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Design and Programming of a Wire Winder Device for Extrusion Activity in the Metal-Mechanical Industry

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Abstract

The present research is focused on the analysis of an industrial activity where the case under study is wire extrusion activity, which has been developed using old machines. This activity is analyzed considering the task and its elements to identify the movements and sequence of actions performed by the workforce and the machines. One of these activities is the roll-up of lead wire coming from the extruding machine. The task is done by the workforce 73 times during a shift and roughly consists in transporting the wire to the pulley guide and driving the lead wire until the container is rolled up manually. The analysis shows that the workers are exposed to hazardous conditions that could affect their health, meaning they are under risk of suffering an injury or a disease by exposure to repetitive actions and high temperatures ($>90^{\circ}\text{C}$). Based on the latter, the design and development of a wire winder device has been proposed, which implements a programmable logic controller and servomechanism to replace the activities done manually. A ladder diagram is proposed to control the action performed by the servomechanism based on a stimulus received from the environment.

Keywords: automation, workstation, design, loop closed control, programmable logic controller

1. Introduction

Metal-mechanical industry activities normally include wire extrusion in their processes, which are developed by old machines and involves wasted time and materials as well as costly reworkings [1]. Once the wire is extruded it is normally stored in a coil-shaped container, where it is rolled up ready for the next steps in the value chain based on industrial requirements such as stretched wire. However, the extrusion machines cannot optimize and perform the wire winding activity efficiently, because of the need for human intervention. However, a method to make this task more efficient is possible and can raise production to a satisfactory level. One of the most common solutions consists of the inclusion of automation systems to simplify and improve each part of the process [2], bringing benefits such as reduction in time [3, 4], knowledge, and the ability to control variables such as velocity and temperature, allowing measurement of efficiency in the production line.

Following the trend of using technology to simplify the activities of a manufacturing process [5], the metal-mechanical industry in Mexico began to analyze one of its processes with the aim of improving it, and involved the wire extrusion of a plumb bar as raw material. The machine responsible for performing the wire extrusion activity was old; moreover, most activities are carried out manually by the workforce. An analysis was done to determine the activities involved during wire extrusion, observing that the wire winder task was one of the most critical because the workforce has to roll it manually, which is not ideal because the wire is hot when it leaves the extruder head of the extrusion machine. In addition to this, wire winder activity is performed at a velocity determined by the machine, making it more difficult to handle and satisfy the level of production established by the enterprise. Wire winder activity can be performed and improved with automation technology through a device focused on developing this task, with the capacity to substitute the work carried out manually by the workforce and reduce risk of injuries or diseases [6, 7]. In this way, programmable logic controllers (PLCs) are now being used in the industry around the world with the aim of simplifying and improving the serial instructions present in a sequence of variables that regulate the control system of a device [8], performing a series of actions focused normally on the manufacturing of raw materials in products with high quality. The control programs for PLCs are developed by using relay ladder logic, which is a graphical programming language consisting of software devices (i.e., relays, timing relays, drum sequencers, and programmable counters) to achieve a control strategy [9]. Additionally, the use of 3D design in device automation has become important since it reduces cost and time invested by building a prototype, since is possible simulated and make a prediction behavior of each element based on the freedom grades provide to each servomechanism or articulation [10].

2. Experimental procedure

2.1. Methodology

For the design and programming of the wire winder task of the extrusion process, the following steps were made:

- Perform a task analysis.
- Determine the elements involved in the task carried out manually by the workforce.
- Identify the system variables of activities such as time, temperature, dimension, and workspace.
- Improve the logical sequence of wire winder activity to reduce the wastage of time.
- Conceptually design in 2D a proposed device for wire winder activity specifying the places where the motor elements will be fixed as well as the articulation device for the coil.
- Design in 3D the wire winder, including its mechanical and electrical components.
- Develop the sequence in ladder logic.
- Virtually test the ladder program developed.

