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Real-time Speed Control of Slider-Crank Mechanism to Perform Punching Operation with Fuzzy Logic Controller

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Keywords: Slider-crank mechanism, V-daq card, Punching operation, Fuzzy logic controller.

ABSTRACT

To accomplish the punching procedure on fabric items, a unique slider-crank mechanism was created as part of this study. A DC motor was used to move the input limb or crank. This allowed for the realization of rotational movement in the mechanism's input and the provision of motion transmission to the connecting rod. The piston placed at the connecting rod's output enabled translational movement. Rotational motion is consequently changed into translational motion. The device for punching fabric was mounted with a separate portion that was created for the piston's end. This led to the development of a new slider-crank system for the textile sector. The developed slider-crank mechanism is unique for the textile industry application. Real-time speed control of the crank using a fuzzy logic control was used in this work to achieve the speed control of the mechanism. Additionally, unlike the cards described in the literature, this V-Daq card was used to control the slider-crank mechanism for the first time. As a result, a different slider-crank mechanism has been created that permits automatic punching of multifold fabrics.

INTRODUCTION

Mechanisms are devices that facilitate the transfer and conversion of motion from one type to another. They find widespread applications in various aspects of our daily lives. For instance, mechanisms are integral to the functioning of bus door opening and closing, automobile jacks, adjustable pliers, damping tools, and vehicle windshield wipers.

Among these mechanisms, one of the most commonly employed is the slider-crank mechanism. The slider-crank mechanism plays a pivotal role, particularly in internal combustion engines, where it transforms translational motion into rotational motion. It is also utilized in pumps and compressors, where it converts rotational motion into translational motion.

Needle-punching technology has been used in the textile industry for years (Patel and Bhramhatt, 2010). Needle punching of composites is carried out with this technology (Chen et al., 2016). To further convert discarded fibers into a continuous network of non-woven fabric is needle punched in the textile industry (Meng et al., 2020). The textile industry places tremendous importance on the punching process for fabrics. Large-scale businesses use needle-punching machines. Due to their high cost, small firms find it challenging to acquire these devices. Because of this, a less expensive solution to the problem was offered in this study, along with the suggestion that the slider-crank mechanism may be used to carry out the procedure. To reduce costs and increase individual work, a novel slider-crank mechanism has been designed and adapted for the textile industry application, enabling automated execution of the punching process. The fact that this mechanism will be used in fabric punching in textile industry applications is a process that has been performed for the first time and has not been available in the literature.

In previous literature reviews, various studies have addressed the control of the slider-crank mechanism from different perspectives. These include the application of a PID controller optimized using the Ziegler Nichols Method for the position control of the slider-crank mechanism (Ahmad et al., 2011), the investigation of the dynamics of the slider-crank mechanism when employing a sliding mode controller for position control (Lin and Wai, 2001), the proposal of a fuzzy network structure for controlling the position of the slider-crank mechanism (Lin et al., 2001), utilizing PID fuzzy control for achieving position control of the slider-crank mechanism (Lee et al.,2004), the development of a genetic algorithm-based Closed-Loop Tracking Control (CTC) system for position control in a slider-crank mechanism used in ship propellers (Faraji and Farzadpour, 2013), the utilization of adaptive computed torque

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techniques for position control of the slider-crank mechanism (Lin et al., 1998), the exploration of control and dynamics of a slider-crank mechanism connected to a pendulum (Kudra et al., 2022), modeling and real-time comparison of the dynamic behavior of the slider-crank mechanism when subjected to a driving force applied at the crank-pin center, using a lumped parameter approach (Sarıgeçili and Akçalı, 2018), investigation of optimal slider-crank arm lengths for cutting multilayer materials (Atakök and Balci, 2022), introduction of an auto-tuning PID control method for experienced-based position control of the slider-crank mechanism (Chuang et al., 2006), proposal of a constant speed control system for the slider-crank mechanism in machine tools (Flores-Campos et al., 2021) , the application of the slider-crank mechanism in the climbing section of a mast climbing robot (Lau et al., 2013), use of the slider-crank mechanism as part of the resonant control unit in a power output system (Sang et al., 2014), introduction of a self-tuning control method based on generalized minimum variance control for rotational speed control of the slider-crank mechanism (Saito et al., 2009), the utilization of the slider-crank mechanism in vibrating olive harvesters (Işık, 2002), the proposal of the slider-crank mechanism for use in pressing applications (Halıcıoğlu and Dülger, 2013), development of a novel method for designing task space controllers for the slider-crank mechanism without relying on mechanism dynamics and linearization methods (Perrusquia et al., 2020). These studies collectively contribute to the understanding and application of the slider-crank mechanism in various fields and control contexts.

