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Design and Fabrication of Automated Stopper Mechanism with PLC-Controlled System and Ball Screw Mechanism

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ABSTRACT

The demand for high precision and efficiency in industrial cutting operations has driven the development of automated positioning mechanisms. Most traditional manual stopper systems in panel saws often suffer from inaccuracies, inefficiencies, and material waste. To address these issues, this study presents the design, implementation, and performance evaluation of a PLC-based automated stopper mechanism utilizing a ball screw system for precise linear motion. The system integrates a Programmable Logic Controller (PLC), stepper motor, ball screw mechanism, and Human-Machine Interface (HMI) to enable accurate positioning and real-time operator control. Performance tests validated the system's reliability, precision, and suitability for industrial cutting applications. Speed evaluations confirmed that the stopper exceeded the 40 mm/s requirement, achieving 43.4 mm/s. Force resistance tests demonstrated structural stability under a 100 N load, with minimal deviations of 0.05 mm at 125 N and 0.10 mm at 150 N. Positioning accuracy tests further confirmed an average error of only 0.1 mm (0.005% deviation). The PLC executed motion commands with an average response time of 0.5 seconds, ensuring quick and reliable adjustments. These findings highlight the effectiveness of PLC-based automation in improving positioning accuracy, production speed, and overall usability in manufacturing environments.

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1. INTRODUCTION

In modern manufacturing, automation plays a crucial role in enhancing precision, efficiency, and productivity. Cutting operations, particularly in panel saw applications, require highly accurate positioning to minimize material waste and ensure consistent product quality. As industries increasingly demand greater precision and efficiency, automated solutions have become essential, especially in manufacturing sectors where cutting operations are critical (Orlowski *et al*., 2020). In Indonesia, panel saws are widely used for processing materials such as cardboard, wood, metal, and composite panels like brake pads, requiring precise dimensioning to maintain quality standards (Nandiyanto *et al.,* 2021).

Panel saws rely on a stopper block to define cutting positions, directly influencing the accuracy of the final product. Traditionally, operators manually adjust these stoppers, a process prone to human error, positioning inaccuracies, and inefficiencies, particularly in high-volume production settings (Farag *et al*., 2020). To address these challenges, some manufacturers have adopted automated stopper mechanisms, which enhance precision and efficiency by ensuring consistent, repeatable positioning using a linear motion control system. However, existing automated systems are often costly, making them inaccessible for many manufacturers.

Among various linear motion control systems, three primary mechanisms are widely used: timing belts, lead screws, and ball screws. Timing belts offer high-speed movement but suffer from lower accuracy and back-driving issues. Lead screws improve precision but introduce higher friction and require frequent maintenance. Ball screws, however, provide superior accuracy, durability, and minimal backlash, making them the preferred choice for high-precision applications (Kumar & Mandal, 2023).

This study aims to develop a cost-effective, high-precision automated stopper system with a programmable logic controller (PLC) that eliminates manual errors and enhances industrial automation. By integrating a ball screw mechanism with an optimized control system, the proposed solution improves cutting accuracy, process efficiency, and material utilization, contributing to the advancement of automated positioning technologies in manufacturing. The design process follows Shigley's design methodology to systematically select and optimize components, ensuring optimal performance. A benchmarking process was conducted to compare different motion control mechanisms, with the ball screw system emerging as the most suitable option due to its superior accuracy, stability, and load-handling capability. This method has been employed in previous studies to simplify and enhance the design process by systematically identifying key parameters, conducting benchmarking comparisons, optimizing component selection, and evaluating overall performance to ensure efficiency and reliability (Triawan *et al.,* 2024).

2. METHODS

The design and development process in this work followed the Shigley method as a guiding framework. Renowned for its structured and systematic approach, the Shigley model is widely recognized in design processes. The design process consists of six key stages: (i) identification of needs, (ii) problem definition, (iii) design and modeling, (iv) analysis and optimization, and (v) evaluation (Zulaikah *et al.,* 2020). Each stage was carefully implemented to ensure the final design meets the required accuracy, durability, and efficiency standards.

2.1. Identification of Needs

The first phase of the project focused on identifying the challenges associated with manual stopper positioning in panel saws. To address these issues, key performance requirements for the new system were established based on industry needs, operator feedback, and prior research on automated positioning mechanisms.