2.2. Structural materials

Based on the environment conditions present in the work area, stainless steel 316 was defined as the structural material because of water condensation combined with other chemical compounds such as chlorides, which come from other activities in the facilities, increasing metallic structure degradation. Some of the most important properties of stainless steel 316 are that it contains 16% chromium, 10% nickel, and 2% molybdenum. Molybdenum is added to improve its corrosion resistance against chlorides. Stainless steel 316 is one of the most used materials in industries such as gas, offshore platforms, and many others due to its low price and active passive behavior [11–13]. It was constructed in a rectangular shape to support the electronic and motor components. The design conceptualization of the device includes the use of a coating of paint to be applied to the metallic structure to avoid electrical conductivity in case of cable damage and improve its corrosion resistance [14, 15].

2.3. Hardware

The hardware components used for the automation and design of wire winder activity include the following elements:

1. Three inductive sensors for non-contact detection to ensure the right position of the wire after the extrusion process before it arrives at the feeding cavity in the wire winder device.
2. A PLC based on an Arduino unit was used as a control interface for the logic sequence established for wire winder activity carried out in the extrusion area. Its architecture comprised 20 I/O digitals with a 24 V DC power supply with the capability of interconnecting with a human/machine interface screen system.
3. A relay system was conceptualized to ensure the correct working of the devices and to avoid drops in potential and current.
4. A step servomotor at 180 and 360° was used to execute the changes defined to make the wire winder activity. H bridges were used to control the polarity of the motor at 360°.

2.4. Software

SoapBox Snap Software was used to program the PLC based on an Arduino unit. It included a ladder logic editor and a "soft" runtime straight out of the box. The ladder editor includes standard instructions such as contacts, coils, timers, counters, rising edge and falling edge, and set/reset instructions.

3D drawings were conceptualized and assembled using the Solidworks version 2017 education edition, which is a mechanical program used to create 3D geometry using parametric solids focused on the mechanical design, assembly, and drawings of the workshop.

3. Results and discussions

3.1. Analysis and determination of the elements involved in the wire winder activity of the extrusion process

Extrusion area distribution is shown in **Figure 1**. It is divided into sections: feedstock, extrusion, guide pulley, and storage of wire after rolling (container). The extrusion process is carried out at a pressure of 500 MPa, heating the billet (feedstock) to 575°F as follows:

1. Loading of the billet in the feedstock area of the extrusion machine.
2. Activation of the hydraulic system to start the extrusion of the billet.
3. Manually driving the lead wire extruded to the wire winder area.
4. Winding the lead wire extruded manually by the workforce into the container.