Many of the aforementioned studies primarily exist in the realm of theory. The slider-crank mechanism, on the other hand, finds practical applications in areas such as climbing robots, vibrating olive-picking machines, pressing machines, and even the cutting of multilayer materials.

In the context of this study, a distinctively designed slider-crank mechanism has been created to automate punching operations on fabric and leather materials within the textile industry. The adoption of the slider-crank mechanism is poised to streamline the punching of multi-layer materials. It's worth noting that the lengths of both the crank and connecting rod play a critical role in determining the speed of the punching process.

Given the significance of controlling the punching speed, this study also addresses the importance of regulating the speed of the crank-connecting rod mechanism. Consequently, within this study, speed control of the mechanism is achieved through the implementation of fuzzy logic, utilizing a V-daq card for this purpose. The parts that make this study unique are the adaptation of the slider-crank mechanism to serve a different purpose in the textile industry, the development of a slider-crank mechanism with a unique design that is completely different from the existing ones, the real-time speed control of the mechanism with the fuzzy logic control method and the first use of the V-daq card in the control of the mechanism.

MATERIAL AND METHODS

Slider-Crank Mechanism

Slider-crank mechanisms are commonly utilized in internal combustion engines for converting translational motion into rotational motion, as well as in pumps and compressors for transforming rotational motion into translational motion. In Figure 1, a slider-crank system is depicted. As per the mechanism's principle, the connecting rod is set into motion due to the rotation of the crank. The connecting rod causes the piston to move back and forth. The rotation of the crank is driven by a motor.

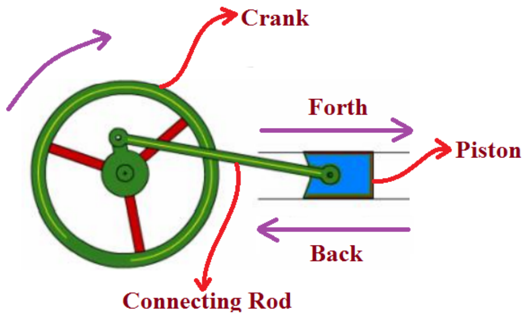

Fig. 1. A slider-crank mechanism system

Design of the Mechanism

The work commenced with the motor holder component. Taking into account the dimensions of the motor intended for use, the motor holder was meticulously designed to securely affix the motor in place. Subsequently, the design process for the crank component, responsible for carrying out the rotational motion, was initiated. Given that the crank part would be mounted onto the engine shaft, it was purposefully designed with this in mind.

Moving on to the next phase, the connecting rod, which serves as the link between the crank and the piston, facilitating the transfer of motion between them, was carefully designed. As a punching apparatus is intended to be affixed to the end of the piston, the piston itself was designed to consist of two distinct parts. The punching apparatus was positioned between the first and second segments of the piston, and the piston was then unified into a single piece using appropriate fasteners.

Figure 2 illustrates the design of the motor holder component within the slider-crank mechanism. During the design process of the motor holder, careful attention was given to the motor's dimensions, ensuring a precise fit.

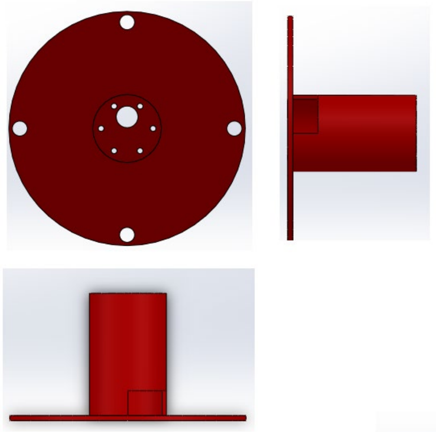

Fig. 2. Motor holder part

Figure 3 displays the design drawings of the crank component, an integral part of the slider-crank mechanism, which will be coupled to the motor. The design of this part was orchestrated around the motor shaft. Moreover, recognizing that the diameter of the crank plays a pivotal role in defining the piston's stroke, the crank's diameter was meticulously determined, taking into account the range within which the piston would operate in the design.