In this case, the machine needs to replace the manual stopper with an automatic design, this machine will also include some requirements, such as:

(i) The stopper needs to have high accuracy to ensure the cutting result of the cardboard is following the datasheet
(ii) The stopper needs to move in a straight line horizontally along the sawing platform
(iii) The stopper will have to move quickly enough to the designated point so that it won't slow down the sawing process.
(iv) The stopper has to be sturdy enough to stay in static condition and hold the cardboard while the cardboard is inserted into the sawing platform.
(v) The control of the machine must be user-friendly to allow the operator to operate it easily.

2.2. Definition of Problems

After identifying the requirements, a detailed problem specification was established to ensure that the final design meets all functional needs. These specifications were categorized into primary, secondary, and tertiary requirements (Antonio *et al.,* 2023).

Table 1 categorizes the machine's specifications into primary, secondary, and tertiary importance. The primary specifications ensure core functionality, requiring the stopper to move automatically along the X-axis (2500mm) for precise cutting and maintaining high accuracy with minimal deviation. It must also withstand horizontal forces from uncut cardboard without shifting. Secondary specifications focus on efficiency and usability. The stopper must move at a minimum speed of 40 mm/s to maintain workflow and include an automatic home position for easy resetting. Future enhancements, such as a safety cover, necessitate a design that allows easy attachment and maintenance. Tertiary specifications enhance aesthetics and usability. These include neat cable management, a professional finish, and visually appealing color choices, contributing to overall quality and user experience.

Table 1. Design specifications.

Category	Specifications	Weight
Primary	The stopper can move automatically in the linear plane on the X-axis for 2500mm	20
	The stopper needs to have an accuracy of at least 1 mm in every operation without deviation	20
	The stopper has to hold a horizontal force of up to 100N without changing its position	20
Secondary	The stopper can move with a velocity of 40mm/s	10
	The mechanism can move the stopper to its "home" position automatically	10
	The stopper can be detached from the sawing platform easily	10
Tertiary	Tidy cable management	5
	Color the machine for better appeal	5
Total		100

2.3. Design and Modelling

After the specifications of the mechanism have been clearly defined, the next step is to determine a design that meets those specifications. Each system has its unique characteristics and advantages, which were carefully evaluated to ensure compatibility with the established specifications. These designs were subjected to a comprehensive analysis to evaluate their suitability for implementation based on criteria such as performance, accuracy, durability, maintenance requirements, and cost-effectiveness.

Figure 1 illustrates a timing belt and pinion gear system for converting rotational motion into linear movement. This design enables high-speed stopper repositioning, is easy to install and maintain, and is cost-effective. However, it has drawbacks, including susceptibility to back driving, reduced precision, and potential wear over time, leading to higher maintenance costs and a shorter operational life.

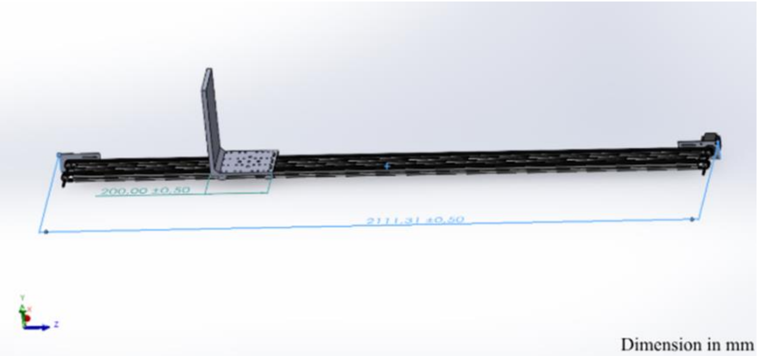

Figure 1. Synthesis 1 (timing belt).

Figure 2 presents a lead screw mechanism for converting rotational motion into linear movement. This design enhances accuracy and eliminates back driving, ensuring precise and stable stopper positioning. However, it requires careful installation and frequent maintenance and comes at a higher cost. Additionally, its limited flexibility in attaching and detaching the stopper can complicate maintenance and adjustments, potentially increasing downtime.