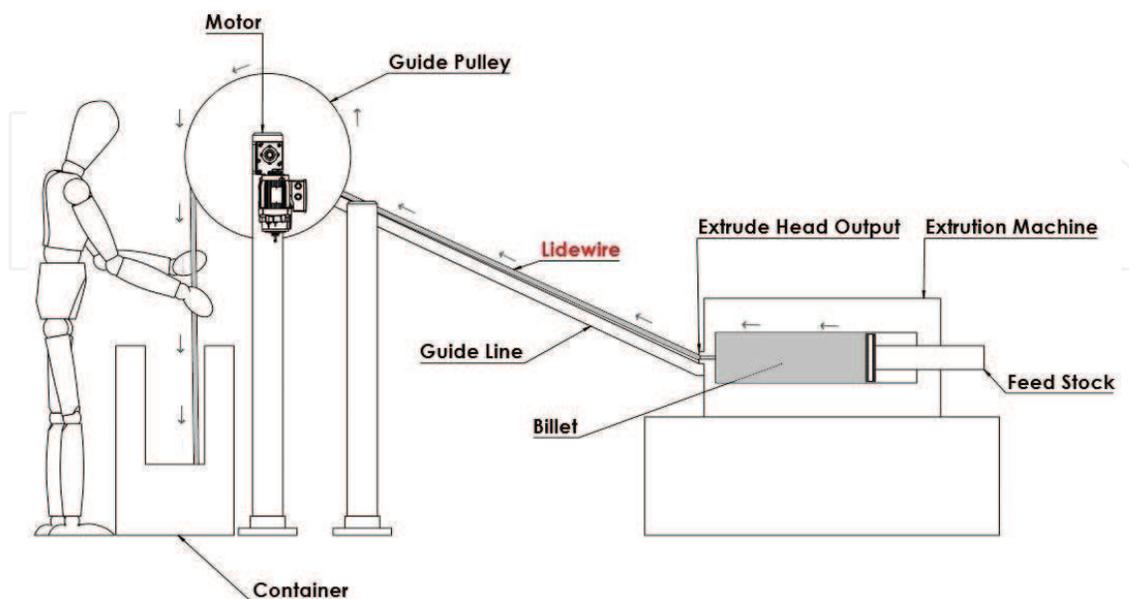


Figure 1. Wire winder element and the devices used to operate it manually.

Analysis of the extrusion process established the elements involved in the wire winder task as follows:

1. Reach.
2. Hold.
3. Move.
4. Roll up.

As was mentioned, the first step to start the extrusion process begins with the loading of the billet, which has a weight of 34 kg inside the feedstock section. Once the hydraulic system is turned on, the extruded product starts to output (lead wire), which is driven manually from the extrusion head output to the guide pulley section. Next, the lead wire begins to roll up manually and is deposited in the storage container by gravity. The devices currently performing the wire winder task have two principal components: a guide pulley and a container for the lead wire after extrusion (**Figure 1**).

The guide pulley has a diameter of 30 cm and is fixed to an AC motor shaft, which is turned on manually before starting to pull the lead wire from the extrusion head output, with the aim of reducing the force applied by the workforce when they pull and guide the lead wire to roll it up. Moreover, the guide pulley is 2 m from the floor making it difficult for the workforce to reach since normally the workforce has a height average of 1.67 m.

During an 8-h shift, the wire winder task is repeated 73 times with an extrusion cycle time of 9.12 min. To roll up the lead wire, the workforce takes 5.32 min in each extrusion cycle to form circles with a diameter between 60 and 10 cm that go from outside to inside and vice versa in each turn to give stability to the lead wire roll-up. According to the wire winder task analyzed, correct roll-up of the lead wire has a number of important variables:

- Motion sequence for rolling up the lead wire, which is carried out by the worker's arm.
- Time taken for each turn based on its diameter.
- Diameter of each turn, which decreases from outside to inside and increases in the opposite direction.
- Temperature of the lead wire to roll up when coming from the extrude head output.
- Capacity of the container to store the wire roll-up.
- Feed velocity of the guide pulley of the lead wire extruded.

Table 1 shows a comparison of the motion sequence executed by the worker's arm based on the elements identified and the motion sequence that the wire winder device must do to simplify the roll-up task. Furthermore, the time used to perform the roll-up of the lead wire is described with the aim of determining the velocity of the servomechanisms to reach a production level considering the industrial goals. Based on the maximum and minimum diameter defined, an equation is proposed to determine the number of turns that the automatized device must do to finish at least one wire bed as follows:

Task elements	Execution time (min)	Worker's arm	Wire winder device
Reach, move, and hold	5.32	Drive the lead wire to the guide pulley	The lead wire extruded is driven to the guide pulley by an elevator device
Hold		Guide the lead wire to the container	The lead wire is fixed automatically in the arm of the wire winder device to drive it to the container
Hold and move		Move the arm from outside to inside and in the opposite direction forming circles until the lead wire is finished and totally rolled	The device starts to roll up the lead wire when it is detected in the correct position and stops when no more lead wire is detected

Table 1. Comparative analysis of the motions performed by a worker's arm and a wire winder device.

$$n_t = \frac{\varnothing_t}{\varnothing_a} \quad (1)$$

where n_t is the number of total turns, \varnothing_t is the maximum diameter of the roll-up, and \varnothing_a is the wire diameter that corresponds to 0.74 cm. Furthermore, for displacement, the wire from outside to inside reduces the roll-up diameter and the device must start with an angular position of 180° and decrease 2.2° each turn as follows:

$$\theta_m = \frac{\theta_t}{n_t} \quad (2)$$

where θ_m is the decrement in degrees by each turn and θ_t is the initial position in degrees before starting to roll up the lead wire.

