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A Novel Robotic Manipulator Concept for Managing the Winding and Extraction of Yarn Coils

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Abstract: Wire rope manufacturing is an old industry that maintains its place in the market due to the need for products with specific characteristics in different sectors. The necessity for modernization and performance improvement in this industry, where there is still a high amount of labor dedicated to internal logistics operations, led to the development of a new technology method, to overcome uncertainties related to human behaviour and fatigue. The removal of successive yarn coils from a twisting and winding machine, as well as cutting the yarn and connecting the other end to the shaft in order to proceed with the process, constitutes the main problem. As such, a mobile automatic system was created for this process, due to its automation potential, with a project considering the design of a 3D model. This novel robotic manipulator increased the useful production time and decreased the winding coil removal cycle time, resulting in a more competitive, fully automated product with the same quality. This system has led to better productivity and reliability of the manufacturing process, eliminating manual labor and its cost, as in previously developed works in other industries.

Keywords: yarn winding; reels; yarn coil extraction; robotic manipulator; robotic arm

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1. Introduction

The rope industry is a very old sector that encompasses three subsectors, namely, synthetic ropes, net ropes and sisal ropes, each of which has a different production process [1]. The production of yarns (spinning) and the textile industry itself may be located in the same company, but they comprise completely different manufacturing processes and equipment, requiring that the yarns are wound into reels after their manufacture, which are then incorporated into the production equipment of the textiles. Thus, the yarn and rope industries need winding and unwinding operations, from the production to their application in the textile product, to be manufactured. The process of manufacturing yarn reels is governed by the final product, depending on whether it is a cable, rope or yarn. However, for any of these products, there is a need to include a system for unwinding, another for tensioning and, usually, accumulating the product to be treated, and yet another for winding, that is, a feeder, a dancer and a winder [2]. Even if automation is perfectly implemented in the main textile yarn production equipment and in the weaving, the initiation and finalization phases of the reels still require human intervention, which prevents this industry from being able to integrate the intended Industry 4.0 (I4.0) principles [3,4]. This situation can still be identified more intensely in the manufacture of synthetic ropes. This was the main motivation for the development of this work, with a view to also automate this type of operations. Nonetheless, it will be necessary to analyze whether the solution should be based on automation only, robotics only, or a hybrid solution. Based on this doubt, a study in the recent literature was carried out in order to consolidate the theoretical foundations that can serve as a support for the development of the solution.

Robotics has assumed a particular relevance in many recent studies, some of which seek to summarize different models for the development of future solutions in this area [5]. Chemweno and Tor [6] developed a model consisting of five steps that allows one to identify opportunities for robotization of manufacturing processes, which incorporates steps such as the decomposition and analysis of tasks aggregated to a given process, distributing, and allocating tasks between the operator and the robot, as well as design and simulate the operation of the production cell. At the same time, an evaluation criterion should also be developed at each of the stages; however, Säfsten et al. [7] argue that it is necessary to have a perfectly defined strategy to make the decision to robotize a given manufacturing process. This strategy involves previously carrying out of some refinements to the processes, properly analyzing the human factors, and only then moving on to the robotization of the processes. Process refinement aims to adjust operations to the robots' way of operating, while human factors intend to analyze operator safety aspects, necessary training and human–robot interaction capacity. Zheng et al. [8,9] carried out interviews having as target SME's (Small and Medium Enterprises) managers trying to identify the main difficulties felt in adopting robotic manufacturing systems. This study had as output an approach able to offer the possibility of switching the design of a labor-intensive manufacturing system to a robotic one. A similar study was also performed by Simões et al. [10] regarding the factors influencing managers in adopting collaborative robots in the industry, having identified 39 different factors, of which 12 have not previously been identified in the literature. The developed framework helps managers to deal with manufacturing evolution needs, helping in decision-making processes regarding the use of collaborative robots. Gultekin et al. [11] and Gadaleta et al. [12] argue that a rigorous study of the movement of robots is mandatory in order to avoid unnecessary energy consumption, which affects the sustainability of production operations. In addition to the numerous models developed by different researchers, some very interesting applications have also been studied. Silva et al. [13] studied the application of a robotic system to a cell for manufacturing suspension mats and cushions usually used in metallic car seat structures. With a hybrid use of robotics and automation, it was possible to develop an integrated inspection and packaging system for that type of product, based on a robot equipped with a gripper specially designed for this purpose. In addition, an artificial vision system was also developed, which allowed one to control different critical zones of the product, validating the previous manufacturing processes, and allowing the later organized packaging of the product in six stacks. This application made the process significantly more productive and efficient, requiring no human intervention, thanks to the automation of feeding and collecting the boxes where the product was deposited by the robot. On the other hand, Castro et al. [14] recovered a robot that was already out of service and adapted it to a welding cell for metallic structures for buses, giving new life to a robot that, through reprogramming and adaptation to a track for movement, still had all the necessary features necessary to meet the requirements imposed on this type of application. Daniyan et al. [15] studied the use of robotic systems in the railcar industry. This study involved a CAD/CAE software to determine the precision of movements when the robotic arm was subjected to the loads imposed by the process, verifying that the robotic system was capable of performing the functions for which it had been selected with the rigour required by the process, significantly improving the overall performance of the production system. Eriksen et al. [16] developed a robotic polishing system for forming tools, which works together with traditional tools, allowing for the texturing of surfaces with a high degree of repeatability. Sujan et al. [17] have developed a robotic system capable of grasping the extremely complex shapes presented by polycrystalline silicon nuggets, which need to be packaged in a fragile fused silica crucible. The system used a processing method consisting of a triple gripper with suction, which is handled by a seven-axis SCARA robot and an optical 3D vision application based on laser triangulation, capable of reconciling the complex shape of the nuggets with the shape of the crucible. It is thus possible to verify that several studies have been carried out in the context of raising awareness and increasing the adoption of robotic systems in manufacturing processes, and additional studies of particular applications of robotic systems to solve specific problems can also be found. Nevertheless, it is clear that robotics also need automation, both in peripheral systems and in the handling of parts and tools. Therefore, coexistence in production systems is recorded quite often, which is why it is also justified to carry out a literature search focused on automation-based solutions.

Magalhães et al. [18] developed a system for collecting, sorting, electronic inspection and repositioning for the next process at the end of automatic yarn bending machines. The system presents a return on investment perfectly affordable regarding the automotive industry standards and eliminates unnecessary manual operations, increasing the profitability of the process. The next process of these bent yarns is the over-injection. Faced with the need to feed and extract already bent yarns to/from plastic over-injection moulds, Silva et al. [19] developed an automatic vertical yarn feeding system, which automatically distributes these yarns on a tray, feeding them to a gripper specifically designed for this purpose. It then rotates with the yarns into the mould, placing them in the correct position in its interior. After over-injection, the same gripper has the proper geometry to extract the yarns already over-injected onto a conveyor belt, which dumps the parts into a finished product container. This system allowed for remarkable productivity gains. Martins et al. [20] and Moreira et al. [21] developed an automatic piece of equipment devoted to the manufacture of Bowden cables, which presents a series of small sequential operations. The aggregation of different stages of the manufacturing process has drastically improved the level of productivity and the reproducibility of the processes, increasing quality and radically reducing the flow of semi-products within the factory layout. Araújo et al. [22] developed an automatic system with application in guillotines for the cutting of thin metal sheets. Through a pneumatic compensation system, it allowed one to eliminate problems of bending thin metal sheets in the final zone of the cut, when they are still attached to the part from which they are being cut, where their weight promotes the deformation of that area. Nunes and Silva [23] developed a new concept of an automatic assembling system for components used in car windshield wipers, which was based on an indexable table provided with stirrer automatic feeding and positioning systems, increasing the flexibility of the process a lot and eliminating some tedious manual operations. Nevertheless, the developed solution needed an operator to feed the main/initial component. Based on a very similar problem, Costa et al. [24] used an in-line approach, completely different from that used in [23], more complex, but eliminating the need for manual feeding of the main component, i.e., the solution developed is fully automatic. These two approaches show how different strategies can be applied to fit an identical problem [25]. Strategic options can have an expressive meaning in several aspects, such as an increase in production, an improvement in quality or a decrease in breakdowns. Santos et al. [26], by substituting the type of cylinders in an APEX tire component manufacturing equipment, significantly improved breakdowns (−62%), also improving equipment efficiency by 9%. Araújo et al. [27] modified the movement strategy of cushions and suspension mats, which are being manufactured along a manufacturing line that still incorporated two manual workstations, eliminating these workstations and achieving an efficiency gain of 40%, requiring a relatively modest investment. Vieira et al. [28] and Figueiredo et al. [29], working on different problems usually detected in the manufacture of Bowden cables, successfully solved these problems through solutions based on conventional automation, reducing quality problems, increasing repeatability and productivity, as well as concentrating disperse operations in a single piece of equipment. The elimination of serious quality problems was also the main motivation of the work developed by Costa et al. [30], who developed a new concept for the assembly of gear subsets used in the movement of windshield wipers, based only on ingenious mechanical solutions and conventional automation, still achieving a productivity gain of 19%. Veiga et al. [31] have also successfully developed a new automatic system for assembling electrical connectors used in automobiles based solely on conventional automation. The literature is practically consensual in mentioning that the automation of industrial processes requires a very rigorous diagnostic phase, which must be followed by a phase of selection of the best solution that takes into account flexibility, rigour of results and a cost/benefit ratio [32]. It is thus clear that conventional automation can be perfectly integrated into more complex robotic solutions, without jeopardizing the total flexibility of the system, and even increasing that flexibility.

This work aimed to develop a new concept of a robotic system for the initiation and completion of the textile yarn winding operation, eliminating the need for operators connected to the process and allowing a manufacturing solution that permits an evolution to an integrated process, following the basic concepts of Industry 4.0.