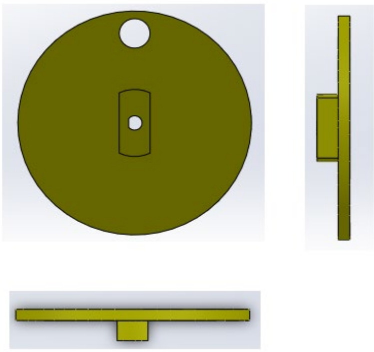

Fig. 3. Crank part

Likewise, during the design phase of the connecting rod component, careful consideration was given to the positions where it would connect to both the crank and the piston. The design of the connecting rod component is presented in Figure 4.

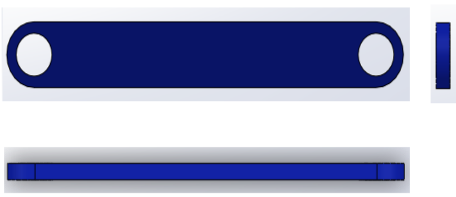

Fig. 4. Connecting rod part

The final component to be designed for the slider-crank mechanism is the piston part. Given the intention to incorporate the punching apparatus within the piston, the piston was devised in two segments. Following the placement of the apparatus inside, it was then solidified using appropriate connecting elements. Figures 5 and 6 respectively showcase the components of the piston.

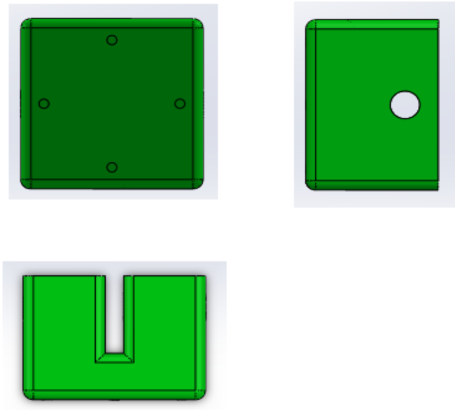

Fig. 5. Piston part 1

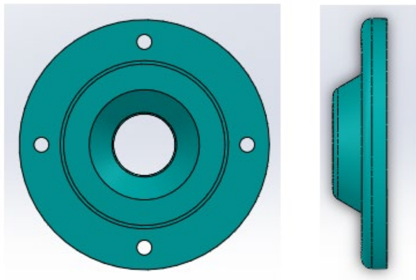

Fig. 6. Piston part 2

If the working principle of the system is briefly summarized, the motor will move first. For this reason, the motor holder part is designed to fix the motor. The movement of the motor will be transferred to the crank part via the motor shaft and the crank will start to rotate. The rotational motion of the crank will be converted into translational motion with the help of the connecting rod and transmitted to the piston. The piston will exhibit linear movement horizontally and go back and forth in a certain stroke depending on the design dimensions. Thus, the punching apparatus located at the end of the piston will perform the punching process.

Taking into account the groove in which the piston will operate, the stroke was precisely adjusted to ensure that the punching apparatus at the end of the piston could extend as intended. The assembly of all components is depicted in Figure 7.

To determine whether the designed mechanism achieved the desired motion, a motion study was conducted by imparting rotational motion to the motor within the Solidworks environment. The results of the motion study revealed that the mechanism indeed executed the desired movement. Subsequently, the feasibility of speed control for the mechanism in the simulation environment was theoretically investigated, marking the progression to the next stage of the study. Theoretically, this method is also possible. It is possible to analyze how the mechanism moves. Numerous equations must be obtained for this. Even additional difficulty may arise from this task, particularly if you are dealing with a complicated mechanism.

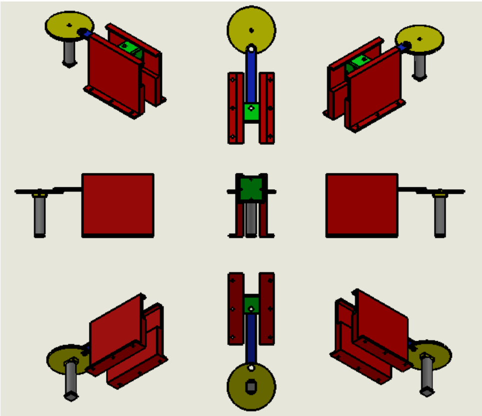

Fig. 7. Finished design of the mechanism

In the assembled configuration of the mechanism, you can also observe the section of the groove where the piston will travel. This same section has been utilized to provide a smooth reciprocating motion for the piston. In essence, the design of the inner part of this component has been entirely crafted to facilitate the piston's comfortable back-and-forth movement.

