop and indication is aligned with electrical machine safety principles in IEC 60204-1 and risk reduction principles in ISO 12100 (IEC, 2016; ISO, 2010).

Manual and automatic operating modes were then developed. In manual mode, the operator has direct control of the blade using panel buttons or the HMI. The blade moves only while the command is active and stops when the command is released or when the limit sensor condition is reached. In automatic mode, the operator presses the DOWN command once, after which the blade lowers until the bottom sensor is activated and then returns upward until the top sensor is activated. This operating sequence reduces repetitive operator action and improves cycle consistency while retaining manual control for setup and maintenance.

Upper and lower limit sensors were integrated as protective input signals. The upper sensor detects the blade maximum position and stops upward movement, while the lower sensor detects the blade minimum position and stops downward movement. These sensors solve the pre-retrofit problem in which the blade could strike the top or bottom of the machine body. In safety-related control-system theory, such limit monitoring is a basic risk-reduction measure because it converts an uncontrolled movement into a bounded movement (IEC, 2021; ISO, 2023; Rausand, 2011).

The blade-gap movement was programmed through forward and reverse logic that commands the table movement solenoids. Because blade clearance must be adjusted to material thickness, this function is central to cutting quality. The motor stopper was also programmed to move in both directions, making workpiece positioning faster and more repeatable. These control functions show the advantage of PLC-based retrofit: several previously separated electromechanical functions can be coordinated under one programmable logic structure.