2. Materials and Methods

The focus of this work stands on a new concept for the removal of successive coils of yarn from a twisting and winding machine. Afterwards, it cuts the yarn and connects the other end to the shaft, so as to continue the process. Originally, this was performed manually, but the need to eliminate human labor and improve the process led to its automatization.

Initially, an evaluation of the previous concept was performed, where the problems related to it and opportunities of improvement were identified. Then, the defined objectives/requirements were described, after which the new concept was proposed. Finally, the automated equipment's project was introduced, revealing the main stages of development and the final results achieved with it.

2.1. Analysis of the Previous Concept

The process described in this work consists in the treatment of a coil yarn and the respective logistics operation of the product. This process arose from the need for an improvement in the rope-making industry, which still needs a high volume of labor, and, therefore, to reduce costs by introducing a more automated system able to integrate the Smart Manufacturing concept in the near future.

The initial process to obtain this product requires a lot of labor, which is described in the diagram present in Figure 1.

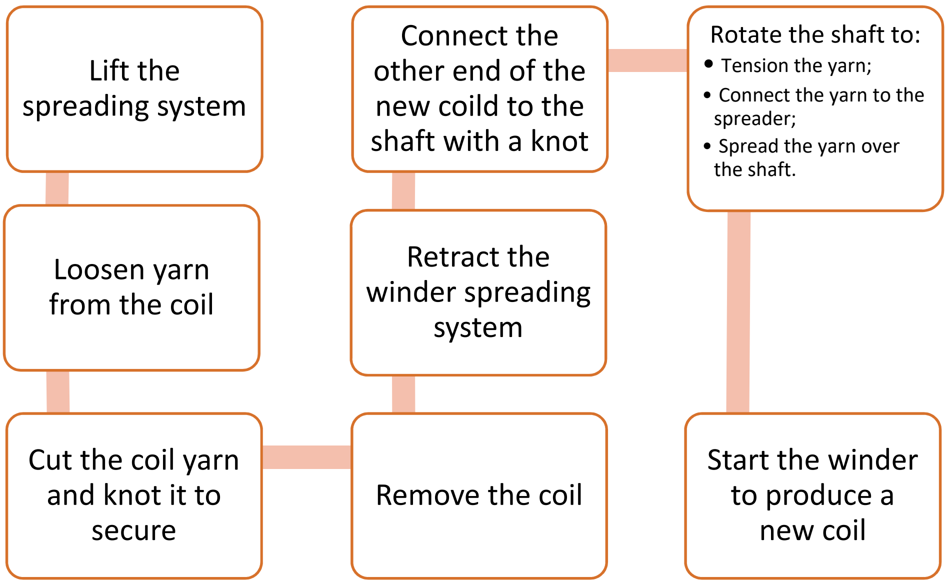

Figure 1. Manual process for obtaining a yarn coil.

In the rope-making industry, intensive labor is still predominant. In the particular case considered for this work, the removal of yarn coils (final product) from a winder and their storage is performed in a completely manual way. This project aims to provide a new concept for the automatization of this process, reducing the labor needed (ideally to make the process fully automatic), and also reducing the rate of defective products, increasing production speed and, in the long term, reducing costs for the company, resulting in a much more profitable process. In this way, the company can also start dedicating these saved man-hours to other, more important activities, in order to improve the final product and meet customer needs, adapting to market demand and always staying one step ahead regarding competitors.

The problem is that, due to the complexity of this process, as shown above, it was necessary to deconstruct the manufacturing process step by step, in order to understand its weak points and where there was room for improvement by automating it, so that no human labor was needed. After splitting into assemblies and subassemblies, a careful analysis of the parts and inserts was carried out, being the machine optimised in design, and being made a careful selection of materials, as well as a deep stress analysis using the CAE method. This is a procedure which involves the continuous work of a specialised engineering team to achieve the best possible result.

2.2. Defined Objectives/Requirements

Some conditions were established previously as requested by the market, which must be respected. Most of these conditions are an addition to the initial requirements defined for the functionalities initially defined.

Hence, the set of requirements determined are as follows:

- Coil dimensions can vary from Ø250 to Ø450 mm;
- Coil longitudinal dimensions can vary between 300 and 500 mm;
- Cycle time must be as low as possible, without exceeding one minute per coil.

The process to obtain the product should also follow the sequence of requirements defined as described in Figure 2.

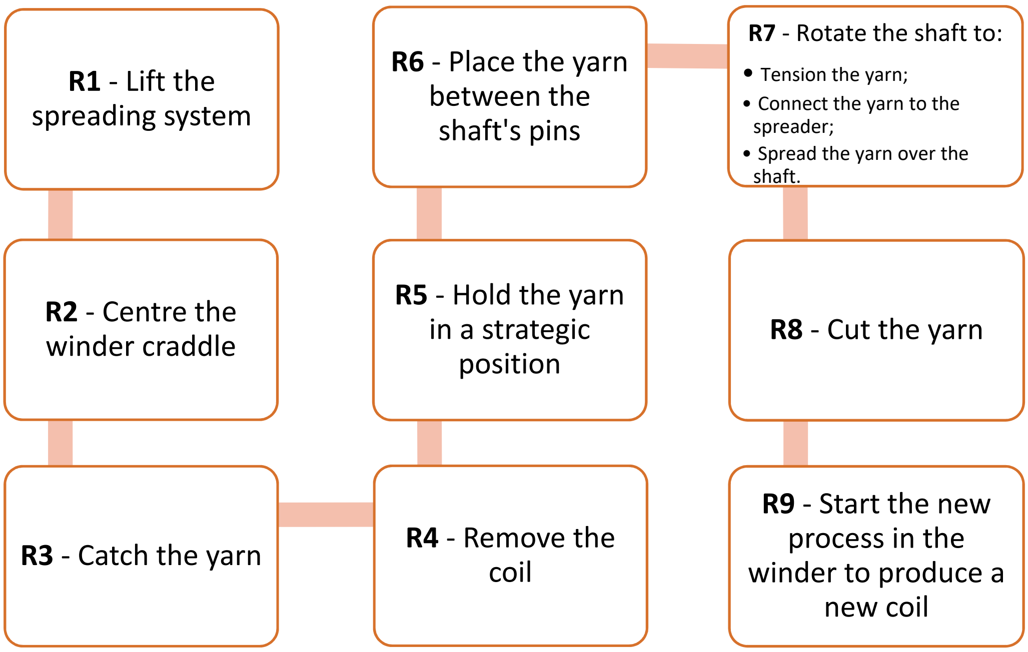

Figure 2. Diagram with the sequence of actions needed for the coil removal.

2.3. Proposed Concept

Taking into account the need to know which was the best approach for the development of this procedure, the strategy followed consisted in:

- A brainstorming process, which was carried out for a better preparation and coordination of the path to follow;

- An evaluation of the possible concepts, which could be adopted for the novel robotic simulator;
- A weighing of the proposed options, in order to choose the best one;
- The development of the selected system, through a mechanical design and an automation programming of the equipment, for it to perform the intended tasks.

During the brainstorming session, considering the defined objectives, the need to address the programming was verified, so a parallel reasoning process was also carried out, where it was determined which types of automation would be feasible. Figure 3 shows that process.

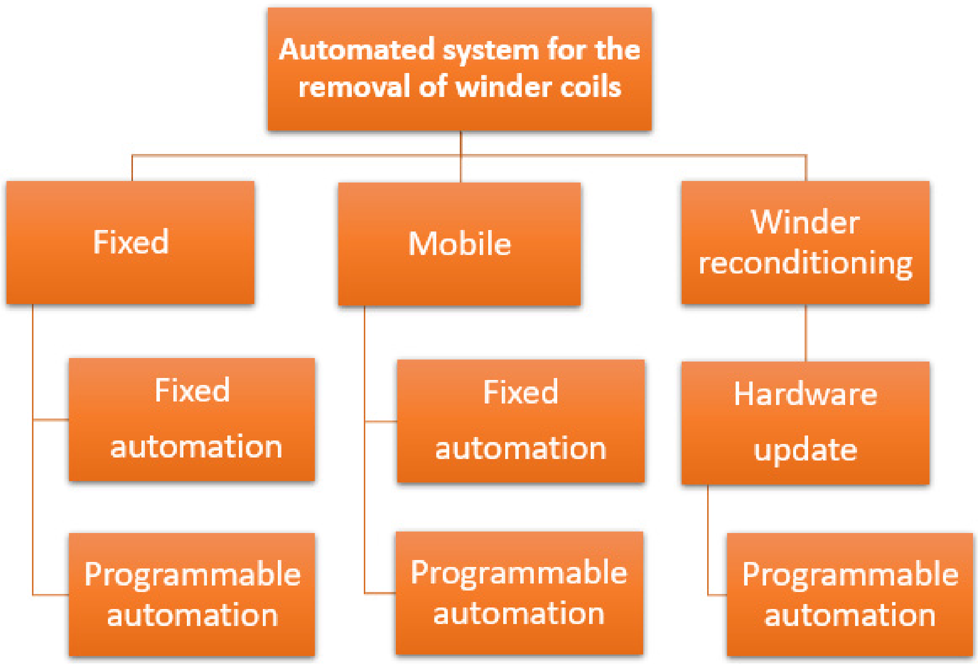

Figure 3. Brainstorming results.

Given the necessary requirements and the results of the brainstorming, a SWOT analysis was performed for each presented idea:

- The fixed solution brings greater freedom in the dimensions imposed on the project and allows for a reduction in cycle time, decreasing the cost of the process and the product; however, it is a solution that already exists on the market, it occupies a large area on the shop floor and each winder requires its own machine.
- The solution of reconditioning the winder is solid and, because it has programmable automation, it allows for the treatment of coils with different dimensions. This type of automation is achievable due to a hardware update, a stage of utter importance to the winder reconditioning. On the other hand, it is a complex project and the machine is limited in terms of space.
- The mobile solution is more dynamic, can treat several winders simultaneously and is an innovative solution, being an introductory method for the I4.0 concept. In spite of this, it is a complex project, with a high cost and design time.