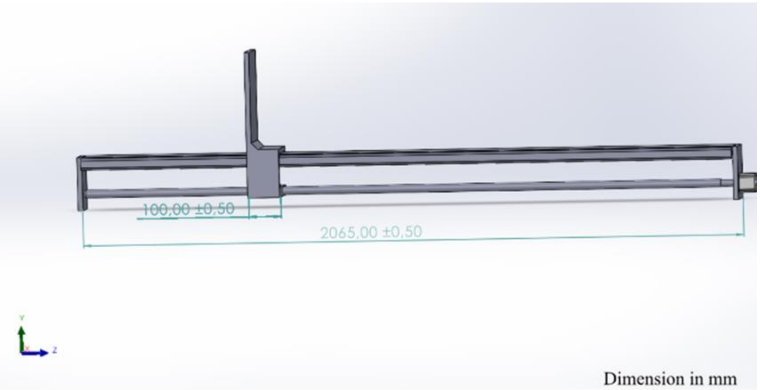

Figure 2. Synthesis 2 (lead screw).

Design 3 in **Figure 3** enhances the lead screw mechanism by incorporating ball bearings, creating a ball screw system. This design offers the highest precision, eliminating back driving and deviation while ensuring smooth, accurate movement (Verl & Hinze 2023). It is highly durable, requires minimal maintenance, and features a hinge mechanism in the stopper block for easy stopper detachment. However, its advantages come with higher costs and increased installation complexity, requiring precise calibration and expertise.

After developing three distinct designs, a thorough benchmarking process was conducted to evaluate each design against the predefined specifications. This evaluation aimed to identify the most suitable design for implementation. By comparing key performance metrics such as accuracy, durability, ease of maintenance, cost, and overall feasibility, the benchmarking process provided a comprehensive analysis of each design's strengths and weaknesses, as shown in **Table 2**. This rigorous assessment ensured that the chosen design would not only meet but also exceed the requirements, leading to an optimal solution for the intended application. The benchmarking process ultimately guided the selection of the best design, ensuring it aligns perfectly with the project’s goals and operational demands.

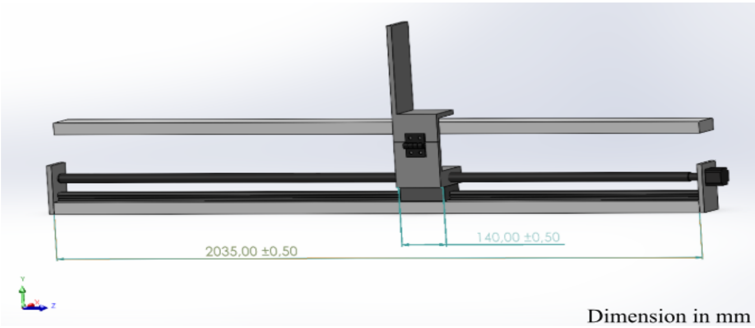

Figure 3. Synthesis 3 (Ball Screw with hinged Stop Block).

Table 2. Benchmarking process.

Category	**Specifications**	**Weight**	**Synthesis 1**	**Synthesis 2**	**Synthesis 3**
Primary	The stopper able to move automatically in linear piane in the X axis for 2500 mm	20	✓	✓	✓
	The stopper need to have an accuracy for at least 1mm in every operation without deviation	20			✓
	The stopper have to hold a horizontal force up to 100N without changing its position	02		✓	✓
Secondary	The stopper can move with velocity 40mm/s	10	✓	✓	✓
	The mechanism can move the stopper to its “home” position automatically	10	✓	✓	✓
	The stopper can be detached from the sawing platform easily	10			✓
Tertiary	Tidy and neat cable management	5	✓	✓	✓
	Color the machine for better appeal	5	✓	✓	✓
	Total	100	50	70	100

2.4. Analysis and Optimization

The evaluation phase of the project involved a comprehensive approach that began with the fabrication of the machine. Following the previous step with the chosen Design 3, the evaluation process is to ensure the fabrication of the machine, including the hardware and the program for the software.

2.4.1. Hardware assembly

This process involved carefully assembling each hardware component into a fully integrated system. Key components included the mechanical structure for support, stepper motors for precise movement, ball or lead screws for converting rotational to linear motion, and. Additionally, electrical components like power supplies, wiring, and control boards were integrated to ensure efficient operation. The proper alignment and connection of these parts were crucial for achieving high accuracy, reliability, and smooth functionality in preparation for the programming and testing phases.

(i) Ballscrew SFU 2510 set; this includes the shaft, bearing nut, and end support
(ii) Linear Guide Block and Railing HGR30 and HGW30CC
(iii) Shaft Coupler 14mm x 17mm
(iv) Stepper Motor Nema 34 12 Nm and Driver
(v) Custom-made metal bar for the base of the machine
(vi) Custom-made welded metal plate for the stopper

This process entailed a detailed and sequential assembly of all hardware components. First, the linear guide rail was securely attached to the metal bar holder using screws, providing a stable foundation for the entire system. The guide rail was essential for ensuring smooth and precise linear motion.