The total turns that the device must execute to finish one wire bed are 82 with a decrement of 2.2° by each turn.

The conditional actions that should be followed in a logical sequence so that the device works to the right parameters are described in the flow diagram of **Figure 2**, and are based on the wire roll-up task variables identified.

3.2. Block diagram to establish the task sequence to schedule in a ladder diagram

The block diagram in **Figure 2** describes the principal action needed for the wire winder device to perform in a loop closed system. The reference value is a flush-mountable proximity switch (S1), which detects the presence of the lead wire when it comes from the head extrude area. Once the wire is in the X0 position and a time of 5 s has elapsed, the clamps are closed and the wire transport system is activated carrying the lead wire until the X₁ position, where a second flush-mountable proximity switch (S2) detects the lead wire, turning on the motor M₁ of the guide pulley and sending simultaneously an instruction to the controller to reset M2 and M3 to their initial position (0), ensuring that M2 and M3 are working correctly. When the lead wire is

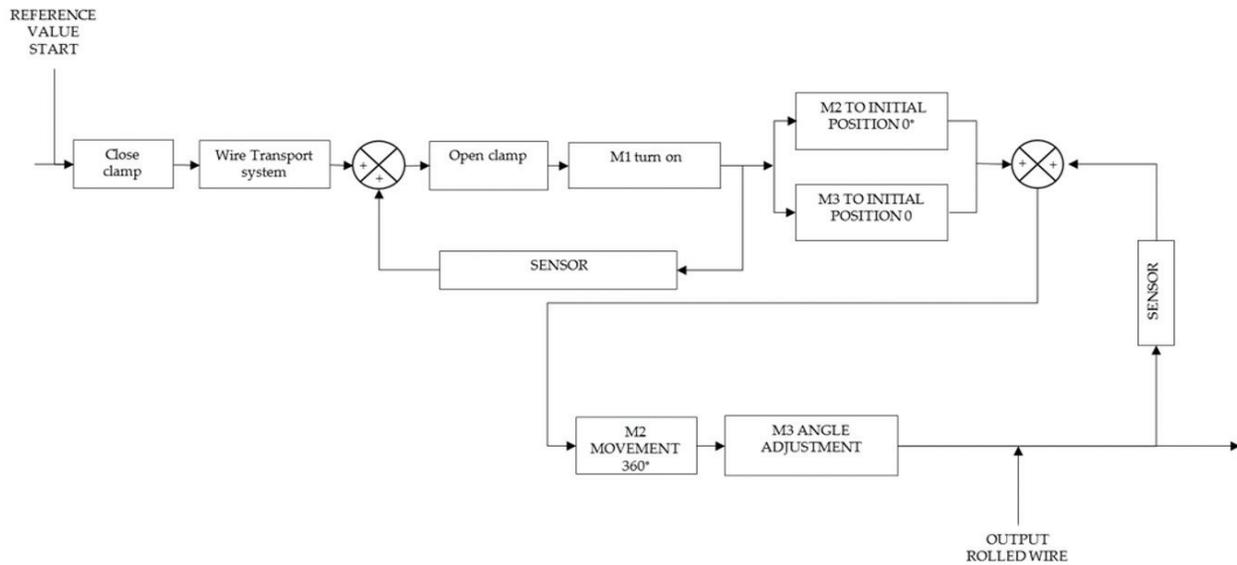


Figure 2. Wire winder element and the devices used to perform it manually.

detected in the X_2 position the flush-mountable proximity switch (S3) closes its contact and in turn M2 starts to spin. As a result M3 increases or decreases its angle to roll up the wire, decreasing or increasing its angle by 2.2° based on its initial position (180 or 0°). The roll-up process ends when the wire is not detected by S2 and S3 in position X_1 and X_2 , respectively, rebooting the system until a new billet has been charged on the feedstock area and new wire starts to be extruded.

