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Trabajo de tesis de grado:

Design and constuction of a robotic thread changer of an industrial braiding machine.

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Trabajo en colaboración con Gemini Bussiness Solutions GmbH.

I hereby confirm that I have written this work independently and no other than the citied sources indicated in the bibliography have been used.

The drawings and pictures in this work have been created by myself or been provided with an appropriate list of sources.

This work hasn't been submitted to any other revision board.

Luis Ricardo Ramírez Martin del Campo

Aachen 18.09.2015

Dedicatory

To my Mom, She always has been there for me.

To Angie, we almost didn't make it, but we did, I love you.

To my family, even though a small one, we stick together.

To my Colleagues at the ITQ, was wonderful being with you guys.

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Abstract

The versatility of the braiding technology for the production of customized braids is nowadays still being done with a high manual effort for setting up the braiding machines. An automation of this process promises lower costs, reduced set-up times and consistently high product quality. In the present study a solution for the automated change of material on a conventional braiding machine is designed and constructed. The specifications and pattern of the braid material should be selected by the customer and transmitted through a network to the braiding machine.

The development process is based on the proven design methodology of the VDI guideline 2206 which stands for the development of mechatronic systems, where a wide range of methods for the processing of the individual stages of development is applied, ranging from the scenario technique for requirements elicitation to heuristic methods for finding solutions through concept-rating means and utility analysis.

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List of Abbreviations.

OEM	Original Equipment Manufacturer
PLC	Programmable Logic Controller.
OLE	Object Linking and embedding
OPC	OLE for Process Control.
UA	Universal Architecture.
IC	Integrated Circuit
IODD	Input output device description
XML	Extensible Markup Language.
CAN	Controller Area Network
AS-I	Actuator Sensor Interfase
RFID	Radio Frequency Identification
VDI	Verein Deutscher Ingenierue (Association of German Engineers)

Chapter I: Introduction

The recent decades have witnessed a fast growth of automation. In consequence of this, the worldwide production systems have changed dramatically in many industries. This has been possible due to the new quality systems and process-customization. Because of this reason, a lot of different technologies can be used to solve any automation problem, this derives on the need for professional business that can consult, build and optimize those systems.

This project is developed in Gemini Business Solutions, which is an Original Equipment Manufacturer (OEM) and technological consulting enterprise that helps their clients to have access to state of the art process automation and design. Most of this projects belonging to the new products and processes construction into a paradigm called “Industry 4.0” that has as its goals the connection, customization, virtualization and tracking of products when they’re being made.

Using this design philosophy, the present project is about the construction of an integrated solution that improves the production of braiding products, in order to enhance the productivity of the process but also adding the key factor of the new industry revolution, the possibility of individualize the production according to the requirements provided to the machine by the customer.

A braiding machine consists on a set of carriers attached to an epicyclical movement mechanism composed of a planetary gear train. These carriers are responsible for producing the threaded product; however, if the colors, amount of carriers and turn direction of the machine are changed; a different thread pattern will emerge, giving the possibility to fabricate different kinds of threads by varying those parameters.

The machine-assisted braiding process has been implemented since 1817, having the characteristic, that the thread change and pattern choice has to be made manually, which constitutes an area of opportunity for the development of a mechatronic system that helps with these task, then the expected result, is an increase on productivity and flexibility of the process.

However, until now, it is still not possible to configure individual braids and weave in small batches, since the plaiting exchange has still to be done manually, making this feature time and resource consuming. This is because the machine elements that carry the threads of the braid must be individually dismounted from the guide rails.

Another reason for not including this feature with a human operator is due to the amount of threads that have to be changed; this can easily be error prone. Then by automating these tasks not only the individual requirements can be fulfilled while maintaining high quality standards but also the error probabilities can be decreased.

Altogether the requirements, for the development of an automatic thread exchanger can lead to a significant improvement of the performance in these tasks.

The purpose of this thesis is to document the development of the electrical and control systems in an automatic thread changer that can operate in a flexible working environment. This will be achieved by selecting the suitable components that can fulfill this task by using a mechatronic design model.