Speed Control of the Mechanism in Simulation

Upon confirming that the designed mechanism achieved the desired motion within the Solidworks environment, the next step involved translating the mechanism into the Matlab/Simulink environment. Figure 8 represents the block diagram of the mechanism as it was transferred to the Matlab/SimMechanics environment.

In mechanism design, it's often assumed that the speed of the crank remains constant. However, in reality, due to the inertia of moving parts in the mechanism, the speed of the crank connected to the engine undergoes periodic fluctuations. These speed variations can significantly impact the performance of the mechanism and hinder the successful completion of the intended task. As a result, the importance of speed control in mechanisms becomes evident.

Controlling and stabilizing the speed of the mechanism's components can enhance its overall efficiency and reliability, ensuring that it consistently performs its designated functions as intended. Speed control mechanisms, such as those utilizing feedback control systems, can help mitigate the adverse effects of speed fluctuations and contribute to the optimal operation of the mechanism. The mechanism has a single degree of freedom. Since the mechanism produces output as a result of the rotation of the motor, controlling the angular speed of the motor allows constant control of the piston output speed. For this reason, it is necessary and sufficient to provide angular speed control of the motor.

Figure 9 illustrates the application of PID (Proportional-Integral-Derivative) control to the blocks of the mechanism for achieving speed control. In the Simscape/SimMechanics environment, the motor input is applied to the input limb of the mechanism, which is the crank element. PID control is employed to regulate the operation of the motor, and the output of the PID controller serves as the control signal applied to the motor. In the structure of PID control, the values of proportional gain coefficient, integral gain coefficient, and derivative gain coefficient must be determined. There are certain methods to determine these gain coefficients. One of these methods is Matlab's automatic tuning tool. The gain coefficients in the PID control structure were found using Matlab's automatic PID tuning.

The objective of implementing PID control in this context is to maintain the mechanism's motion at the desired speed, compensating for any speed variations or disturbances. The specific PID control coefficients necessary for achieving this goal were determined through an automated tuning process. This tuning ensures that the control system effectively adjusts the motor's operation to achieve the desired speed of the mechanism.