Next, the ball screw shaft was carefully positioned on top of the rail. This shaft, crucial for converting rotational motion into linear movement, was aligned with the rail to ensure optimal performance. The bearing nut was then mounted on the ball screw shaft, with support brackets installed at both ends to provide stability and minimize any potential wobble or misalignment as shown in **Figure 4**.

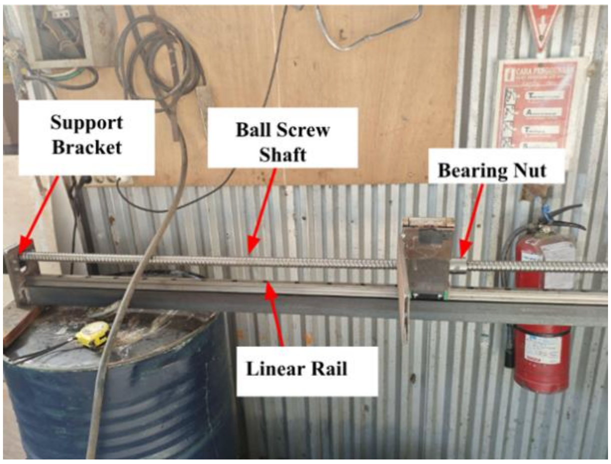

Figure 4. Fabrication process.

With these components in place, the stopper was affixed to both the linear block and the bearing nut, as shown in **Figure 5**. This step involved ensuring that the stopper was firmly secured and properly aligned with the linear block, allowing it to move accurately along the guide rail. The stopper's precise positioning was vital for achieving the required operational accuracy and reliability of the mechanism.

Finally, the stepper motor was mounted at one end of the ball screw shaft using a flexible coupler. The coupler, which connects the motor to the shaft, needs to be properly aligned and securely fastened to ensure the torque is transferred properly from the motor to the shaft shown in **Figure 6**. This connection was crucial for the accurate and reliable operation of the mechanism, enabling the stepper motor to drive the ball screw and facilitate the linear movement required for the system's functionality.

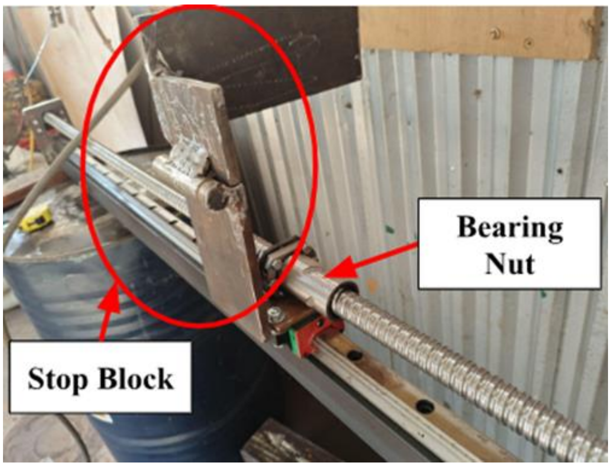

Figure 5. Fabricated stopper block.

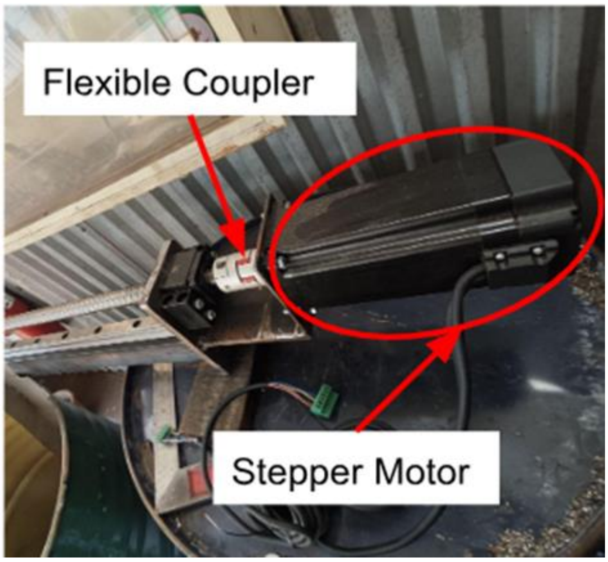

Figure 6. Installation of the stepper motor.