In this project; two principal technologies coexist, both in cooperation are pretended to fulfill the requirements. In one side the 2D braiding, a traditional method for the textile industry and, a recently emerging subject, the so-called "industry 4.0", which provides this process with modern day features.

The first step is to explain the principal features of these two dissimilar areas of technology and how their combination in a mechatronic system can lead to the development of an innovative production system with a promising potential to improve the production in the upcoming future. The main objective will be to preserve the already proven quality provided by the ancient technology but with the advantage of faster, automated and personalized fabrication features derived from this integration.

2.1 Braiding Technology

Nowadays through the employment of modern manufacturing technologies it is possible to create complex braided structures whose technical characteristics are demanded on high performance applications, such as the aerospace, medical and retail industry. On this chapter an overview of the different main braids and their different characteristics will be explained before getting into the functionality of the conventional braiding machine.

“Braiding is the process of interlacing three or more threads diagonally to the product axis (parallel to the longest dimension of the resulting product) either to obtain a thicker, wider, stronger product or to cover (over braid) a given profile.” [KYOY15] It is one of the oldest technologies still present in modern era and has been used for many years in a wide range of areas such as the braiding of threads, flowers, hair, food, etc. The main reason of still using this technology is that, it allows joining single yarns to a final product and the addition or replacement of yarns during each step of the whole process.

In addition there is a similar technology which is often confused with braiding; the weaving technology which is also intended to join different flexible materials. Nevertheless, “Weaving encompasses two discrete sets of threads: wrap and fill. They have a similar interlacing effect as braiding but two threads are placed perpendicular to each other. *“Wrap threads run in longitudinal direction, also known as the machine direction and fill threads run laterally typically through a shuttle system thus forming an interlaced structure.”* [www01] The Figure 2.1 shows clearly the difference of both processes: While in the braiding (left), the thread always runs diagonally to the product axis, its bent and perpendicular to the braid edges. Also weaving threads (right) of the weft thread (blue) are always perpendicular in the direction of the stationary production, and when the edge is reached, the fabric is turned 180° and reinserted in the thread.

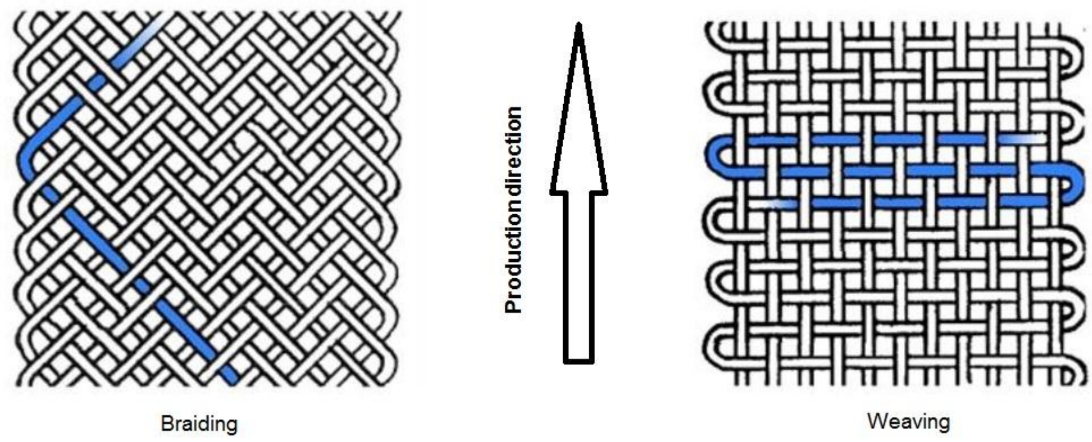


Figure 2.1 Differences between Braiding and Weaving [Eng90]

In a simple braid (Fig.2.1 left) the filaments are disposed only in two orientations on which they cross over, resulting in what is known as biaxial structure. This type of braid can be stretched elastically along its longitudinal axis and decreased in diameter due to the lack of any kind of resistance to perpendicular forces. In order to avoid this kind of problems, some opposition against the force is needed.