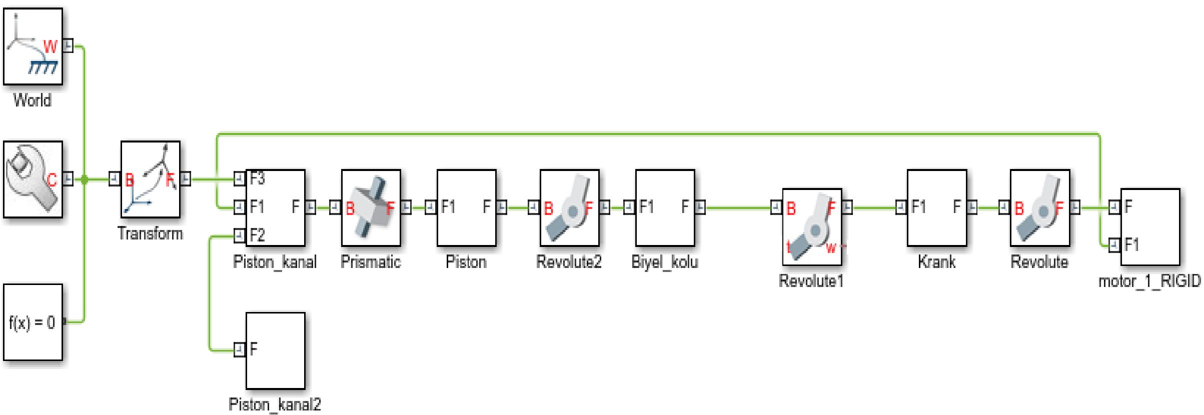

Fig. 8. Matlab/Simscape blocks of the mechanism

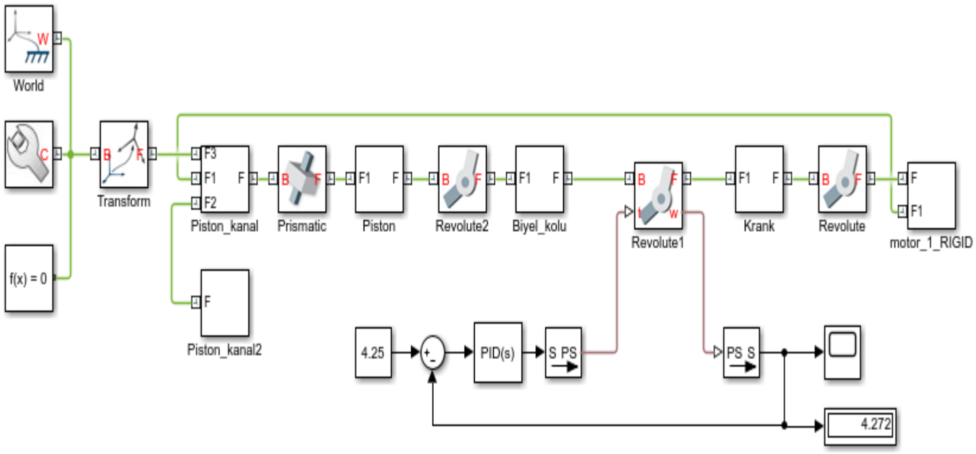

Fig. 9. PID speed control of the mechanism in Matlab/Simscape

Figure 10 showcases the various consumables used in the mechanism:

Punching Apparatus: This is the tool attached to the end of the piston for performing the punching operation.

PLA Filament: The PLA filament is used as the material for 3D printing the custom-designed parts of the mechanism.

Jumpers: These connectors are utilized to establish the necessary electrical connections within the system.

12-Volt Power Supply: This power supply provides the energy required for the operation of the mechanism.

DC Motor with Encoder: The DC motor with an encoder is responsible for driving the crank, generating rotational motion within the mechanism.

Motor Driver: The driver is used to control and drive the DC motor effectively.

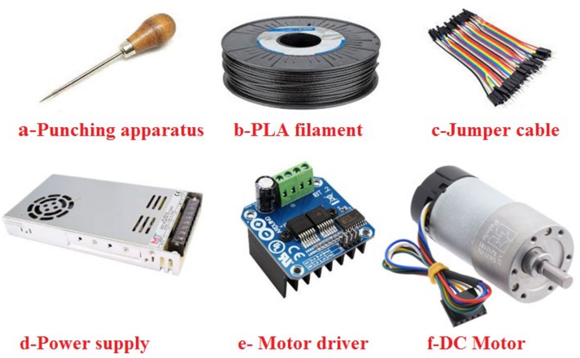

Fig. 10. a- Punching apparatus, b- PLA filament (1.75 mm), c- Jumper cable, d- Power supply (12 V 29 A), e- Motor driver (BTS7960B 20 A), f- DC motor (12 V, 100:1 reduction ratio, 64 CPR encoder)

Figure 11 provides detailed images and information about the V-Daq card, which is employed for data transfer: The V-Daq USB card is a data acquisition card that utilizes Matlab/Simulink real-time libraries. It offers a control loop frequency of up to 2 kHz and is compatible with Windows 7, 8, 8.1, and 10 (x64). The card operates via USB and plays a crucial role in data acquisition and control within the system.

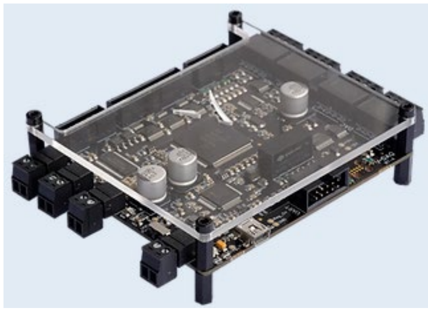

Fig. 11. V-daq usb card.

The culmination of the project involved the assembly of the final 3D-printed versions of all designed components, connections, pre-made parts, and hardware elements, resulting in the physical realization of the mechanism. Figure 12 provides a visual representation of the completed version of the mechanism in its finished form, ready for operation and testing.

Fig. 12. The finished version of the mechanism.

When the finished mechanism is examined, Figure 13 includes the piston part, piston grooves, connecting rod, crank, motor, punching apparatus, power supply, motor driver, and V-daq card.