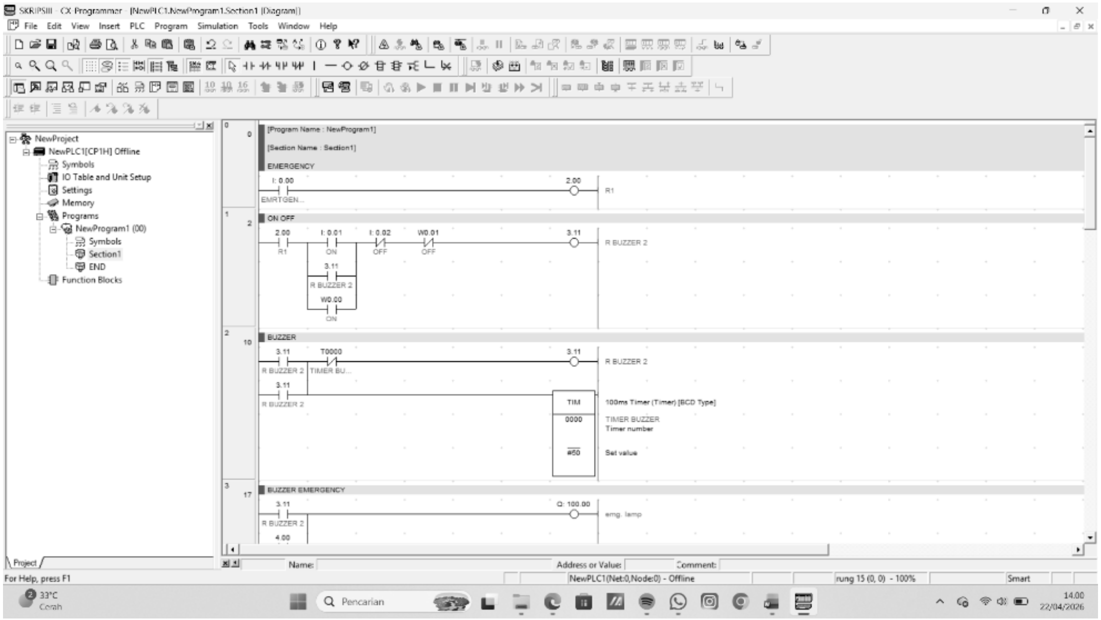

Figure 7. Emergency stop and buzzer ladder logic

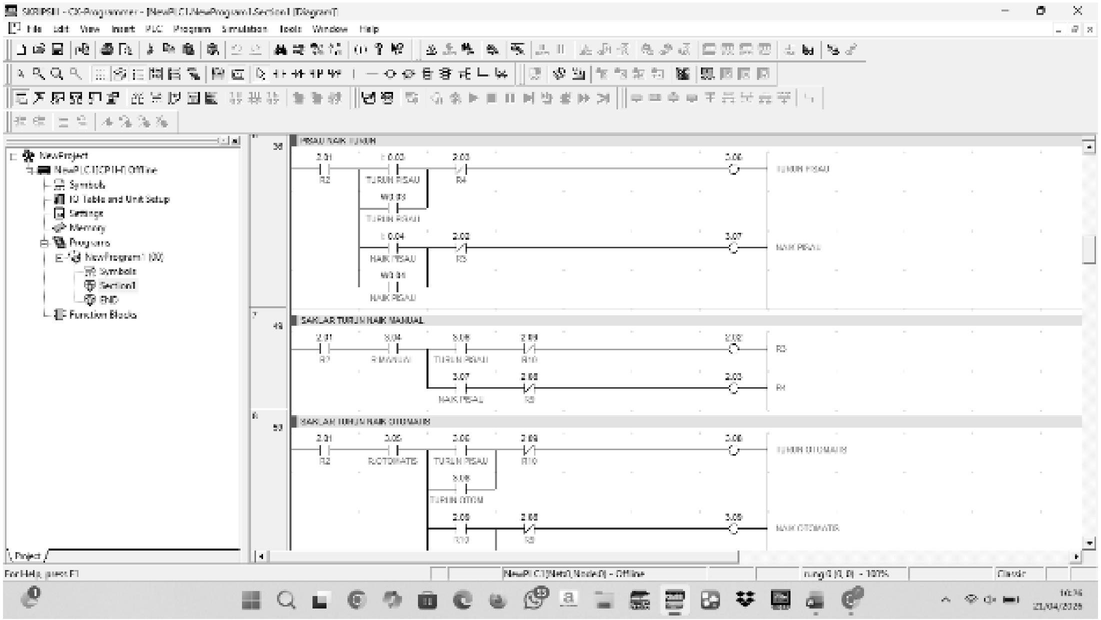

Figure 8. Ladder logic for manual and automatic blade movement

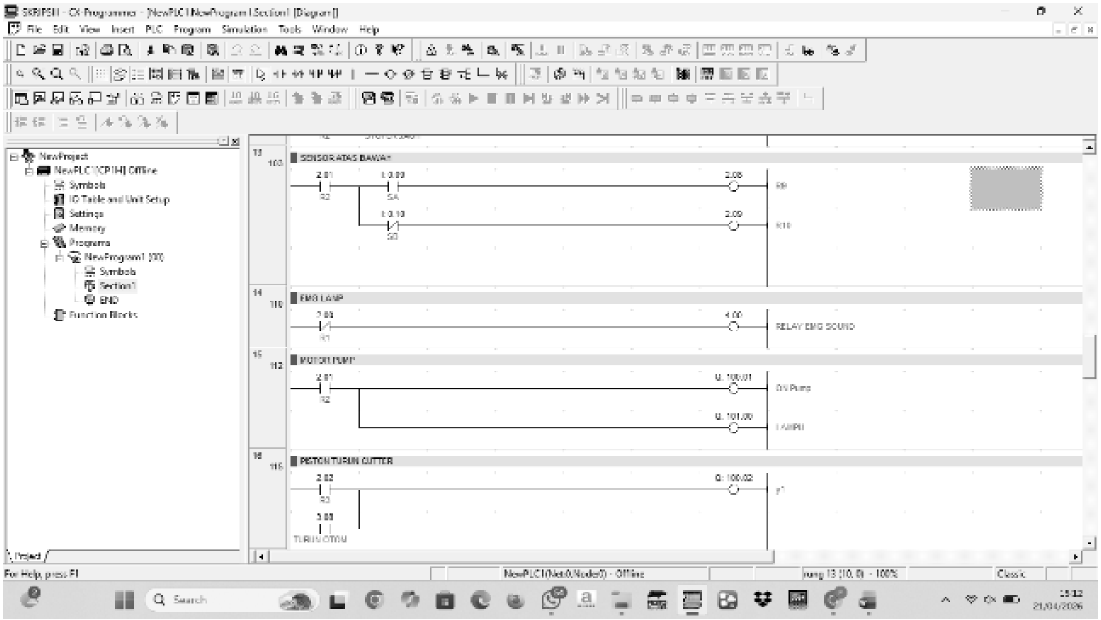

Figure 9. Upper and lower limit sensor ladder logic

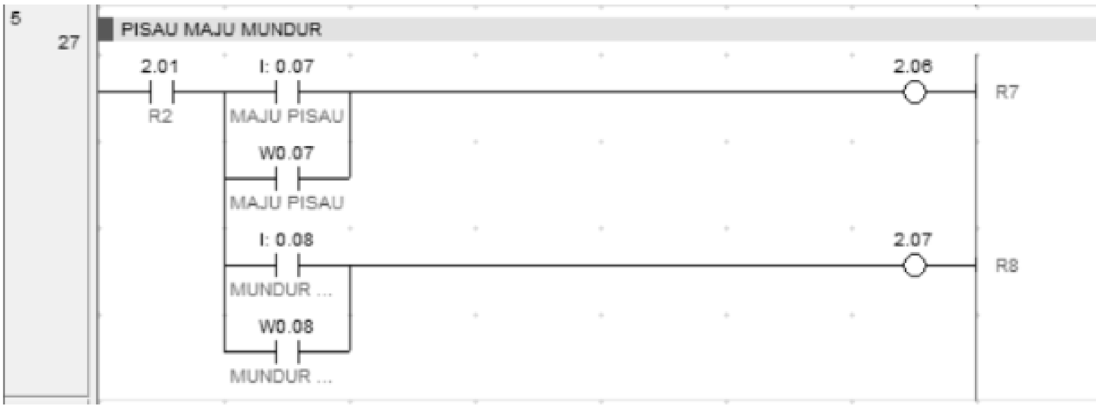

Figure 10. Ladder logic for forward and reverse blade-gap movement

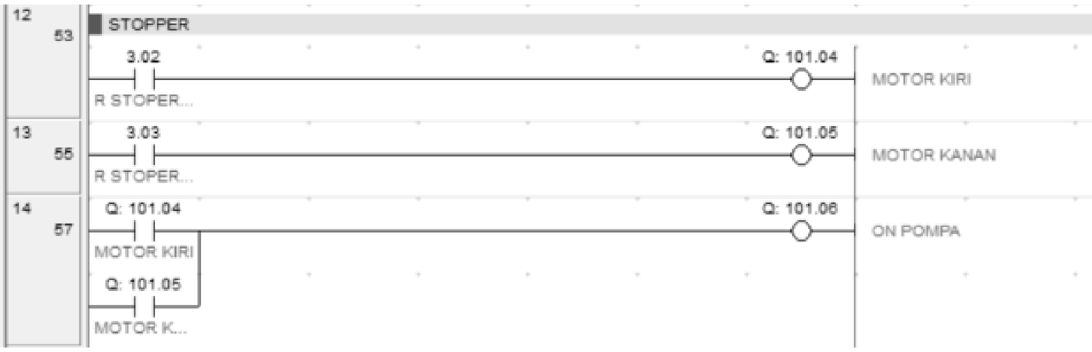

Figure 11. Ladder logic for motor stopper control

HMI implementation and operator usability

The HMI was developed in NB-Designer to provide a visual operator interface. The first screen controls blade up-and-down operation, while the second screen controls blade table movement and stopper movement. Both screens include ON/OFF commands and directional buttons. The HMI complements the physical control panel by giving operators an additional way to command and monitor the machine. This arrangement is consistent with the principle that automation should provide transparent feedback and support operator situation awareness rather than hide machine state behind the cabinet door (Endsley, 1995; ISA, 2015; Parasuraman et al., 2000).

From a usability perspective, the separation between blade movement and table-stopper movement is important because these functions have different operational purposes. Blade movement is associated with cutting and safety, whereas table and stopper movement are associated with setup and positioning. Separating them on the HMI reduces the chance that an operator will accidentally command an unintended subsystem. The physical selector switch also reinforces this separation by distinguishing manual and automatic operation at the panel level.