Accordingly, weighing up the advantages and disadvantages, the conclusion was reached that the idea with the greatest potential for innovation is the Mobile System, due to the fact that it allows for continuous twenty-four-hours-a-day work on the coil production line, with little manpower involved.

3. Results

This section will include the design of the final equipment, detailing its most important components, as well as how they function. After the design, the development and implementation of the new production process will be described, as well as the results obtained after implementing it.

3.1. Equipment Presentation

Through the development of this project, it was decided to subdivide the EOAT (End of Arm Tool) assemblies by their functions in the tool and/or by where this assembly will be connected. The subdivision of the assemblies was carried out as can be seen in Figure 4.

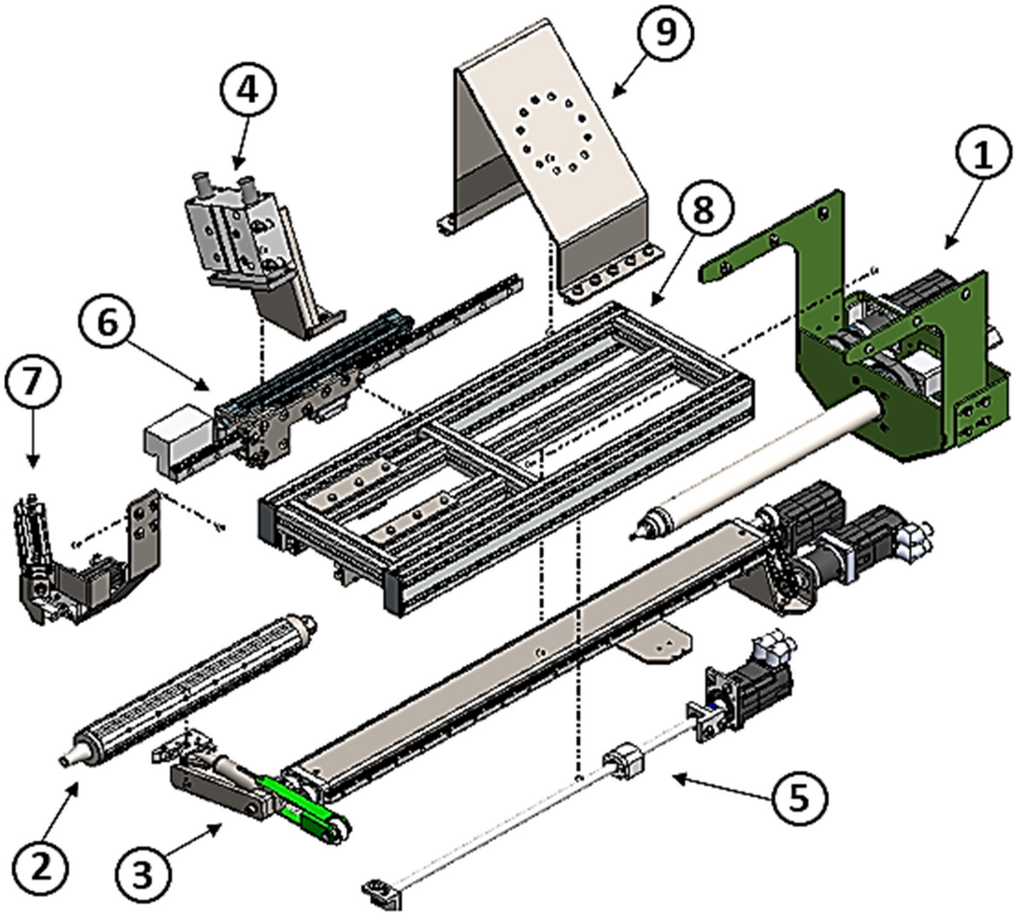

Figure 4. EOAT exploded view.

In Table 1, it is possible to observe the caption for Figure 4.

Table 1. EOAT exploded view's caption.

1—Coil Support Assembly	2—Expandable Pneumatic Shaft
3—Extensible Arm Assembly	4—Nozzle Activation Assembly
5—Ball Screw Assembly	6—Cradle Alignment Assembly
7—Handle Cut Assembly	8—Base Structure Assembly
9—Robotic Arm Linking Assembly	

3.1.1. Mechanical Project

For a better understanding of the various EOAT assemblies functioning, these will be deconstructed. The methodology for the sub-assemblies' presentation is by association with the product in chronological order and the other sub-assemblies dependent on it. This way, all the sub-assemblies that constitute the tool will be exposed. The diagram of

Figure 5 gives a better perspective of the assemblies to be presented and which are their dependences.

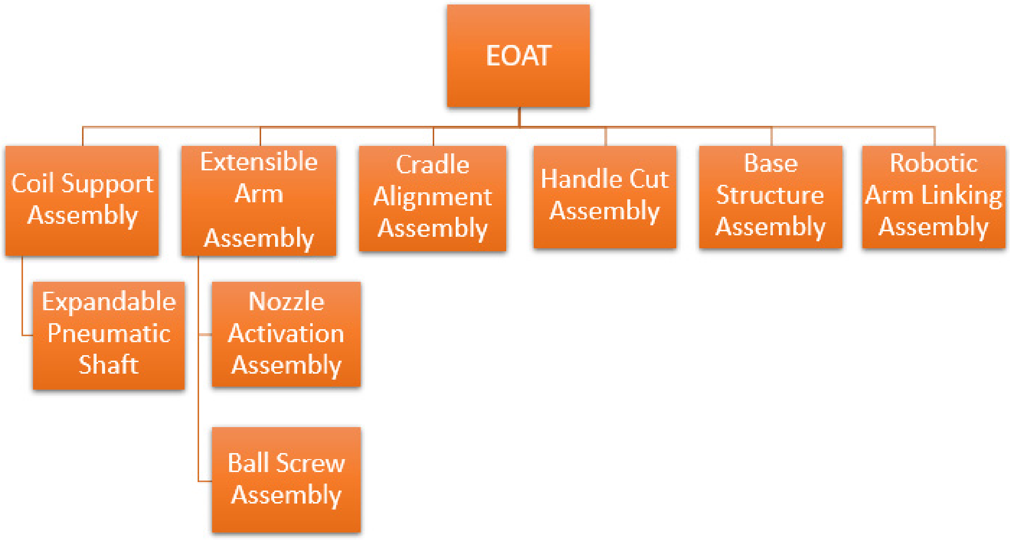

Figure 5. Diagram of EOAT's sub-assemblies.

Coil Support Assembly

The coil support assembly (Figure 6) is responsible for supporting the coil and every element attached to it.

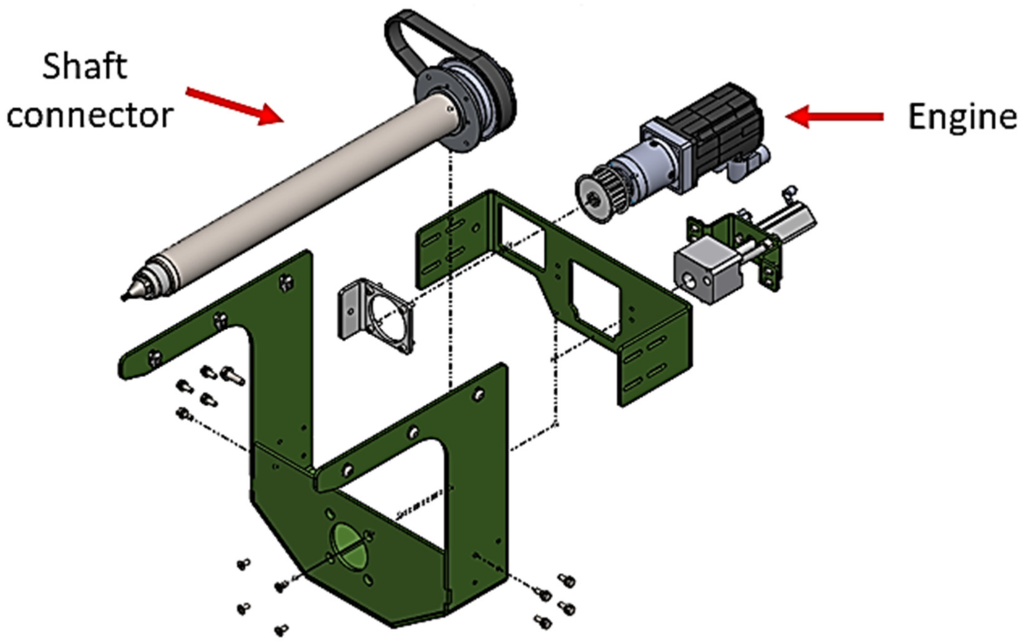

Figure 6. "Coil Holder" assembly's exploded view.

Within this assembly, there is a sub-assembly that needs to be explored more rigorously, depicted in Figure 7. This sub-assembly has four functions, namely:

- Connect and maintain the link between the EOAT and the Expandable Pneumatic Shaft;
- Support the coil in the EOAT;
- Transmit rotation to the Expandable Pneumatic Shaft;
- Activate the valve inside the Expandable Pneumatic Shaft.