As two-push button security system has been configured as a start/stop system in case the workforce has to manually fix the wire winder in positions X_0 , X_1 , and X_2 or deactivate and reset the system to the initial position when the billet is finished.

3.3. Ladder program in PLC M-Duino 19 R

The electrical components of the wire winder device at a prototype level are described in **Table 2**. A PLC based on an Arduino unit has been selected as controller (**Figure 3**). The PLC M-Duino 19 R is a compact PLC based on open source hardware technology with different input/output units and its principal characteristics are listed in **Table 3**.

The principal symbology used to build the ladder diagram to be loaded in a PLC based on an Arduino unit is described in **Tables 4–6**, declaring the signal inputs that can be defined as an input of electrical stimulation, which can be analog or digital depending of the physical phenomena measured, such as light, sound, pressure, temperature, or the presence of an object. This means that execution of an action by an actuator or software configuration based on the received input allows the logic sequence to produces a response by the controller system through the declared outputs in the ladder diagram. They are in effect electrical floodgates that can open or close the flow of an electrical signal depending of the action to be

Devices	Description
Inputs	
S1	Inductive sensor NPN 24 V DC
S2	
S2	
B1	Push button 22 mm 24 V
B2	
Outputs	
CLAMPS	Servomotor 24 V DC with control driver
MOTOR 1	1/2 HP motor with reducer shaft mounting system 110 V AC
MOTOR 2	1/8 HP motor with reducer shaft mounting system
MOTOR 3	Stepper motor Nema 24 with control driver
SOLENOID 1	Bistable pneumatic solenoid valve 5/2 24 V DC to control a pneumatic rodless cylinder
SOLENOID 2	

Table 2. Electrical components of the wire winder device.

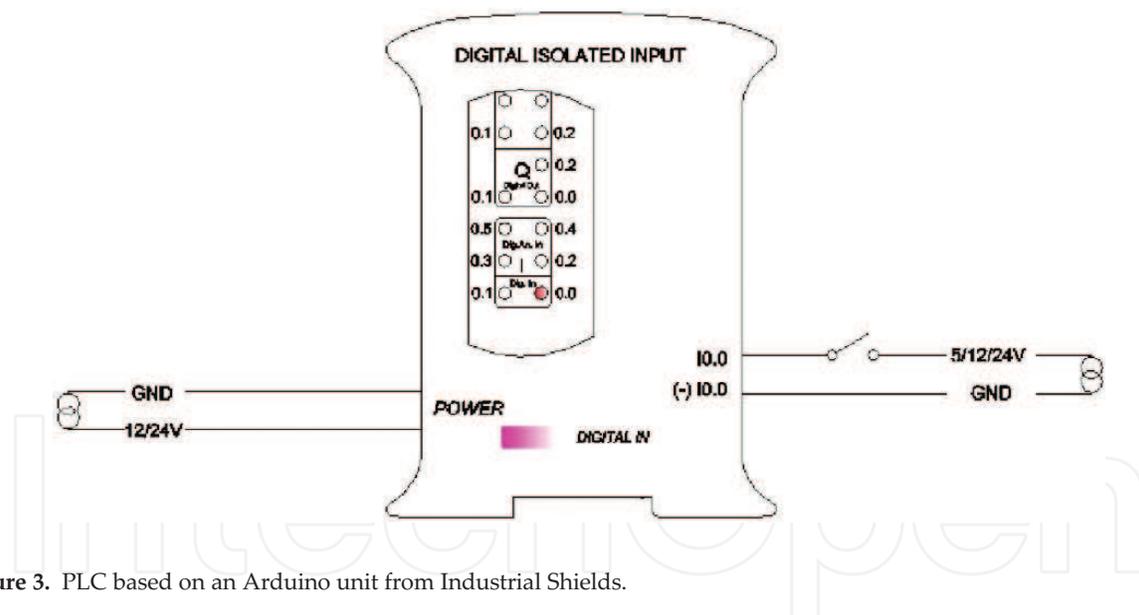


Figure 3. PLC based on an Arduino unit from Industrial Shields.