2.4.2. Software program

This process also involved programming the PLC software to manage the overall mechanism and developing the HMI software to facilitate operator input, converting it into PLC signals. The software tools used were CX-Programmer One and NB-Designer, both developed by Omron. Manufacturer of the PLC employed in this project. These tools were essential in ensuring seamless integration and communication between the operator interface and the machine's software, enabling efficient and reliable operation.

2.4.2.1. PLC Software

The Programmable Logic Controller (PLC) used in this study was the Omron CP1H, programmed with a CX-Programmer to ensure smooth operation of the ball screw-driven stopper mechanism. The control logic was designed to initialize the system by setting the absolute home position of the stopper, receiving positioning commands from the Human-Machine Interface (HMI), and calculating the required motor steps based on the target position. To achieve precise movement, the PLC sends pulse signals to the stepper motor driver while continuously monitoring feedback and making necessary adjustments.

The logic programming incorporated key functions, including home position initialization, where the stopper was set to an absolute reference point upon startup, and precise positioning control, which enabled the system to calculate and move the stopper to the exact coordinate input from the HMI. Additionally, the PLC dynamically adjusted the stepper motor speed based on the distance to be traveled, ensuring efficient motion control.

A critical aspect of evaluating the PLC's effectiveness was its response time between receiving an HMI input command and executing the corresponding movement. The system demonstrated an average response time of 0.5 seconds, making it suitable for industrial applications requiring real-time adjustments. The PLC logic programming flowchart, as shown in **Figure 7 and 8**, illustrates the sequence of operations, from input processing to executing motion commands. The system was tested under various conditions, including different positioning commands and speed variations, consistently exhibiting reliable response times, further validating its effectiveness in automated production environments.

Figure 7. PLC programming flowchart.