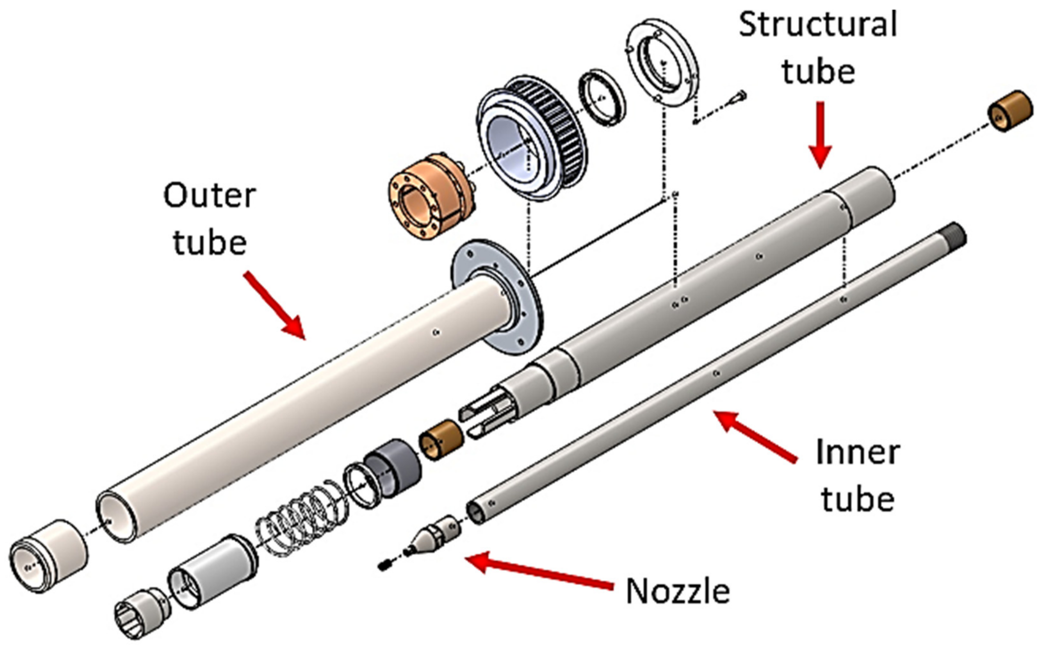

Figure 7. "Shaft connector" sub-assembly's exploded view.

In Figure 8, the mechanism that was developed in order to fulfil the functions described above is represented, where the nozzle has the purpose of activating the valve present in the expandable pneumatic shaft. The outer tube's task is to support the coil and protect the mechanism, and it is made of AISI 304 stainless steel in order to prevent damage to the product when they contact each other. The connection function is carried out by the box wrench, which has a mechanical linear movement performed by a spring. The nozzle, together with the inner tube, also serves to inflate the expandable pneumatic shaft. The linear movement is provided by a cylinder, and the mechanism responsible for this movement is also shown in Figure 8.

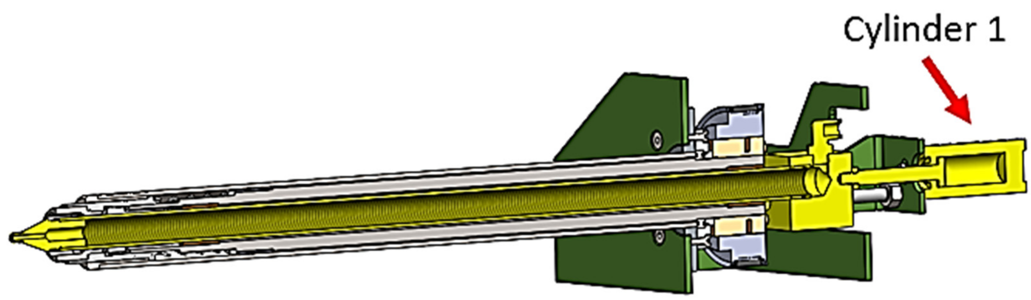

Figure 8. Sectional view of the mechanism responsible for picking up and expanding the expandable pneumatic shaft.

For the spring present in the "Shaft connector", the biggest restriction is its dimension, as it is limited both by the rotation transmission tube to the expandable pneumatic shaft and by the structural tube supporting the coil. Thus, a compression spring is required to ensure that the affected elements are always forward. The elements in question are two machined parts, one acting as a mating part in the hexagonal section of the expandable pneumatic shaft (which is threaded), while the other acts as a stop for the spring and also as an advance limiter.

A more pragmatic method was followed, where a spring was made for testing, obtaining optimum results, which is the reason why this concept has been adopted. This spring has its working displacement limited by stops, so it will not lose its quality. In addition, this shaft also has a mechanism for transmitting rotation to the expandable pneumatic shaft, shown in Figure 9. This mechanism should be able to prevent the inertia of the expandable pneumatic shaft and all the elements of which it is comprised.

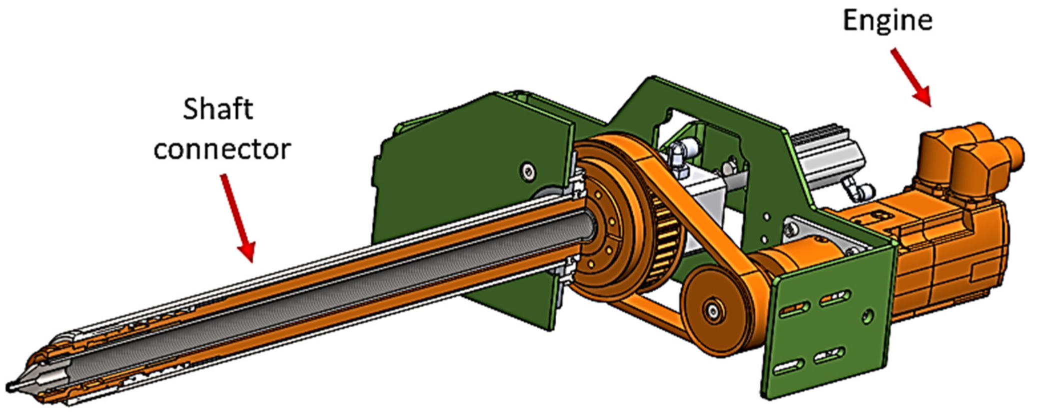

Figure 9. Sectional view of the mechanism responsible for rotating the expandable pneumatic shaft.

The torque, angular velocity, and the time for one revolution of the expandable pneumatic shaft have been calculated so that, with any future changes/improvements to the tool, the designer can be able to perform the calculations for the tool's modification without difficulty.

The expandable pneumatic shaft shown in Figure 10 has been sized to have an expansion of 10 mm in diameter, so that it can expand from Ø50 to Ø60 mm, with a valve at the inlet to ensure that this effect is possible.

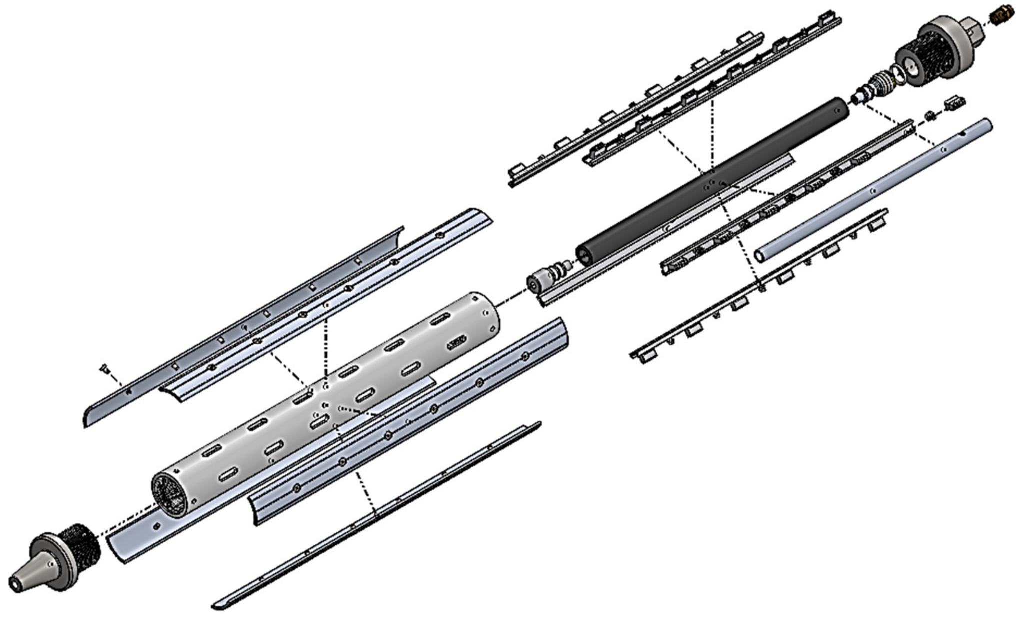

Figure 10. Expandable pneumatic shaft's exploded view.

The nipple valve present in the mechanism of Figure 11, which is located on its right side (brown), is activated by the nozzle present in the shaft connector, emptying the pneumatic shaft so that it is possible to remove the yarn coil. It should also be noted that it is the same valve that will allow the opposite process to be carried out before a new winding process begins. Figure 11 also shows, through the centre of the shaft, the air flow (in blue) from the valve to the expandable rubber sleeve, which is responsible for expanding the diameter of the shaft.

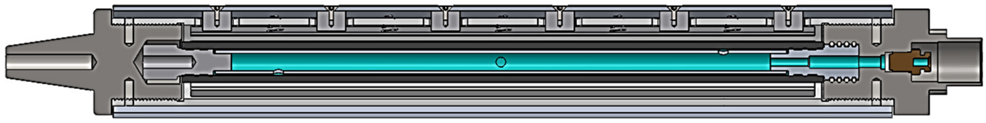

Figure 11. Sectional view of the YZ plane of the expandable pneumatic shaft's mechanism.

The airless shaft remains retracted by the action of conical springs, as depicted in Figure 12.