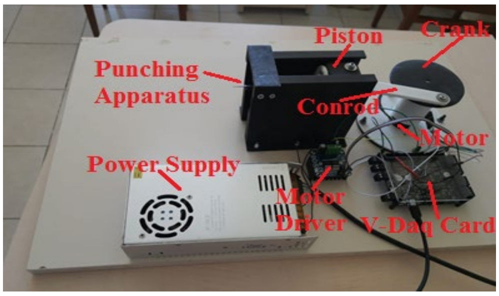

Fig. 13. Side view of the finished mechanism

Real-Time Fuzzy Logic Speed Control of the Mechanism

Using the Matlab Real-time toolbox, an interface was developed to implement speed control for the mechanism using a fuzzy logic method. Figure 14 showcases this interface, which serves as the control platform for regulating the mechanism's speed through fuzzy logic control techniques. This interface likely provides various control parameters and settings to fine-tune and monitor the speed control system, ensuring the mechanism operates at the desired velocity.

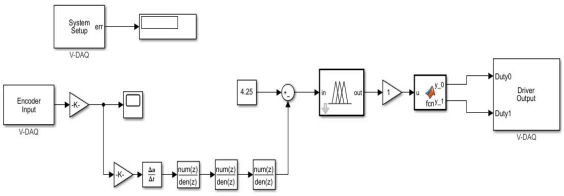

Fig. 14. Matlab/Real-time interface program

The interface program was created step by step. First, data was taken from the encoder block to read the encoder information of the motor. Since the received data contains angle information, the speed information was obtained by taking the derivative of the data. To eliminate the noise in the speed data, the speed data is filtered and sent to the sum block to generate the error information that will form the input of the fuzzy logic control structure. The error is generated from the difference between the reference value and the filtered speed data and sent to the fuzzy logic structure. The output of the fuzzy logic control structure gives the control signal. The control signal was sent to the V-daq card to provide signal flow and thus the speed control of the motor was realized. The sampling rate of the interface program developed in Matlab/Simulink/Real-time was taken as 0.001.

To help visualize the system's operation, Figure 15 provides a flowchart. The motor driver receives power from the power supply when the start/stop button has been activated. Concurrently, the driver receives the control signal from the V-daq card, which verifies the motor's movement. The encoder assists in measuring the motor's rotation, which is then sent to the V-daq card. At this point, the control signal is produced by the interface software shown in Fig. 14. The crank rotates in tandem with the motor. Translational motion is produced from rotational motion by the connecting rod that is attached to the crank. The piston swings horizontally back and forth as a result of the connecting rod's output. Therefore, the apparatus at the piston's end is used to perform the punching operation. Until anybody contacts the button and turns off the power, the system operates.

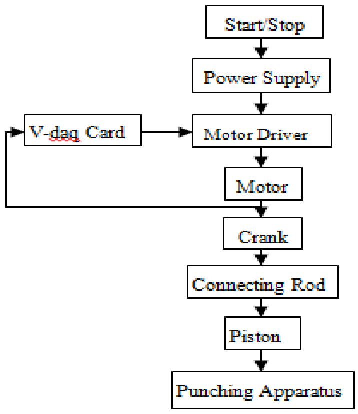

Fig. 15. Flowcart of the system

RESULTS AND DISCUSSION

As a result, the entire process began with the initial design of the mechanism in the SolidWorks environment. Subsequently, the functionality and correctness of the designed mechanism were verified through animation within the SolidWorks software. Figure 16 provides snapshots of the animation, specifically depicting the images captured at the first, second, third, and fourth seconds of the animation sequence. These images collectively demonstrate that the mechanism indeed operates as intended, following the rotation of the motor, thereby confirming its proper functionality.

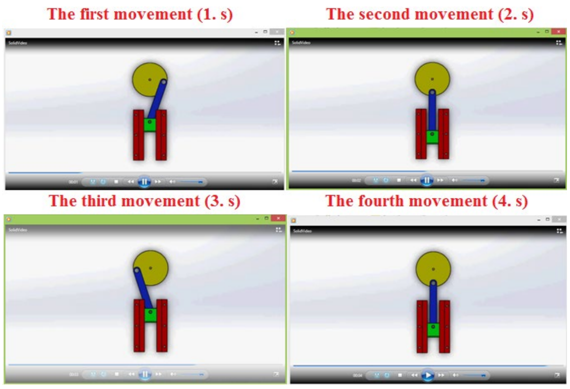

Fig. 16. Solidworks animation of the slider crank mechanism.