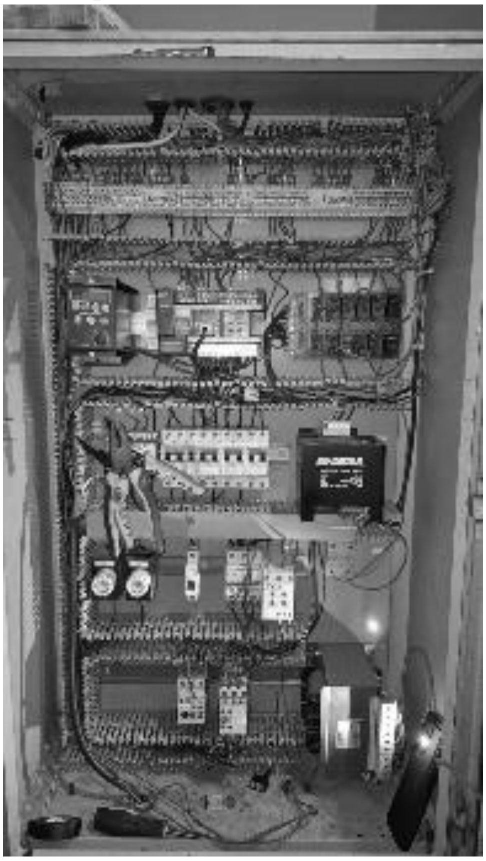

Figure 12. Cable assembly after retrofit installation

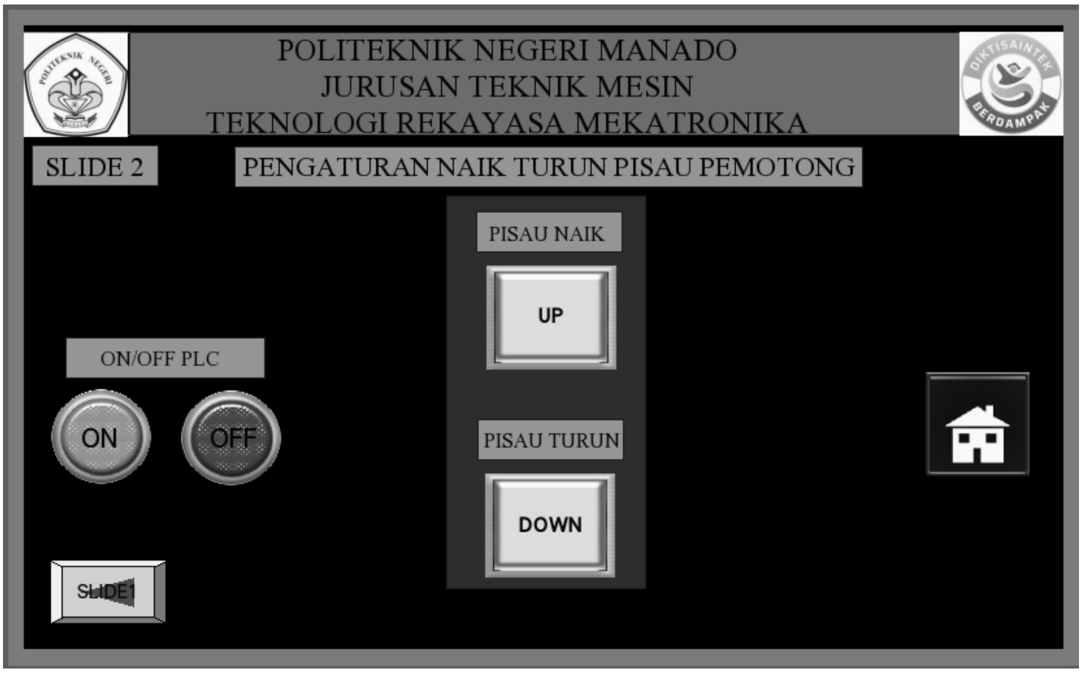

Figure 13. HMI screen for blade up-and-down operation

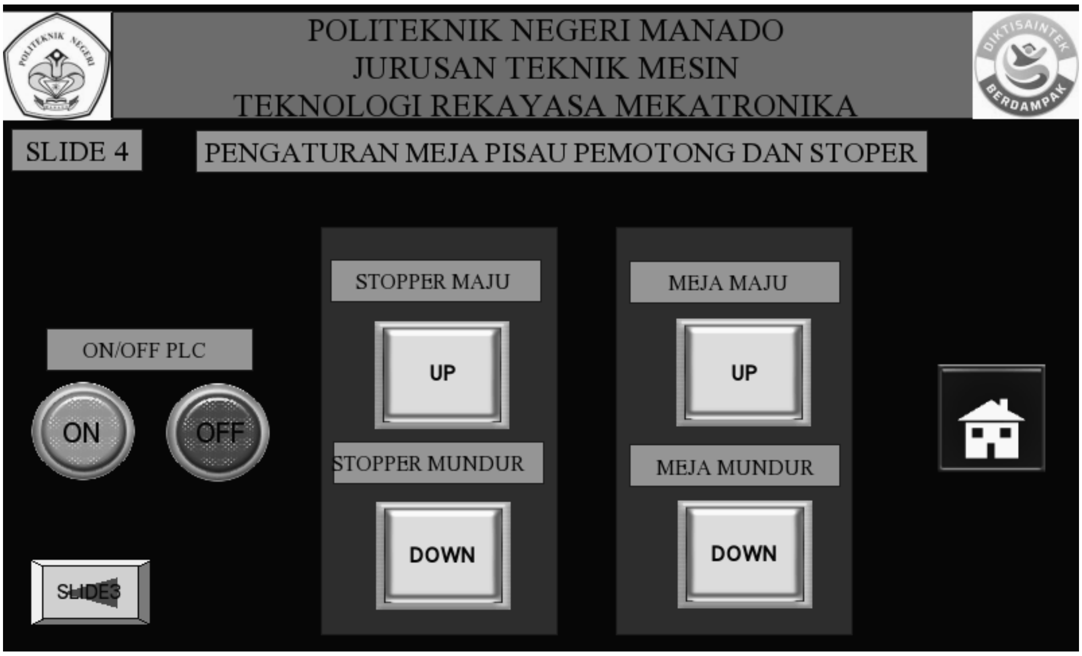

Figure 14. HMI screen for blade table and stopper movement

Figure 15. Control panel with selector, push buttons, and indicators

Post-retrofit testing and cutting performance

After the ladder program and HMI screens were downloaded, functional testing was conducted. The blade could be moved upward and downward in manual mode through both the panel and the HMI. The automatic mode also operated correctly: one DOWN command caused a complete down-and-up cycle without requiring the operator to press the UP command. The upper and lower sensors stopped the blade at the intended positions, thereby eliminating direct collision with the machine body during testing.

The blade-gap adjustment system also returned to normal operation. The test results showed that the blade-to-table gap could be set at 0.35 mm for a 2 mm steel plate and 0.75 mm for a 6 mm steel plate. These measurements indicate that the table movement mechanism and control logic were functional enough to support thickness-based adjustment. The stopper mechanism operated again, making it easier to position steel plates during repetitive cutting. The overall result confirms that the retrofit addressed the main symptoms identified in the baseline condition.

Table 2. Post-retrofit functional and cutting test results

Test item	Observed result	Interpretation
Manual blade movement	Blade moved upward and downward through panel and HMI commands.	Manual mode restored and suitable for setup.
Automatic blade cycle	One DOWN command executed a full down-and-up cycle.	Automatic mode restored and reduced repetitive operator input.
Limit sensor response	Upper and lower sensors stopped blade movement at the required positions.	Collision risk with machine body reduced.
Blade gap for 2 mm plate	Measured gap was 0.35 mm.	Thin-plate adjustment function operated normally.
Blade gap for 6 mm plate	Measured gap was 0.75 mm.	Thicker-plate adjustment function operated normally.
Stopper movement	Stopper moved forward and backward according to command.	Workpiece positioning support restored.
Emergency and alarm	Emergency stop, buzzer, and indicators responded during testing.	Basic safety feedback restored.