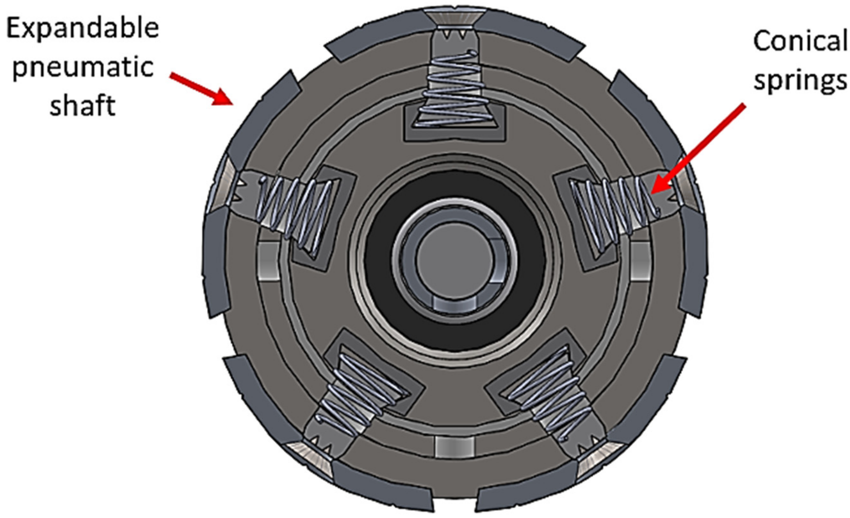

Figure 12. Sectional view of the XY plane of the expandable pneumatic shaft's mechanism.

The winder's pneumatic shaft spring is held inside a U-shaped aluminum profile, with the flaps more closed, and it is through these flaps that the spring remains fixed.

Extensible Arm Assembly

In order to meet the requirements, a method is needed to take the coil, pick up the yarn and transport it to some strategic points without damaging it.

Firstly, it is necessary to remove the coil without damaging the product, where all the yarn of the coil is tensioned and, when the pneumatic shaft is contracted, the coil contracts a little, a resistance that the bar must be able to withstand. A welded reinforcement has been added to this sub-assembly, and the plate has also been oversized so that it does not wrap. This sub-assembly shown in Figure 13 should also activate a lever that lowers a spreader present inside the winding machine.

The coil bar sub-assembly must have a rotation movement in order to reach certain necessary positions inside the winding machine. This movement is made by the mechanism represented in Figure 13, the extensible bar assembly.

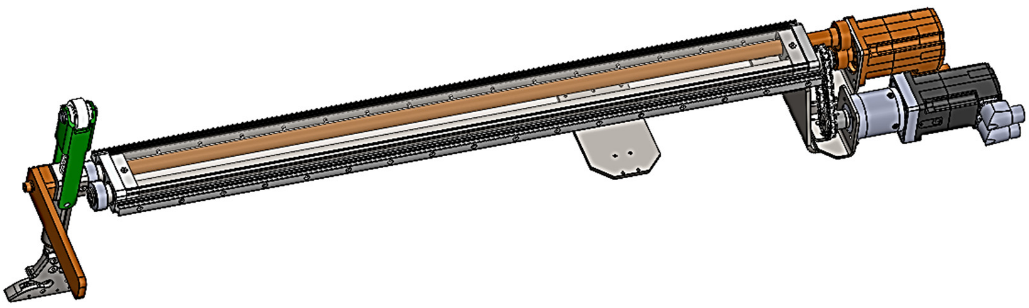

Figure 13. Mechanism responsible for rotating the reel bar.

The first sub-assembly in Figure 14 is named "coil bar", the second "yarn arm", and finally the third "extensible bar". The latter has the function of housing the entire mechanism for transmitting movements to the other two sub-assemblies.

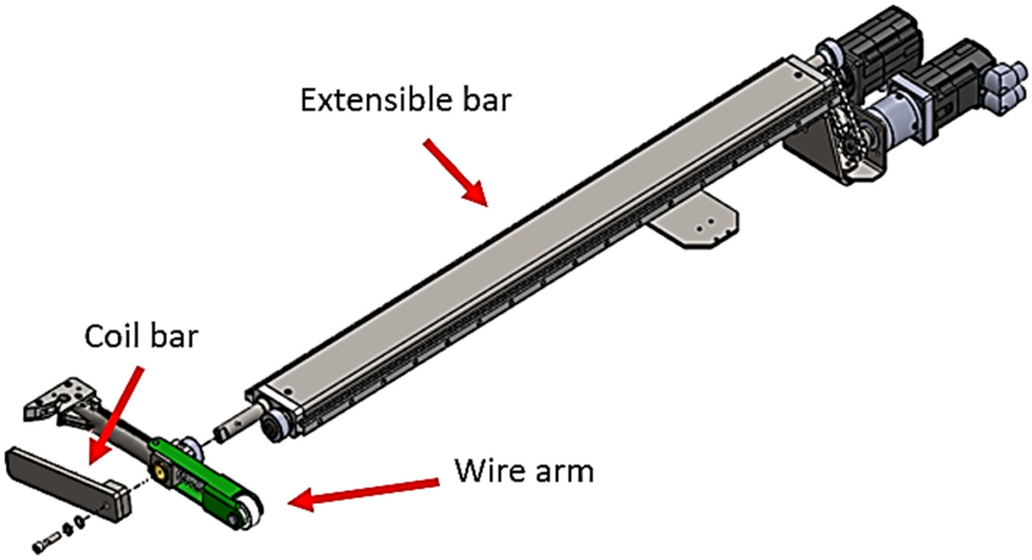

Figure 14. Exploded view of the three sub-assemblies present in the extensible arm.

Besides the rotational motion, the yarn arm sub-assembly has a crucial movement in allowing for a better accomplishment of the requirements, which is a linear motion, depicted in Figure 15.

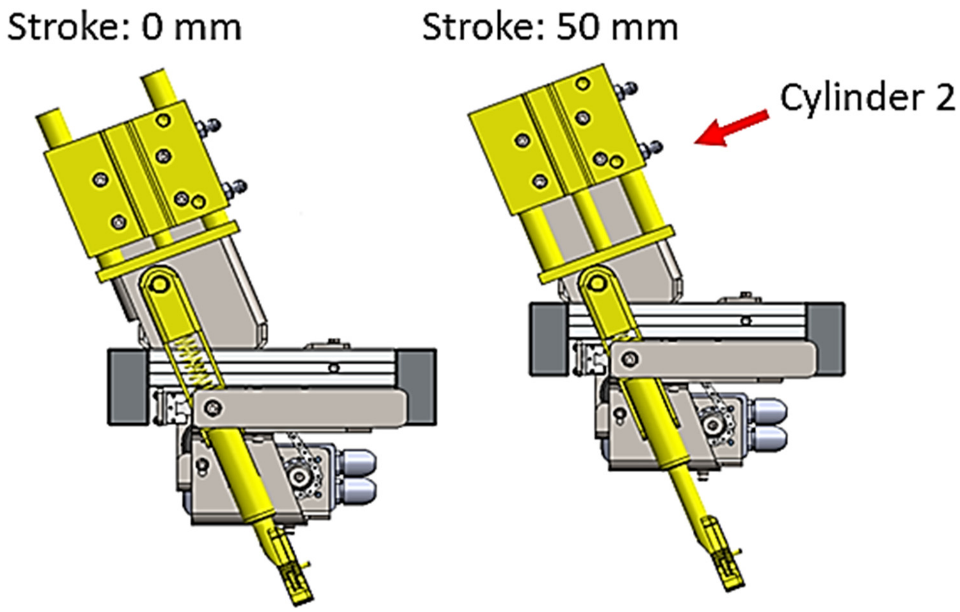

Figure 15. Linear movement of the yarn arm sub-assembly and its dependence.

The linear movement of the yarn arm sub-assembly is guided, with a 50 mm stroke. The cylinder exposed in Figure 15 is embedded in the nozzle activation system and has the visible inclination so that there is not much loss of stroke due to the angle at which it must act, thus allowing it to act in a straight line with the yarn arm sub-assembly.

The yarn arm stroke has the purpose to fulfil the requirement of attaching the yarn to the pneumatic shaft. This way, when the need arises to attach the yarn to the expandable pneumatic shaft, it is necessary to operate this mechanism together with a 30° rotation movement in all the EOAT, by moving the robotic arm. This 30° angle is essential, so that the yarn can reach the pins of the pneumatic shaft, since the stroke of the yarn arm sub-assembly is limited in size. As such, the mechanism is able to catch the yarn.

As the cylinder will exert a force on the yarn arm sub-assembly, and as the tension amount exerted on the arm is not known, a stock cylinder was used to carry out tests and get a better idea of the force required. Nonetheless, in the first instance, it is necessary to estimate the force it must overcome.

Within the yarn arm sub-assembly, another mechanism also exists, responsible for catching the yarn and keeping it attached, so that it is manoeuvrable; this being the "hand" of this tool. The mechanism is represented in Figure 16.

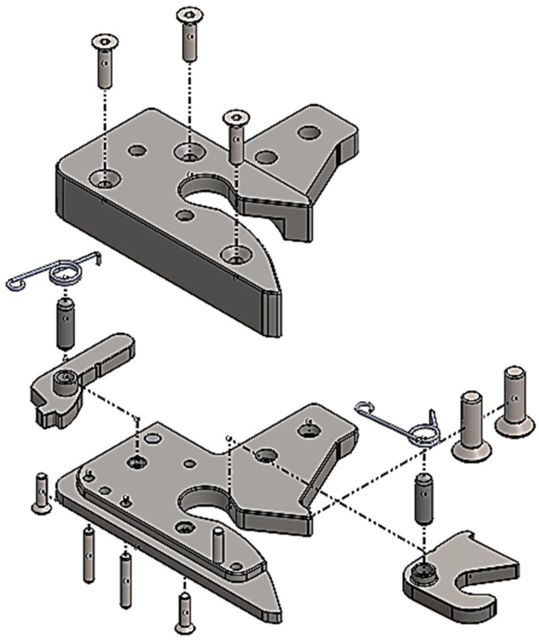

Figure 16. Gripper mechanism's exploded view.