Following the design and verification in SolidWorks, the mechanism was transitioned into the Matlab environment, where various blocks were established. In this Matlab environment, speed control was implemented using PID control applied to the mechanism through these blocks. The outcome of this application is visually represented in Figure 17, indicating that the mechanism not only moved at the desired speed but also maintained a consistent speed in the Matlab environment. This successful implementation of speed control using PID control demonstrates the effectiveness of the control system in regulating the mechanism's motion.

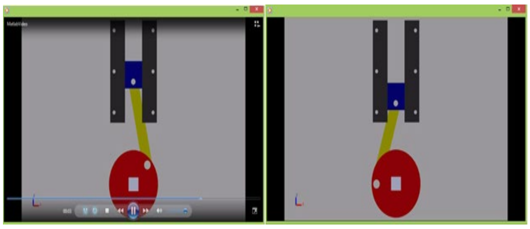

Fig. 17. Matlab speed control of the slider crank mechanism (simulation).

In the subsequent phase, a detailed numerical analysis of the mechanism, which had its speed control realized using PID control in the simulation environment, was conducted. Following the application of the PID control process to the mechanism's blocks, a specific target speed of 4.25 rad/sec was set for the mechanism. The speed control results indicate that the mechanism achieved a speed of 4.272 rad/sec, as depicted in the graphical representation shown in Figure 18. However, it is evident from the graph that there are fluctuations in the speed, indicating that the speed control system did not achieve an entirely constant value. This is a common outcome in speed control systems, and even in the simulation, a small error of approximately 0.02 rad/s was observed. Such a minor level of error is expected and considered normal in the context of speed control systems. The maximum overshoot occurred in 0.039 seconds with 4.765 rad/s. % Maximum overshoot is 12.12. The average angular velocity value is 4.243 rad/s. There were fluctuations in speed at a few points and then it started to repeat the same movements periodically. Considering the points where these fluctuations occur, the most error values occur here. When these error percentages are examined, errors of 1.58%, 2.12%, and 0.92% occur respectively. The average error value is obtained with 0.007 rad/s. The average percentage error is 0.17%.

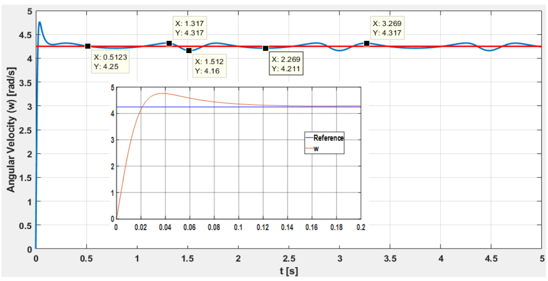

Fig. 18. Angular velocity change (simulation)

Figure 19 displays the graph of the angular velocity error, where ideally, the error should be zero for precise speed control. Upon analysis of the graph, it becomes apparent that after approximately 0.1 seconds, speed control for the mechanism is indeed achieved, albeit with minor fluctuations. These fluctuations are generally expected during the initial phase of the control process and tend to stabilize over time. In practice, this level of speed control with small fluctuations is considered acceptable and satisfactory for many applications.

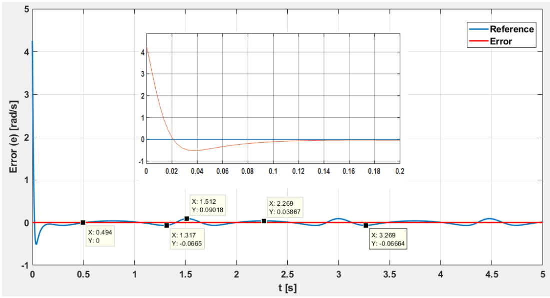

Fig. 19. Angular velocity error change with time (simulation).