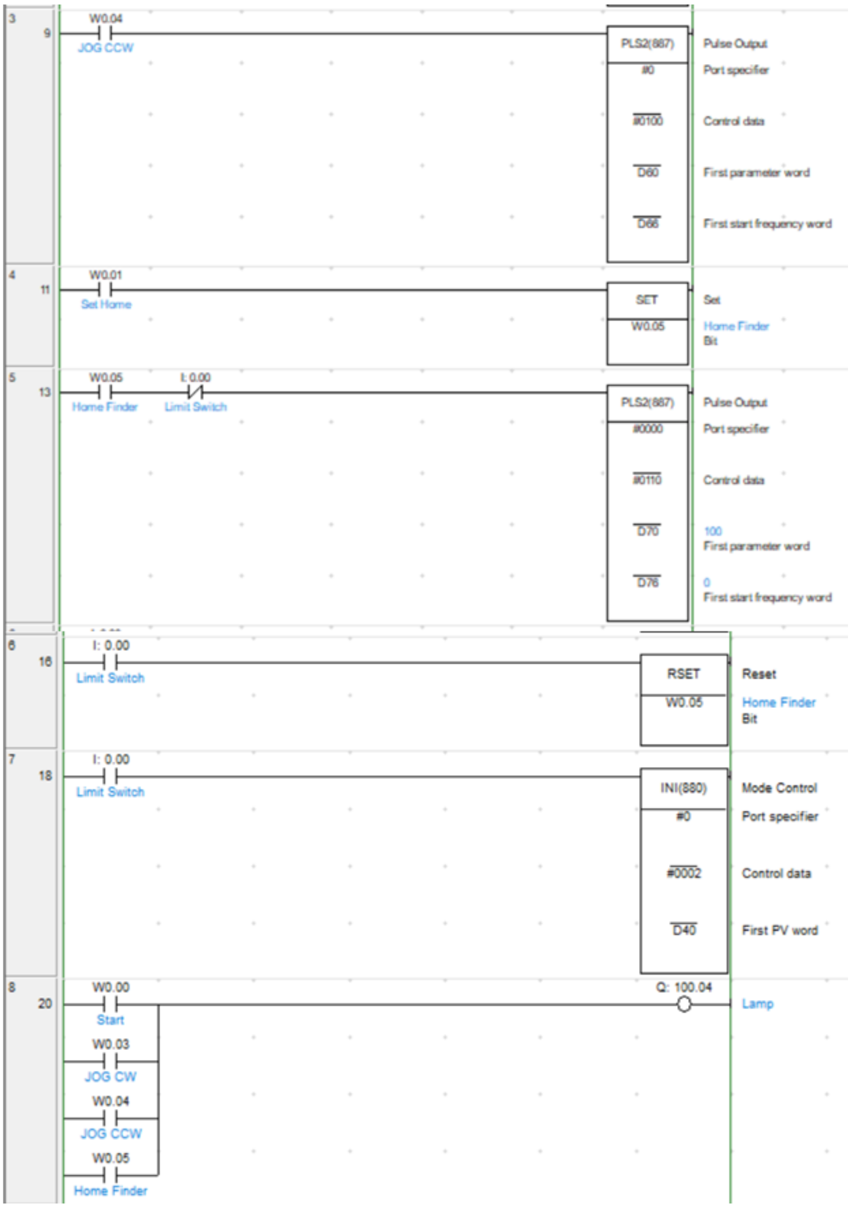

Figure 8. PLC programming flowchart (continued).

2.4.2.2. HMI development

The Human-Machine Interface (HMI) was developed using Omron NB-Designer, allowing operators to input position commands and monitor system status efficiently as shown in **Figure 9**. The touchscreen interface featured a position input field for specifying the desired stopper position in millimeters a home position button to reset the stopper to its absolute zero position, and a jog mode for manual fine adjustments. Additionally, a real-time feedback display provided continuous updates on the current stopper coordinates and system status. The HMI was connected to the PLC via RS232 communication, ensuring seamless real-time data exchange.

During testing, the HMI interface proved to be user-friendly, with a minimal learning curve for new operators. The average operator input time was recorded at 2–3 seconds per command, and the system executed movement commands with a 100% success rate. This setup significantly reduced operator workload and enhanced overall system usability, making it an effective solution for precise and efficient control of the stopper mechanism (Basile *et al.*, 2013).

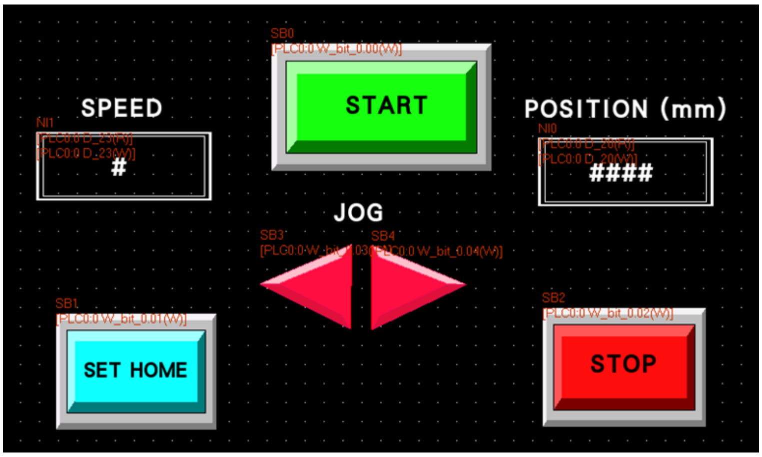

Figure 9. HMI display software.

2.4.2.3. System calibration and testing

To ensure optimal performance, the system underwent calibration through several key steps. Homing calibration resets the stopper to its absolute zero position, aligning it with the reference point. Speed tuning was conducted, programming the stepper motor to achieve a movement speed of 43.4 mm/s, exceeding the 40 mm/s target. Accuracy verification tests confirmed that the stopper maintained an average positioning deviation of just 0.1 mm. Finally, the system was tested under real industrial conditions to validate positioning precision, PLC response time, and overall operator usability.

The stepper motor (NEMA 34, 12 Nm) played a crucial role in converting electrical pulses from the PLC into precise linear motion via the ball screw mechanism. The accuracy of the stepper motor was evaluated based on the deviation between commanded and actual stopper positions, with results showing an average accuracy error of only 0.1 mm and zero deviation in most cases. Minor deviations were observed at 650 mm and 843 mm, likely due to external vibrations and slight friction inconsistencies in the guide rail.

The stepper motor was also tested for repeatability through multiple stop-and-start cycles, consistently maintaining accurate positioning across repeated movements. This confirmed the reliability of the PLC-controlled stepper motor system. Additionally, the stepper motor and driver setup ensured that precise pulse signals from the PLC were translated into controlled linear motion, further enhancing the system's accuracy and performance.