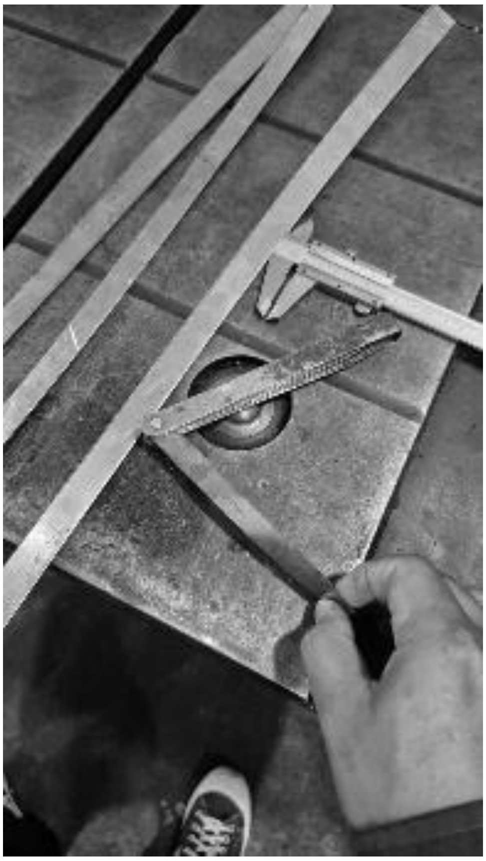

Figure 16. Post-retrofit cutting test on a 2 mm steel plate

Figure 17. Post-retrofit cutting test on a 6 mm steel plate

Discussion of retrofit contribution

The retrofit demonstrates that a legacy sheet-metal cutting machine can be modernized by replacing the control layer rather than replacing the entire machine. This is important for polytechnic laboratories because a complete machine replacement is costly, while control retrofitting can simultaneously improve safety, functionality, and learning value. By integrating the PLC, HMI, VFD, sensors, and interlock logic, the machine became easier to operate and more consistent in movement. The project also created an authentic learning platform for industrial automation, because students can observe real relationships among inputs, ladder logic, outputs, actuators, and mechanical response.

Compared with the previous condition, the most important improvement is the restoration of controlled blade movement. The machine no longer depends on uncertain legacy wiring and faulty sensor behavior. Instead, the PLC coordinates the sequence and enforces boundary conditions through upper and lower sensors. The HMI also makes the machine state more transparent for operators. This aligns with broader developments in industrial automation, where legacy systems are gradually upgraded toward cyber-physical and smart maintenance approaches that emphasize visibility, data-based decision making, and modular modernization (Bokrantz et al., 2020; Boyes et al., 2018; Lee et al., 2015).

Nevertheless, the study has several limitations. The validation was performed on one machine and used functional testing rather than long-term endurance testing. The results therefore confirm the success of the installed retrofit but do not yet provide data on long-term reliability, hydraulic stability, blade wear, or repeatability across many production cycles. Further studies should add cycle-count endurance tests, detailed measurements of cutting quality, fault-tree or FMEA-based risk analysis, electrical safety verification, and a comparison of cutting accuracy before and after retrofit across multiple materials and plate thicknesses. A future version can also add data logging, maintenance alarms, and structured operator training modules to extend the retrofit toward smart laboratory practice.

CONCLUSION

The PLC-HMI-based retrofit successfully restored and improved the control system of the Colgar sheet-metal cutting machine. The integration of the Omron CP1H PLC, HMI screen, selector switch, VFD, solenoid outputs, upper and lower limit sensors, emergency stop, buzzer, and indicator lamps enabled manual and automatic blade operation, reactivated the blade-gap adjustment mechanism, restored stopper movement, and strengthened operational safety. The post-retrofit tests showed that the machine could perform a complete automatic cutting cycle through one DOWN command, while manual mode remained available for setup and controlled operation. The measured blade gaps of 0.35 mm for a 2 mm plate and 0.75 mm for a 6 mm plate demonstrated that the blade-gap mechanism operated normally after retrofit. Overall, the system met the functional, practical, and safety-oriented targets of the study and can serve as a cost-effective modernization model for legacy manufacturing-laboratory equipment.

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