Following the simulation and analysis stages, the mechanism was physically manufactured and integrated with the hardware elements to create the final operational version of the mechanism. To facilitate real-time speed control in the Matlab/Simulink environment, an interface program was developed using the V-Daq USB card. At this crucial stage, the speed control process that had initially been conducted at 4.25 rad/s in the simulation environment was replicated in real-time using the fuzzy logic method. The speed control response obtained as a result of the fuzzy logic control is illustrated in Figure 20. Upon examination of the graph, it is evident that the response closely aligns with the results obtained in the simulation environment. It's important to note that achieving real-time speed control can be more challenging than simulation, which can lead to minor variations in the response. However, the close resemblance between the real-time and simulated results is a positive outcome, indicating the effectiveness and reliability of the implemented control system in real-world conditions. Real-time angular velocity results move periodically between 4.11 rad/s and 4.33 rad/s for a reference value of 4.25 rad/s. At the lower and upper limits, the system operates with an error of 3.29 % and 1.88 %, respectively.

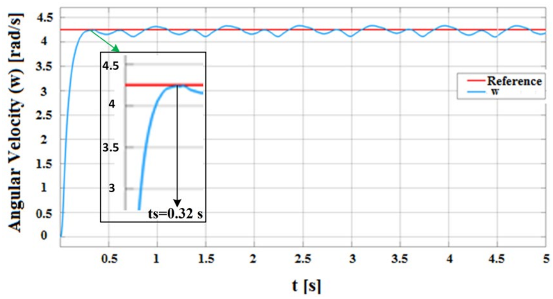

Fig. 20. Angular velocity change with time (real-time)

The time-dependent error value of the mechanism, resulting from the fuzzy logic speed control, is presented in Figure 21. Notably, the error fluctuations are primarily centered around zero, with a periodic pattern. This suggests that the fuzzy logic speed control system is effectively maintaining the mechanism's speed close to the desired target value, resulting in minimal and periodic errors. Such periodic variations in the error signal are often associated with the nature of control systems and can be considered acceptable, especially when they remain relatively small and centered around the target value, as observed in this case.

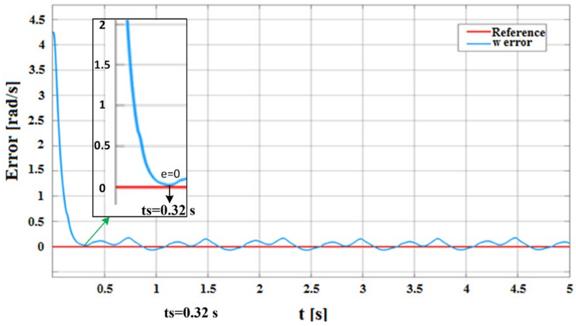

Fig. 21. Angular velocity error change with time (real-time).

The mechanism's performance was put to the test by conducting fabric perforation while the fuzzy logic speed control was actively implemented. Remarkably, as evident from Figure 22, the mechanism executed this operation with great success, successfully punching through 20 layers of fabric stacked on top of each other. This outcome demonstrates the practical and reliable application of the mechanism, particularly in tasks requiring precision and control, such as fabric perforation in industrial settings.

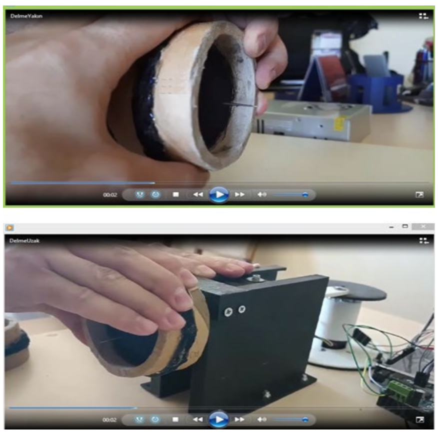

Fig. 22. Angular velocity error change with time (real-time).

CONCLUSIONS

In this study, a unique design of the slider-crank mechanism was made to perform the punching process in the textile industry. The slider-crank mechanism introduced is a unique mechanism that has been implemented for this purpose for the first time in this sector.

In the framework of this investigation, a unique slider-crank mechanism has been developed to automate punching processes on leather and fabric materials in the textile sector. An average error of 0.007 rad/sec occurred in the angular speed control results of the mechanism designed for this purpose, which was carried out in the simulation environment using PID control. The percentage error is 0.17 in the simulation. In the real-time angular velocity control of the mechanism, the amount of error was slightly higher than the theoretical results. This is an expected result. It is normal for there to be slight fluctuations in speed control. This situation occurs due to inertia occurring in the system. The fact that a periodic movement was observed shows that the speed control response showed a successful result. The system operates with a margin of error of -0.14 to +0.08. Error change as a percentage varies between 1.88 and 3.29.

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