2.5. Evaluation

The evaluation phase of this study focuses on assessing the performance of the automated stopper mechanism through a series of tests designed to measure its efficiency, precision, and durability. The speed test is conducted by setting the stopper to its zero position and moving it to a predetermined position while measuring the time it takes to reach the target, ensuring that the system operates within acceptable speed parameters. The accuracy test involves using the automated stopper in actual cutting operations multiple times, measuring the resulting cut dimensions, and comparing them with the values displayed on the HMI to verify the precision of the system. Additionally, the force resistance test evaluates the stopper's durability by subjecting it to horizontal impacts of varying magnitudes to determine its ability to withstand operational forces. The detailed findings and analysis of these tests will be further discussed in the results section, providing insights into the system's overall performance and potential areas for improvement.

3. RESULTS AND DISCUSSION

3.1. Results

The results of this study focus on evaluating the performance, accuracy, and force resistance of the ball screw-based stopper mechanism designed for panel saw applications. Performance tests were conducted to assess the system's compliance with design specifications, and the outcomes are discussed in the following sections.

3.1.1. System implementation and prototype evaluation

The automated stopper mechanism was successfully assembled and tested at PT Tri-Wall Indonesia, as shown in **Figure 9**. The system integrates a ball screw mechanism, stepper motor, linear guide block, and PLC-based control system, ensuring precision movement and repeatability. The prototype was subjected to a series of performance evaluations, including speed tests, force resistance tests, and accuracy assessments, to determine its effectiveness in industrial applications.

The hardware assembly of the system was completed using key components such as a Ball Screw SFU 2510 set, Linear Guide Block HGR30, and NEMA 34 Stepper Motor & Driver. The system's stability and alignment were verified through mechanical testing, ensuring that the stopper moved smoothly and precisely along the X-axis. The testing procedures followed Shigley's mechanical design methodology to systematically analyze and validate the mechanism's performance.

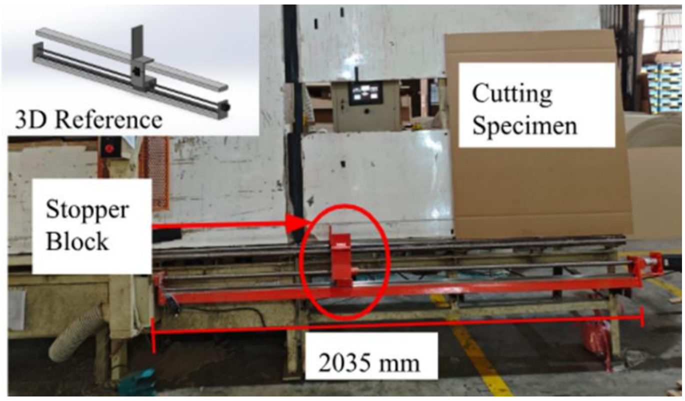

Figure 9. Completed mechanism.

3.1.2. Speed performance test

The speed of the stopper movement was tested to evaluate whether it met the required speed specification of 40 mm/s. The test involved setting the stopper in the zero position and moving it to a predefined target distance of 1000 mm while recording the time taken to reach this position. The results showed that the stopper achieved an average speed of 43.4 mm/s, which is above the target specification. The time variations recorded across multiple tests were minor, demonstrating consistent performance and reliable motion control. The achievement of this speed indicates that the ball screw mechanism, coupled with the stepper motor, provides efficient and controlled movement, making it suitable for high-speed manufacturing operations.

3.1.3. Force resistance and stability test

A crucial aspect of the stopper's functionality is its ability to withstand external forces exerted during the cutting process. A force resistance test was conducted to analyze whether the stopper remains stable under horizontal pressure when the material is pushed against it. The system successfully maintained zero displacements up to an applied force of 100 N, confirming its rigidity and stability. However, when the force was increased to 125 N, a slight shift of 0.05 mm was observed, and at 150 N, the displacement increased to 0.10 mm. These results indicate that while the system is structurally robust, forces exceeding 125 N may introduce minor positional deviations, which should be considered in high-pressure applications.

The findings align with prior research on linear motion guide mechanisms, which suggests that ball screw systems provide superior stability but may require additional reinforcement in high-load scenarios. The force resistance test results confirm that the stopper is sufficiently strong for standard manufacturing conditions, with minimal risk of deviation during operation.

3.1.4. Accuracy assessment and positioning precision

One of the most critical evaluations was the accuracy test, which measured how precisely the stopper could position itself according to the HMI input values. The test compared the stopper's actual measured positions with the HMI input values and recorded any deviations. The results presented in **Table 3** from the original document confirm that the system achieved an average error of only 0.1 mm, with an extremely low deviation of 0.005%.