The so-called stationary or 0° threads can be incorporated into the fabric that are not crossed each other but deducted only perpendicular to the braiding with in addition to the braiding in order to counteract the force. This type of threads supports the structure of the braid by giving a third direction of threads, creating with this another type of braid, the triaxial braid. A direct comparison can be found on figure 2.2, where on the left side a biaxial is presented and on the other side a triaxial braid with the 0° threads blue highlighted.

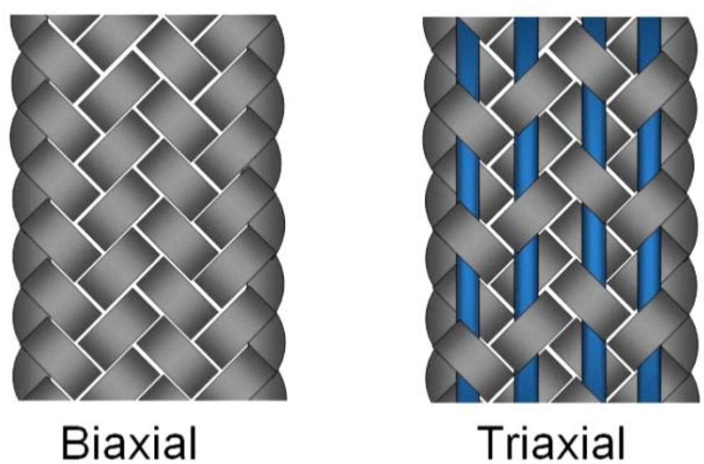


Figure 2.2 Difference between biaxial and triaxial braids [SCH12]

The form of the braid (linear, curved or solid structures) defines its type between one, two or three-dimensional fabrics. Figure 2.3 gives an example of each of those three mentioned types of braids. This work is restricted to circular braids, flat braids and the wide range of 3D meshes.

Curved and linear braids are very similar to each other and both are classified among the 2D braids, even when they have a measure in all three axes. The definition of Ko et al. states that *"in the 2D braids only threads are placed in a level above the other, but no more than threads are included in the direction of the wall thickness"* [KPH89]. This statement separates then the 3D braids from the other two, due to the possibility to add woven fabric into a third plane in the direction of the wall thickness of more threads, so several braided profiles can be produced.

The profile shape in 3D braids also can be adjusted during the braiding process, the way that it can be done is along the withdrawal direction; therefore complex parts with shape changes are possible.

There is also another type of braid the so-called tubular braid, which is a derivation of the flat one but what makes them different, is the fact that they are constructed around a circle, giving

them the option of creating a kind of a cover for this circular shape just like the case of the normal ropes.

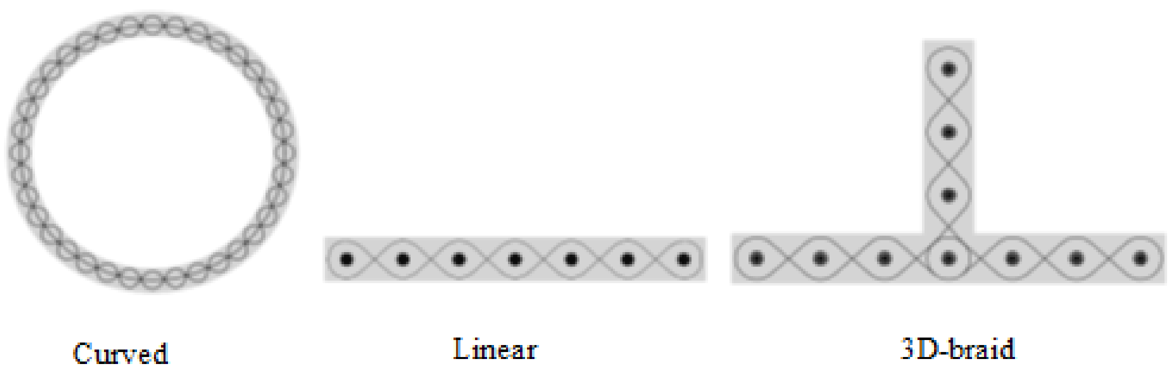


Figure 2.3 Curved-, Linear- and 3D-Braid [LAO11]

In order to generate an even assembly, it is important to maintain a constant tension on all the yarns involved in the production. There are many different ways to do it, depending on the type of setup employed for the braiding process; it can be achieved in manual braiding by simply attaching a constant weight to the yarn ends. This will ensure that the final product will have the desired quantity of material from each yarn and not a random distribution which can lead to mistakes in the mechanical characteristics of the product.