This mechanism has three important positions: the rest, engagement and disengagement positions. Figure 17 shows the working positions of the gripper mechanism, and in the coupling situation, the pawl/knob locks the coupling part in the pictured position.

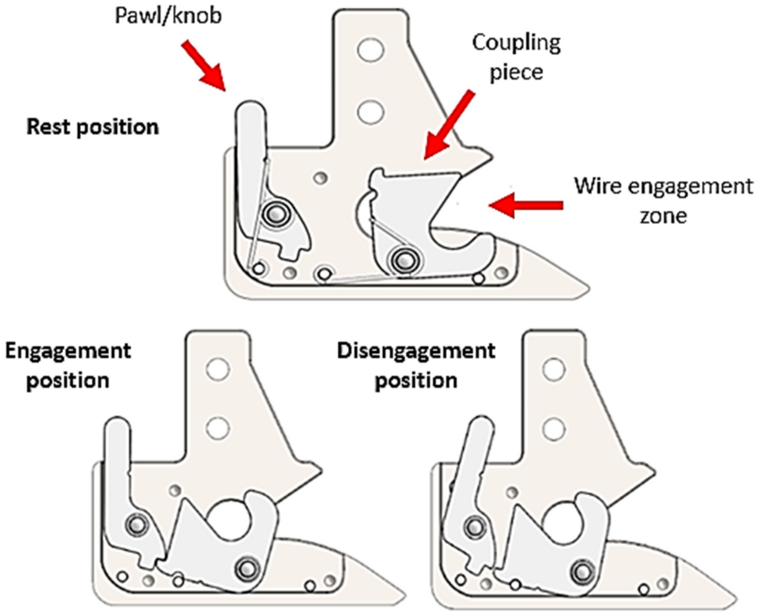

Figure 17. Working positions of the gripper mechanism.

In the situation where it is necessary to disengage for a new process, the pawl is activated, and the springs must act to return the mechanism to its rest position. Finally, the linear movement of the arm is carried out by the assembly shown in Figure 18.

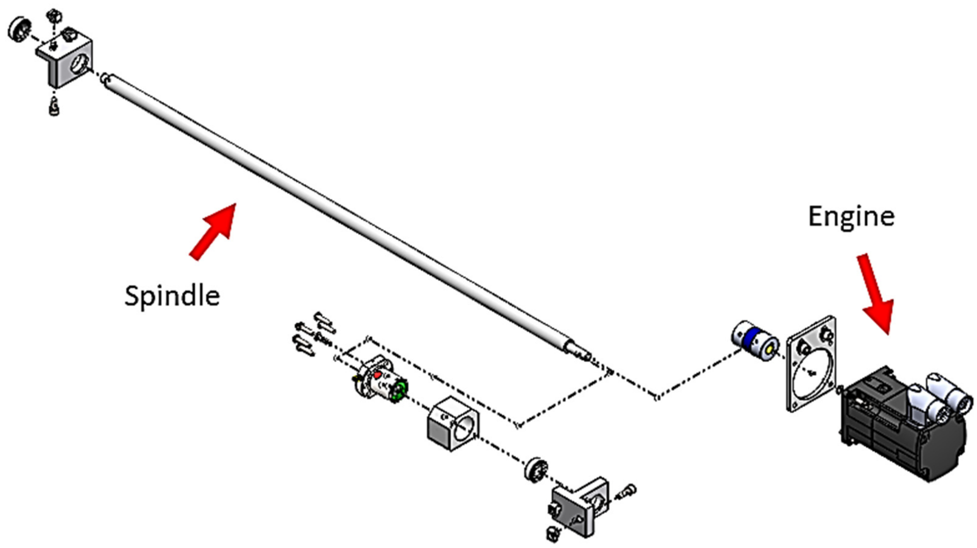

Figure 18. Spindle assembly's exploded view.

The assembly represented in Figure 19 is responsible for providing an axial movement to the extensible arm, allowing it to move inside the winding machine. The axial linear movement executed by the spindle allows the mechanism to perform what is demonstrated in Figure 19.

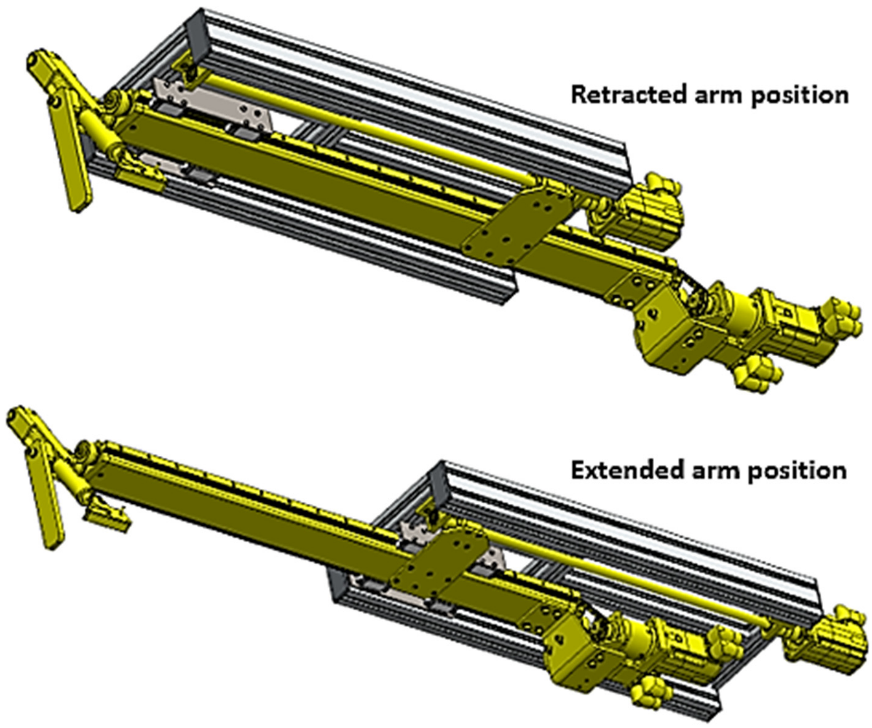

Figure 19. Linear movement of the extensible arm assembly and its dependence.

Cradle Alignment Assembly

The following assembly has a very simple function: to keep the cradle parallel to the floor. This procedure is aided with the movement of the robotic arm, being performed by a cylinder. This assembly was positioned at a strategic distance from the connection shaft (see Figure 20), so that, with the cradle aligned, the coupling between the connection shaft and the expandable pneumatic shaft, present in the winding machine, can be performed. The cradle alignment assembly is shown in Figure 20 and is fitted with a guide so that the pneumatic cylinder does not have to bear the strain exerted by the cradle.

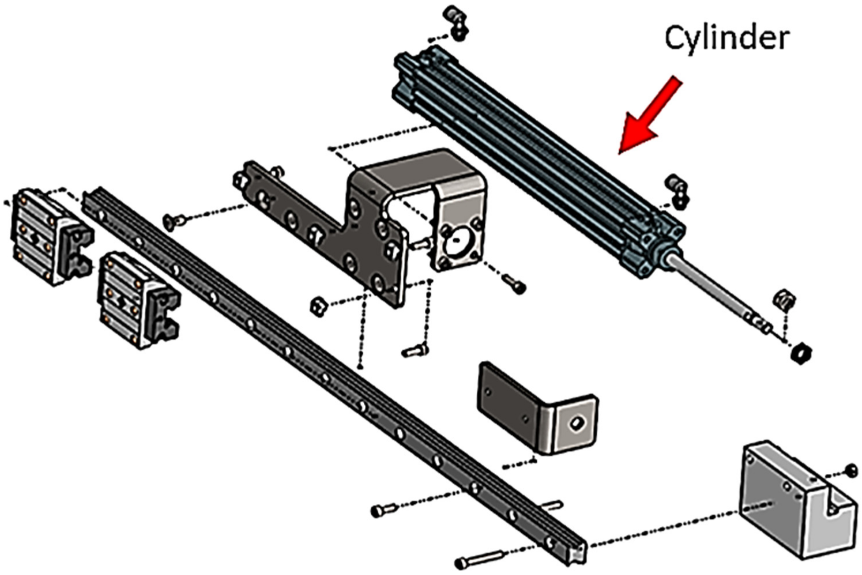

Figure 20. Cradle alignment kit's exploded view.

The pneumatic cylinder of this assembly must be able to overcome the frictional force generated by the linear guide and the acceleration force.

Handle Cut Assembly

The assembly represented in Figure 21, besides guaranteeing the cut, must assure that the yarn remains located in a strategic position, because the heated blade alone does not guarantee a clean cut of the yarn.

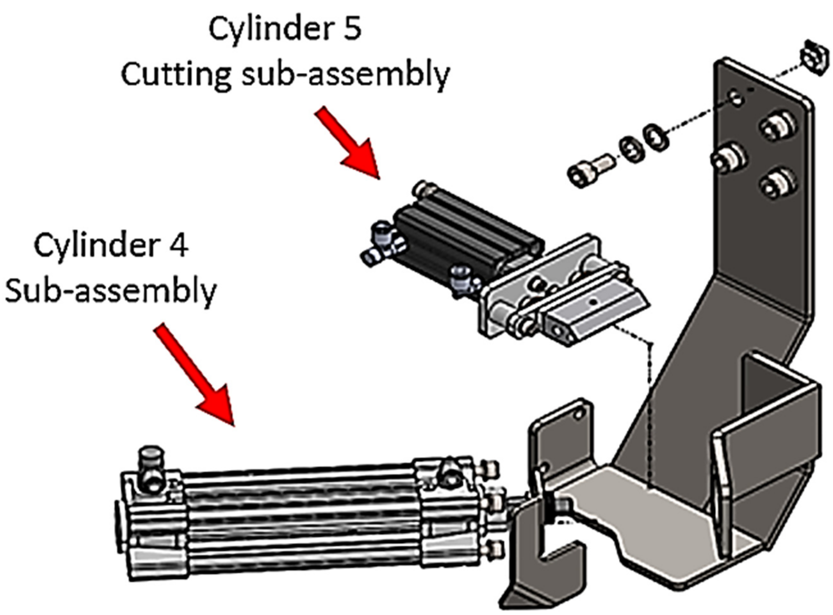

Figure 21. Handle cut assembly's exploded view.