performed, allowing the servomechanisms configured in a mechanical device to be energized, which in this case correspond to the wire winder. **Figure 4** shows the ladder diagram proposed to control the wire winder device as well as the guide pulley and the wire system transport. Following the condition established in the block diagram (**Figure 2**), the system is turned on when a push button connected to the I.3 input of the relay based on an Arduino unit turns on allowing the auxiliary relay interlock M1 to be energized, which allows timer TT1 to be energized whenever S1 detects the presence of lead wire in the X0 position. Once the I1 contact of the S1 sensor is closed, the timer TT1 is activated, closing its contact T1 after 5 s and

Input voltage	12–24 V DC polarity protection
I_{max}	0.5 A
Size	101 × 119.5 × 70.1 (mm)
Clock speed	16 MHz
Flash memory	256 KB
Communications	I2C1 – Ethernet port – USB – RS485 – RS232 – SPI – (2x) Rx, Tx (Arduino pins)
Total input points	6
Total output points	14
Type of signal	
Analog/digital input 10 bit (0–10 VCC) (5/12/24 V DC)	4
Digital isolated input (24 V DC)	0
Interrupt isolated input HS (24 V DC)	2
Analog output 8 bit (0–10 VCC)	3
Digital isolated output relay	8
PWM isolated output 8 bit (24 V DC)	3

Table 3. Principal characteristics of the PLC M-Duino 19 R.

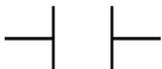
No.	Symbol	Function	Comment
I1		Digital input	S1
I2			S2
I3			B1
I4			B2
I6			S3

Table 4. Physical inputs.

No.	Symbol	Function	Comment
Q1		Digital input	SOLENOID 1
Q2			SOLENOID 2
Q3			CLAMPS
Q4			M1
Q5			M2
Q6			M3

Table 5. Physical outputs.

No.	Symbol	Function	Parameters	Comment
C1		Counter	Objective VALUE: 1; CON	N/A
C2		Counter	Objective VALUE: 1; CON	
M1		Auxiliary relay	N/A	E-B1
TT1		Timer	Preset: 5 s; TON	N/A
TT2		Timer	Preset: 10 s; TON	

Table 6. Configurable functions.