Table 3. Accuracy test results.

Test No.	HMI Display (mm)	Manual Reading (mm)	Error (mm)	Deviation
1	1730	1730	0	0.00%
2	650	649	-1	0.15%
3	1150	1151	1	0.09%
4	574	574	0	0.00%
5	295	295	0	0.00%
6	1376	1376	0	0.00%
7	237	237	0	0.00%
8	600	600	0	0.00%
9	843	844	1	0.12%
10	2234	2234	0	0.00%
Average			**0.1**	**0.005%**

The accuracy test table provides a detailed breakdown of the different positioning points tested. The table confirms that the measured positions closely matched the input values, with most readings showing zero deviation. The only minor discrepancies were observed at 650 mm and 843 mm, where the deviations were -1 mm and +1 mm, respectively. These slight variations could be attributed to external factors such as mechanical vibrations or minor friction inconsistencies in the guide rail.

This level of precision demonstrates that the ball screw mechanism successfully eliminates backlash and ensures high-accuracy positioning, making it ideal for automated cutting applications. The findings are consistent with previous studies on high-precision actuator systems, which highlight the importance of ball screw-based motion control in minimizing positioning errors (Gieras, 2013).

3.2. Discussion

The results from the speed, force resistance, and accuracy tests validate the efficiency and precision of the ball screw-based stopper mechanism. The system exceeded speed expectations, remained structurally stable under applied forces, and achieved exceptional positioning accuracy. These characteristics make it highly suitable for industrial manufacturing, where repeatability and precision are crucial for maintaining production quality and minimizing material waste.

Compared to traditional manual stopper systems, the proposed automation method offers several advantages. The system ensures consistent cutting operations throughout production by eliminating human error and enabling automatic repositioning with ±1 mm accuracy. The PLC-based control system further enhances efficiency by allowing precise adjustments without the need for manual calibration, reducing setup time, and improving operational workflow.

From an engineering perspective, the successful application of Shigley's systematic design approach has optimized mechanical components, ensuring smooth operation with minimal maintenance. The study confirms that ball screw-driven automation is a viable solution for improving industrial cutting processes, delivering benefits in terms of speed, durability, and positioning accuracy.

The implementation of the PLC-controlled positioning system in the automated stopper mechanism has proven to be highly reliable and precise. Key findings from the tests confirm the system's ability to respond quickly to input commands, with an average response time of 0.5 seconds, and to ensure precise positioning with an accuracy error of only 0.1 mm. Additionally, the system maintains repeatability, ensuring that the stopper reaches the same position across multiple cycles. The HMI interface further enhances usability by providing seamless control with minimal operator training.

By integrating real-time feedback mechanisms, the PLC-based control system eliminates human error, reduces trial and error in adjustments, and improves manufacturing consistency. This study reinforces the effectiveness of combining PLC automation with a ball screw mechanism for industrial control systems, highlighting advantages in accuracy, efficiency, and ease of operation. These findings align with previous research on PLC-based automation, which has demonstrated the effectiveness of programmable motion control systems in precision manufacturing.

4. CONCLUSION

The development of a PLC-based automated stopper mechanism for panel saws utilizing a ball screw system has been successfully implemented and tested, demonstrating significant improvements in precision, efficiency, and usability. Integrating a stepper motor, PLC, and HMI for real-time control, the system eliminates human error and enhances production repeatability. Performance evaluations confirmed that the stopper exceeded the 40 mm/s speed requirement, achieving 43.4 mm/s while maintaining stability under 100 N of external force without deviation. Accuracy assessments further validated its precision, with an average positioning error of only 0.1 mm, well within the design tolerance of ±1 mm. The PLC executed motion commands with a rapid response time of 0.5 seconds, ensuring efficient and reliable operation. The HMI interface played a crucial role in reducing operator workload and improving system usability by enabling seamless input and monitoring. Compared to traditional manual stopper systems, this automated solution enhances production efficiency, minimizes material waste, and ensures consistent accuracy. The ball screw mechanism proved superior to alternatives like timing belts and lead screws in terms of stability, precision, and repeatability. Additionally, validation in diverse industrial settings could provide deeper insights into durability and scalability, underscoring the viability of this automated stopper mechanism as a high-precision, efficient solution for industrial manufacturing environments.

5. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. Authors confirmed that the paper was free of plagiarism.

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