2.1.1 Conventional braiding machine and its roots

As explained before, braiding is an ancient technology developed for bringing different flexible materials together in order to obtain a thicker and stronger one. It has been used in a wide range of areas, ranging from medical industry to normal products like ropes, cables, laces and large scales such as tubes used in the oilfield sector, by following the same principle of interlacing yarns in a defined braiding angle "α" according to the function that the final product is intended for. Figure 2.4 gives an example of the mentioned angle on a braid which in order to be able to consider the product a braid has to be between 1° and 89° even though it is usually in the range of 30° to 80°. This braiding angle is the most important geometrical parameter of braided structures.

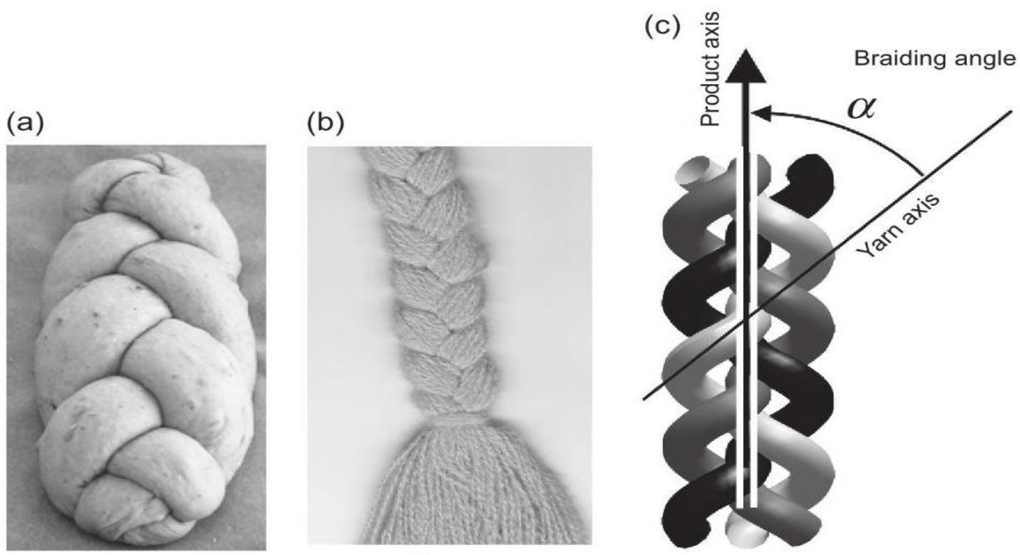


Figure 2.4: Braided cake (a), lace (b) and idealized representation (c). [KYOY15]

All braided products are manufactured in the same way of interlacing yarns at a given angle to the main product axis. Derived from the simplicity of the process, it can be noticed that this procedure can be done easily by hand just by following the steps clearly explained in figure 2.5 where the first one is to interlace the left two yarns followed by interlacing the right two yarns. It can also be extended to a bigger number of yarns just by being careful to keep the order of the overlapping. The final product is a flat cross-sectioned braid, also called flat braid.