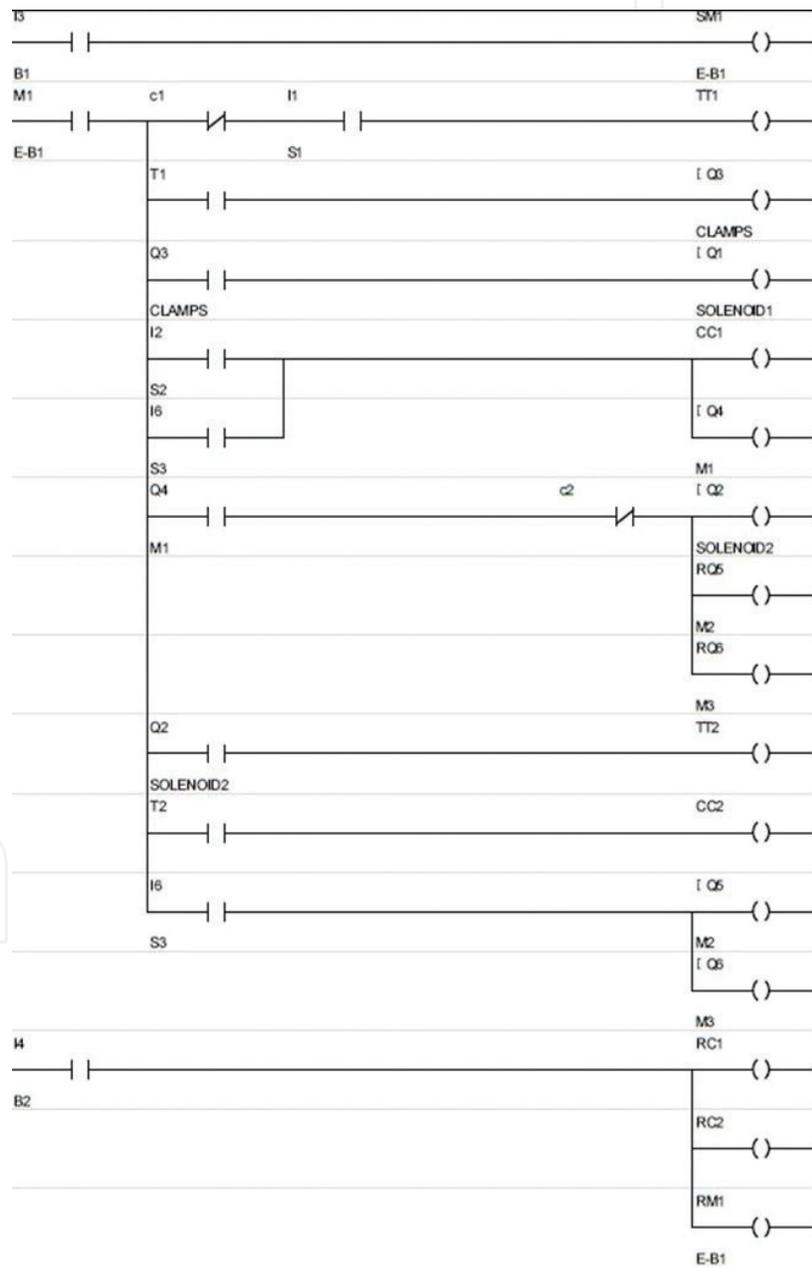


Figure 4. Ladder diagram for the wire winder device.

activating Q3 and Q1 output at the same time, where the first output closes the clamps and the second one turns on the solenoid of a 5/2-way pneumatic valve that activates the wire transport system. When the wire transport system has finished rising in the X1 position the S2 sensor closes its contact activating the I2 input, which closes its contact allowing the 5/2-way pneumatic valve to be turned off, which allows the wire transport system to return to its initial position. At the same time I2 activates the Q4 output closing its contact to turn on the M1 motor of the pulley guide, transporting the wire until the X2 position where the S3 sensor detects the lead wire closes its contact and activates M2 and M3 motors to start the roll-up of the lead wire.

The design proposed for the wire winder device to be implemented in the extrude machine is shown in **Figure 5** where it can be appreciated that the wire transport system, which consists