By combining the two sub-assemblies in this mechanism, the plate creates a fixed and flat surface where the yarn will be enclosed for the proper functioning of the cutting blade. This system is represented in Figure 22.

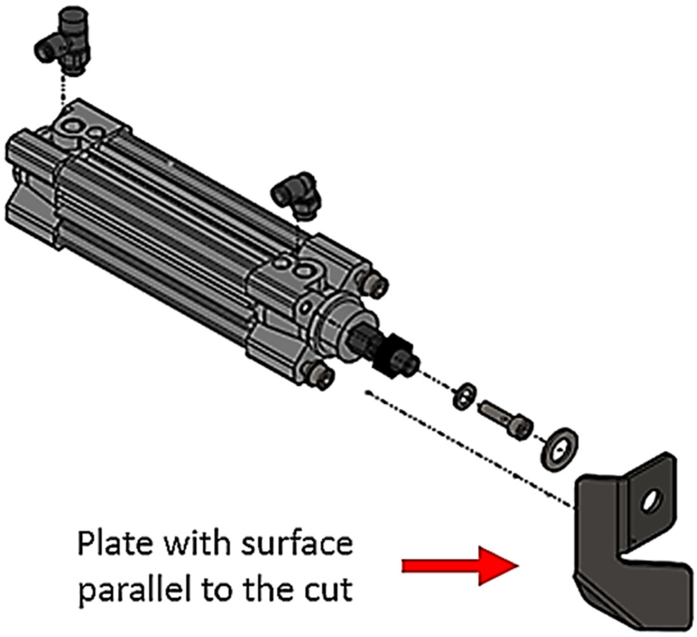

Figure 22. Handle sub-assembly's exploded view.

In this system, it is necessary to place the yarn in a certain position in order to achieve the cut, and the plate attached to the cylinder of the yarn pulling system has its own design for this purpose. Additionally, providing a flat area for the cutting system, it also ensures that once the yarn is pulled, it does not escape. On the other hand, in order to guarantee that the position of the sheet is not altered, a cylinder with an anti-rotation system (hexagonal rod) was selected.

The cutting system, as can be seen in Figure 23, comprises a blade that is heated through a resistance, and a probe to control the temperature. However, as most of the materials are metallic, this mechanism was made to avoid the temperature from damaging the cylinder, using Celeron to decrease the thermal transmission between the fixing materials to the cylinder.

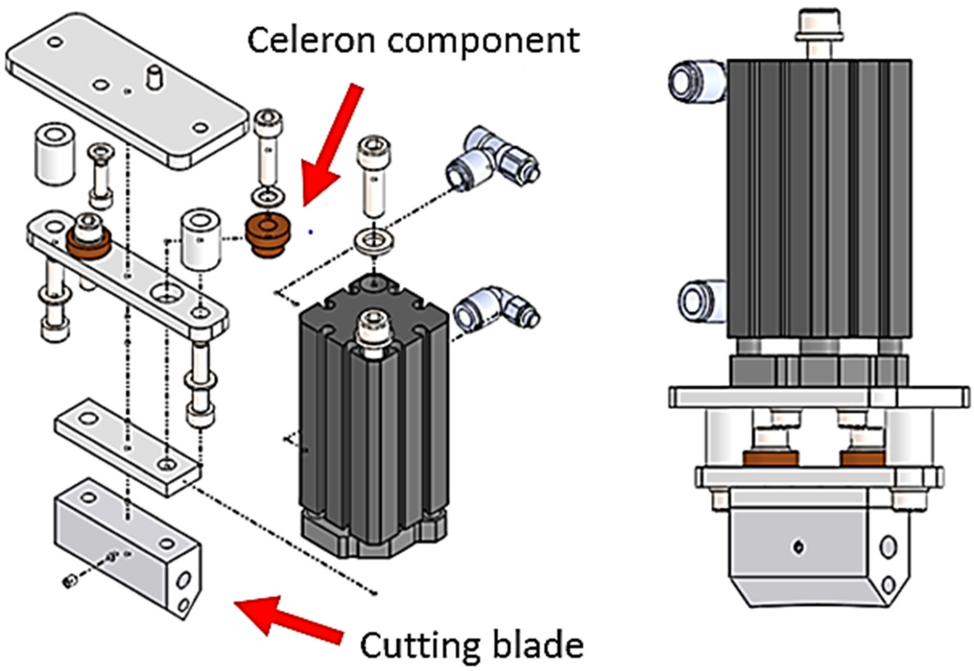

Figure 23. Cutting sub-assembly's exploded and assembled view.

Base Structure Assembly

All the developed assemblies need a common base that will serve as support and connection to the robotic arm. This assembly was developed in an aluminum profile, as shown in Figure 24, as it allows for greater freedom for adjustments if necessary.

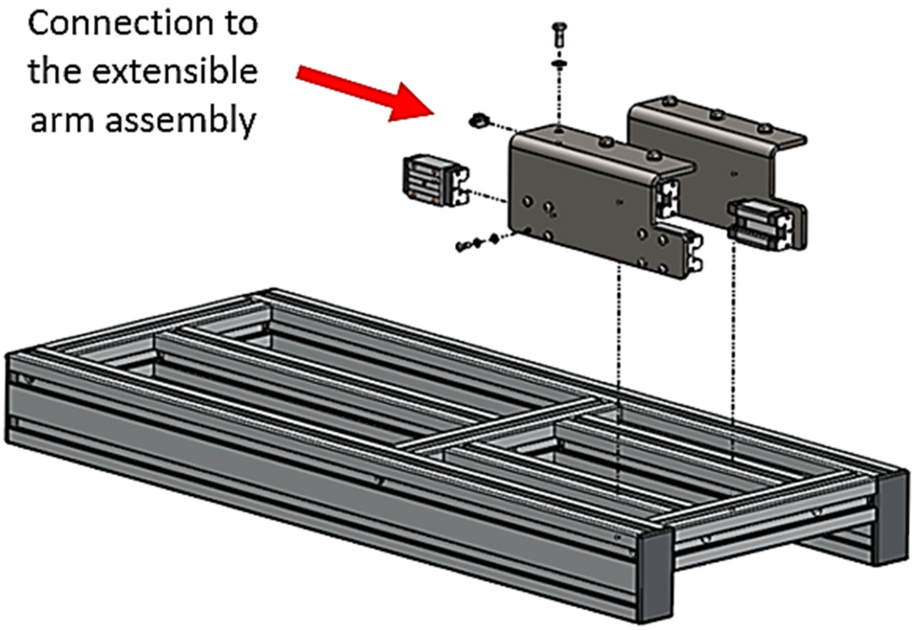

Figure 24. Aluminum profile frame with connection and support function.

The assembly that connects the base structure assembly and the robotic arm is the robotic arm linking assembly, and is depicted in Figure 25.

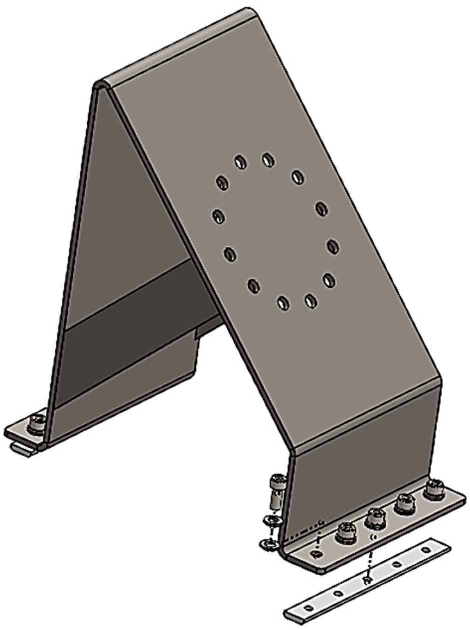

Figure 25. Robotic arm linking assembly.

This system possesses the function of supporting the entire EOAT, including the coil. Accordingly, as it is a critical point that must ensure the integrity of the entire system without collapsing, it must be studied to verify if its structural functionality has to be redesigned.

After a finite element analysis was performed, the simulation showed that it was necessary to introduce a reinforcement in the part's structure, as the EOAT was not safe in any position. Figure 26 displays the optimised design.

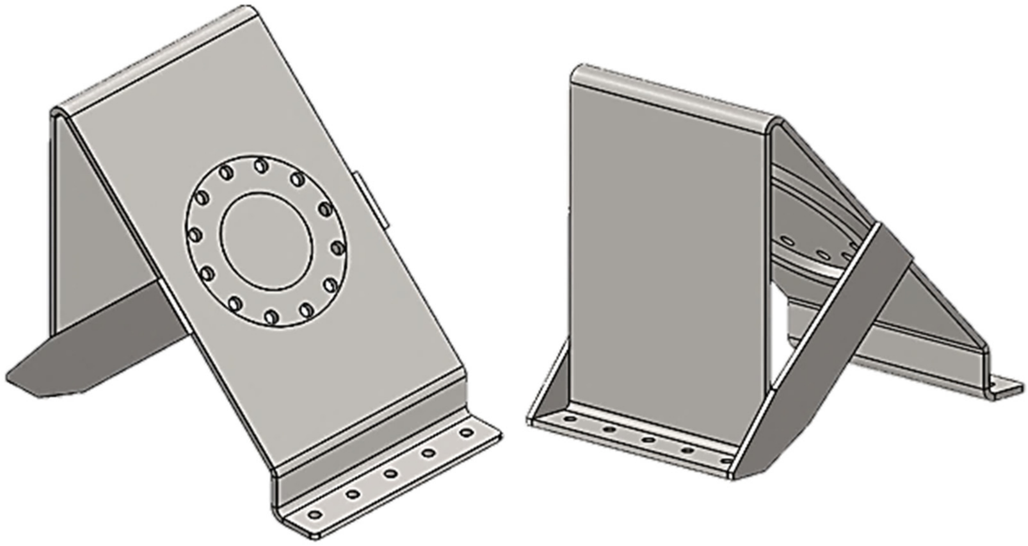

Figure 26. Optimized EOAT backing plate design.