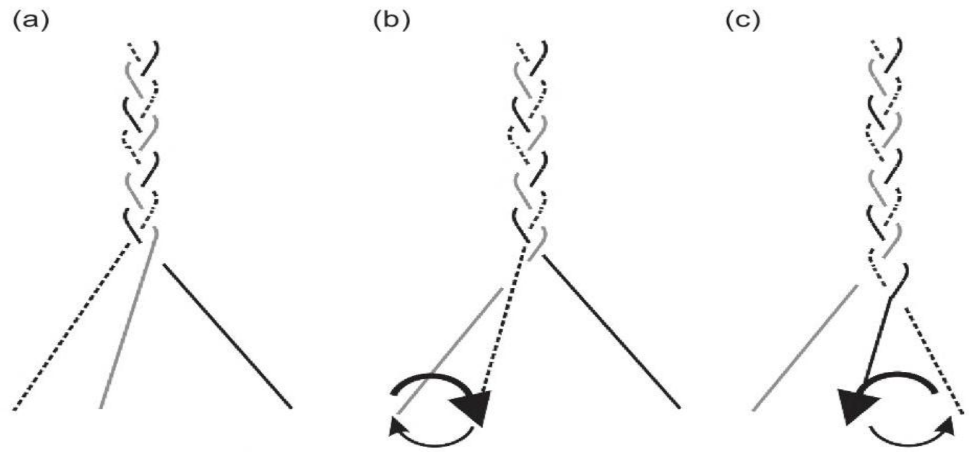


Figure 2.5: Principle of hand braiding [KYOY15]

The braiding machines were developed by following that principle of interlacing threads, they consist of a set of carriers attached to an epicyclical movement mechanism composed of a planetary gear train. Thus providing motion to the carriers with the aid of a motor, the threads can be constructed. As shown on figure 2.6.

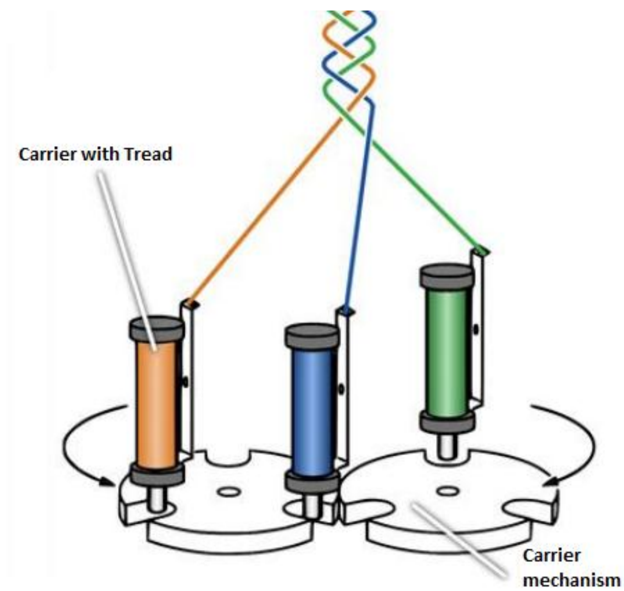


Figure 2.6 Braiding mechanism example [IHPH14]

In the illustration the orange carrier arrives to the center, then it travels to the next horned gear, and then held the interference of the green and orange threads through the rotation around the right impeller; however, if the color, amount and turn direction of the machine are changed, a different pattern of thread will emerge, giving the possibility of fabricating different kinds of threads by varying those parameters. As shown in figure 2.1 for the characteristic plaits crossing at the web edges and diagonal orientation of the fibers is also evident here on a smaller scale.

On any given braiding machine the main principle of operation is to move the carriers in two epicyclical movements, one clock wise and the other anti-clock wise giving the possibility of making a braid with the given threads. This combination of contrary movements as can be seen in figure 2.7 leads to a braid by interlacing the yarns.