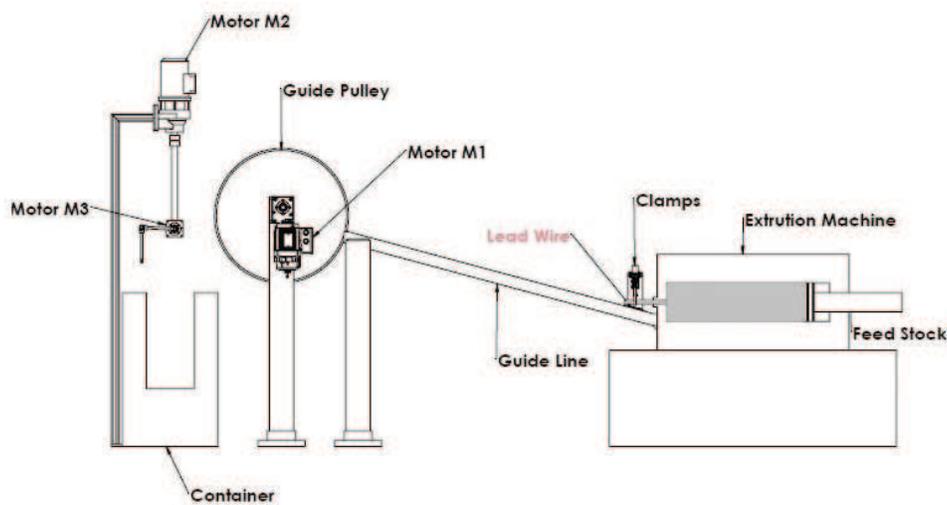


Figure 5. Wire winder device implemented in the extrude machine.

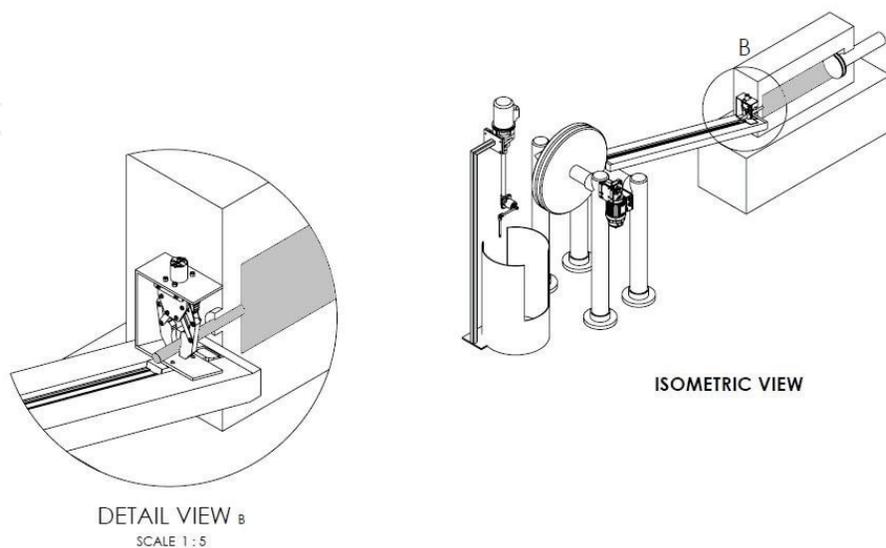


Figure 6. Detail of the clamps fixed over a linear actuator without a stem.

of clamps to take the lead wire coming from the head extrude area (**Figure 6**), after a time is moved to the guide pulley fixed over a linear actuator without a stem, which is activated based on the instruction loaded on the PLC. The wire winder device is operated by two servomotors M2 and M3, which are located after the guide pulley and are activated when the lead wire in the positions previously defined has been detected. Positions X0, X1, and X2 are indicated to understand the working of the new device based on the instruction programmed in the ladder diagram shown in **Figure 4**. It is important to understand that the device is designed to simplify and improve the working conditions in the extrude area to help reduce exposing the workforce to hazardous conditions of high temperatures and repetitive actions.

4. Conclusions

Based on the analysis done it was possible to determine the principal variables of the wire winder system used to conceptualize and design a device with the capacity to perform roll-up of a wire winder after the wire has been extruded. The diameter of each turn was defined, making it possible establish the degrees at which the step motor M2 at 180° should be executed. An equation was determined to understand the angle of reduction in each turn. The split of the wire winder activity was divided based on elements such as reach, hold, move, and roll up. With the aim of avoiding the workforce operating under risky conditions, after extruding a wire transport system was conceptualized mounted over a pneumatic device capable of transporting the wire in a safe and faster way. The sequence of the roll-up task was developed based on previous analysis and allowed the building of a ladder program to control the servomechanism, solenoids, and actuator. A 3D design was proposed to understand the implementation of the wire winder. The device was supported by a stainless steel bar situated to the side of the container two position where declared as balance point to ensure that the roll-up activity will be done.

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