3.2. New Production Process

The exposed design corresponds to one part of the solution for the idealised line, shown in Figure 27. The complete project is a set of mechanical systems, which sums up to an automated line capable of handling 17 winders and able to be expanded. The entire line is formed by various mechanical components, namely, conveyor belts for transporting the final product, robotic arms and rails for their movement, EOAT's, a support structure and a safety system.

Figure 27. Designed line with 17 winders and their feeders (Image from KUKA SIMPRO).

Before the implementation of this new production process, all the winders were operated manually, with only the human intervention to perform the removal of each coil and replace it with another, in order to begin a new winding of the yarn. This had many problems, such as waste of time, because a single operator was not able to remove all the coils simultaneously from every winding machine, in addition to the time taken to replace it with another. This manual process led to production delays, which caused a huge profitability loss, besides the possibility for mistakes to happen due to the human factors (operator's fatigue, mood variations or lack of attention). Accordingly, an automatic production process solved every single one of these problems: the extraction of a coil and placement of a new one can be made simultaneously in all the 17 winders, eliminating the time loss. In addition, the winders are programmed, so the chance for mistakes to occur in their usual function is reduced to almost zero. This way, this process constitutes a novelty in the yarn rope manufacturing industry, where the Industry 4.0 methods were put to practice in order to overcome the existing obstacles originating from the manual labor.

3.3. Implementation Results

According to data provided by stakeholders of this project, three operators are needed to handle the 17 winders and, in order to meet the production output of the automated solution, three shifts are required. It was empirically assumed that the annual salary of the operators is EUR 14,000.

Another data provided by stakeholders is the time to remove the coil, which, according to them, corresponds to about 60 s for an operator. On the other hand, the robotic arm will be optimised (Equations (1) and (2)) to achieve a time of 40 s per coil removal.

$$Optimisation\ (\%) = 100 - \left(\frac{100 - automatic\ coil\ removal\ time}{manual\ coil\ removing\ time}\right) \tag{1}$$

$$100 - \left(\frac{100 \times 40}{60}\right) = 33\% \tag{2}$$

Taking into account a gain in productivity of about 33%, which is achieved by switching to the automated system, it is also necessary to consider the number of operators required to get the same productivity, shown in Equation (3).

$$\frac{100}{3} = \frac{133,(3)}{x} \rightarrow x \cong 4\ operators \tag{3}$$

Table 2 shows the annual cost data related to this process.

Table 2. Annual cost data with salaries if the automated systems are not implemented.

.	Operators/Line	Cost/Year/Shift	Shifts	Cost/Year
Operator salary	3	EUR 42,000	3	EUR 126,000
Optimization	+1	EUR 14,000	3	EUR 42,000
Total cost/Year				EUR 168,000

Electricity and maintenance costs were disregarded to calculate the return on the investment made in this system. The investment made, considering the line, was 400,000 EUR.

The payback period (PBP) is calculated according to Equations (4) and (5):

$$\text{PBP} = \frac{New\ equipment\ cost}{Profit\ generated\ per\ year} \tag{4}$$

$$\text{PBP} = \frac{400{,}000}{168{,}000} = 2.53\ years \tag{5}$$

Assuming empirically that the service life of this line is 10 years, without requiring corrective maintenance, the implementation of this solution brings an expected profit of approximately EUR 1,000,000.

4. Discussion

The industry is experiencing new times of change, through the integration of information and an even greater automation of processes; however, these changes cannot be carried out without the automation of all processes being completed and able to be integrated. This problem had already been addressed by Pinto et al. [33], in a study focused on SMEs. Automation can go through the robotization of processes when several models of the same family of products are manufactured in the same production system and setups are required with high frequency. In spite of this, in many cases, more conventional automation is sufficient to meet the needs at a lower cost, essentially when there is very little variation, or no variation at all, in the product to be manufactured, as referred to by Silva et al. [19] and Araújo et al. [27]. Sometimes, only a mixed solution integrating robotics and conventional automation is able to overcome the real needs of the industry. Indeed, Costa et al. [24] have also mixed a robotic system with conventional automation, generating some novel mechanical solutions able to overcome all requests required by a workstation devoted to the assembly of a semi-product used in widescreen washer engines in the automotive industry. As referred in that work, high-level automated systems have been used around a robot, as well as smart and cheap mechanical solutions, allowing for a high grade of flexibility of the workstation, which became able to assemble a series of different sets of the same family. Castro et al. [14] went further, reusing an out-of-service robot to use it in a welding cell for bus side-body-frames, reusing it and expanding its initial capabilities, through an integrated automatic system that made it possible to extend its range of action, as the bus body-frames have a considerable length. The robot's reprogramming and the integration of its operation with the ability to move along the structure were the key to success in overcoming the need presented by a company that manufactures that type of bus body-frames. Silva et al. [13] also developed a solution based on a robot, due to the need for flexibility and reprogramming, but they used conventional automation integrated with robotics to develop a new system capable of controlling, through artificial vision, cushions and suspension mats used in seats of vehicles, and then proceed to pack them in an organized manner. The solution, although complex, made it possible to guarantee that the quality control became practically 100% reliable and not dependent on possible human errors, complying with the cycle time required by the automatic operation of the existing equipment. Martins et al. [20] and Moreira et al. [21] developed integrated solutions based only on conventional automation, eliminating intermediate stocks of components, reducing internal logistics, and increasing productivity. This is almost always the main motivation of this kind of works, but the development of solutions must be properly supported by an economic study that allows for analyzing the feasibility of its implementation. In the present study, the payback time is around three years, which is at the limit of what is normally acceptable by the industry in general; however, it must still be safeguarded that the reliability of the process is also highly enhanced. This value is much higher than the one found by Magalhães et al. [18], which took just over 8 months, but the complexity of the systems is also quite different. In fact, the complexity of the solution now developed is closer to that of another solution designed by Silva et al. [13], which presented an estimated payback period of 21.5 months. Despite this, in addition to the effort and economic return of the project, it is clear that this solution translates into a production system that can be fully integrated. This is similar to the work presented by Barbosa et al. [34], in which the flexibility of processes and the integration of information allow the systems to approach the concepts usually defined as Smart Manufacturing or Industry 4.0.

Although many studies have as main motivation the reduction in the production cycle time and the cutting of jobs, the main motivation of this work was essentially to ensure a continuous workflow and the integration of a large amount of equipment in the same production line, as this is the reality normally experienced in the textile industry. This contrasts a bit with the reality experienced in the automotive components industry, where competitiveness is in most cases the main motivation, but it is also possible to find works in which the main motivation was quality improvement [22,30], or process integration [13,21,33,34]. There are also cases where automation is modified/improved in order to reduce production stoppages due to breakdowns, as mentioned by Santos et al. [26]. The mechanical solutions developed around the automation used in this work are also noteworthy, being at the level of others developed in similar works [18,23,24,27,28,30], and represent systems that, in addition to solving the problems defined in this work, may constitute extremely interesting solutions to overcome other similar problems in other types of industry. Therefore, the innovative solutions presented by this work can, alone or together, be used to solve other problems. This is one of the main reasons for the presentation of this work, which is intended to enable the integration of these systems, or the development of even more sophisticated ones, which may constitute a starting point for further studies. Video S1 provided as supplementary material, corresponding to the first tests performed with the prototype resulting of this work, will help to understand the operational functioning of the novel robotic manipulator in action.

5. Conclusions

The spinning/textile industry uses coils as systems for storing and transporting yarn between production operations. The winding of these coils, despite being automatic, also included manual operations of starting and ending the winding. Automating this process was the main motivation of this work and, to this end, new solutions were developed to couple to a robotic arm that collects the coils. The developed solution translates in the total automation of the process, allowing it to adapt to a system usually defined as Smart Manufacturing, or Industry 4.0, in which the coils are finished, sent to a common conveyor belt, and the winding of a new coil is started fully automatically, i.e., without human intervention. The developed system made use of several ingenious solutions, which are effectively innovative and, in addition to solving the problem described in this work, can be used to solve other similar problems in other types of industry, which may contain their own specificities. A portfolio of relatively simple and economic solutions is thus created, but interesting enough to be disseminated and included in other solutions aimed at solving other problems. It is worth mentioning that the coils' extraction system was designed to fulfil the necessary functions, always without damaging the yarn used in the process.

The developed equipment is capable of extracting coils of yarn automatically and can be adapted to extract coils of other materials, as well. With the flexibility offered by the robotic arm together with various components in the developed project, this complex operation became feasible. In addition, an equipment capable of cutting and burning the end of the thread was developed, so as not to deprive the product of its quality due to fraying. In order to allow easy cleaning and maintenance, all the equipment has a modular construction. Finally, the cycle time was reduced, since at the end of this project, the execution time was 40 s. The payback time of this solution is about 36 months, which is within the usual acceptable period for this kind of project.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/machines10100857/s1, Video S1: Prototype working.

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