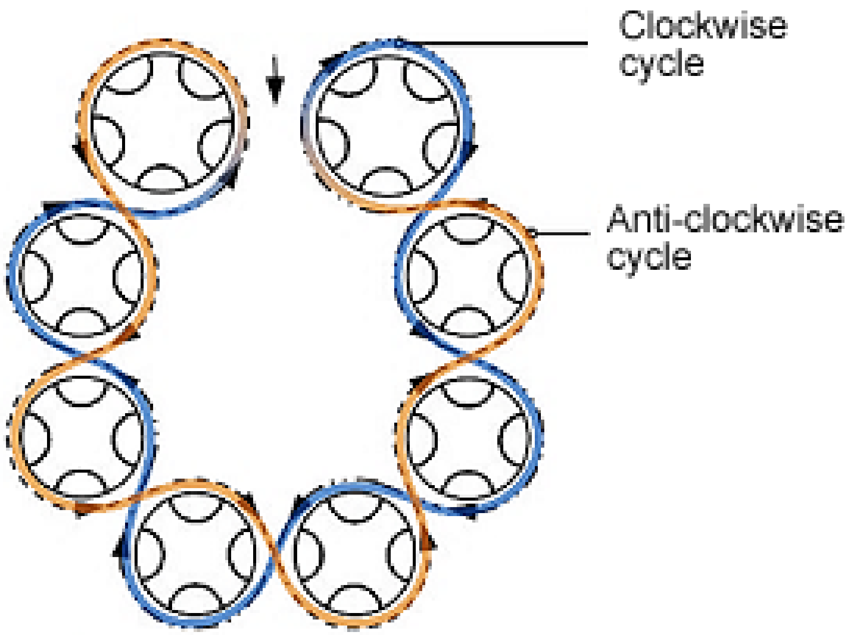


Figure 2.7 Thread movement description [IHPH14]

Also providing the same tension to each yarn during a braiding process becomes as important as the correct interlacing of the threads in order to obtain an evenly produced braid. This task was solved by using weights attached to the ends of the yarns. "*Then that technology was replaced with the use of wooden carriers, which were able to maintain the yarn tension and also to hold extra yarn wound around it. "*[KYOY15]

For braiding machines it was not possible to fulfill that task with such carriers mainly because of the varying distance between carriers and braiding points along the process. The solution to this problem came by using carriers with a lever which can move up and down in order to compensate the need of increasing or reducing the tension resulting from varying the distance to the braiding point. These works by either pull the thread into the compensation area, or release it when is needed. An example of the modern carriers normally used in braiding machines can be seen in figure 2.8, where such the lever is used.

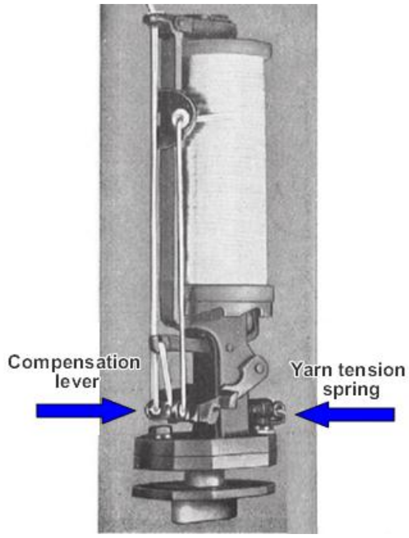


Figure 2.8 Industrial Carriers for textile yarns. [KYOY15]

Another aspect of the braiding machines is the employment of horn gears that convey the carriers on the desired track during the he process. Each horn gear has normally 4 slots where the carriers can be placed in, however, only in two positions a carrier can be inserted, those are referred as full positions whereas the other two have to be free (empty positions) in order to be able to receive another carrier from the neighboring horn gears.

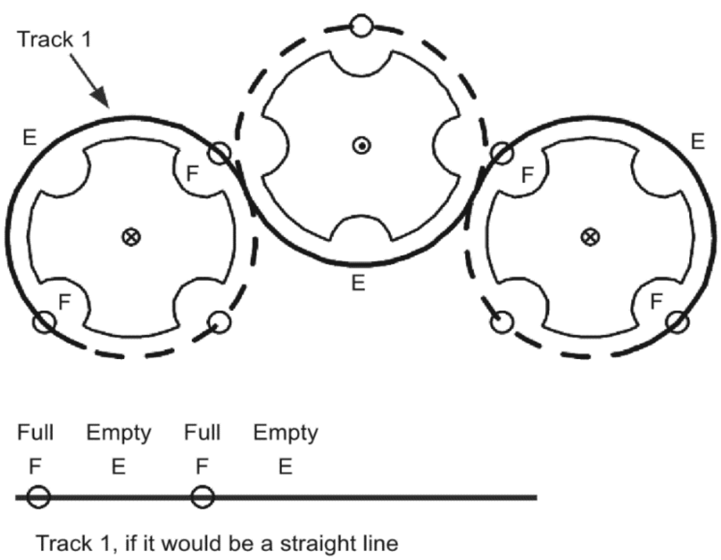


Figure 2.9 Track notation for Horn gears [KYOY15]

The disposition of the carriers among the horn gears is notated for every track in a way that the full (F) and empty (E) positions can be noticed and so an idea of the braiding pattern can be figured out. An example of this type of nomenclature is given in figure 2.8 where “1 Full – 1 Empty” is written shortly by 1F 1E.

With the proper arrangement of the bobbins there is the possibility to generate braids with color patterns for specific applications like shoe laces, decorative textiles, etc. For getting the desired pattern it becomes indispensable to specify the organization of the threads in addition to the previously explained disposition of the carriers in order to ensure that the outcome is precisely as designed.

Such personalized braids have been made since the beginning of this technology by just organizing the bobbins before the braiding process takes place making the production in one hand flexible due to the possibility to personalize the final products but in the other hand slow and costly because of the need to stop the production for setting the carriers in the proper arrangement, task that is normally performed by operators; therefore, this leaves room for innovation in terms of production technology and automation.

Contrary to the traditional braiding technology, the industry 4.0 is a recently developed production concept which is only around four years old. Nevertheless, theories and visions are already united on the future of industrial production under this term. In addition, the industry 4.0 represents a key project in the High-Tech Strategy 2020 of the German Federal Government. Figure 2.10 gives an overview of the wealth generated in billion USD around the world on the previous generations and the forecast for this fourth one, giving a clear idea of the importance that this concept will obtain in the upcoming future.

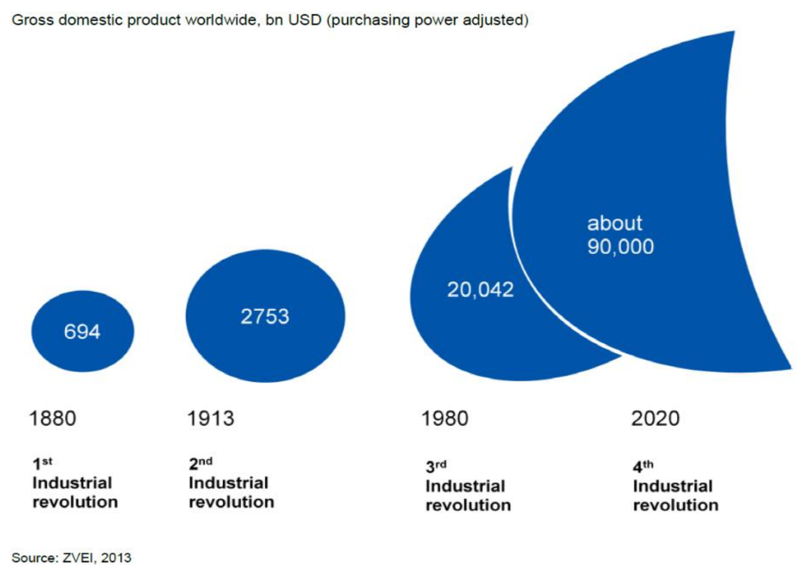


Figure 2.10 Development of economic output since first industrial revolution [HEN14b]

According to Roland Berger: *"The Industry plays a central role in the economy of the European Union, accounting for 15% of value added (compared to 12% in the US). It serves as a key driver of research, innovation, productivity, job creation and exports for the EU. Including its effect on services, industry could be considered the Social and Economic Engine of Europe*". [BERO14] This statement enclosures the need of keep developing ways for things produced uninterruptedly due to the new demands of the market that keeps changing every single day demanding faster and more flexible procedures.

The macroeconomic objective is to strengthen the German industry to keep being one of the leading suppliers for technologies in the near future and the goal from a technical perspective is the creation of smart factories where the networking of all production components leads to an increment of the efficiency and virtually autonomous manufacturing processes

The name "Industry 4.0" (also known as integrated industry) is the concise notation for the fourth industrial revolution. In this, information technology and modern electrical control systems are programmed and thus the automation of production is promoted. With the passage of time while the complexity of the production processes steadily increased. Fig 2.11 shows the four stages of industrial development in the last centuries with the main focus of each one of the generations highlighted.

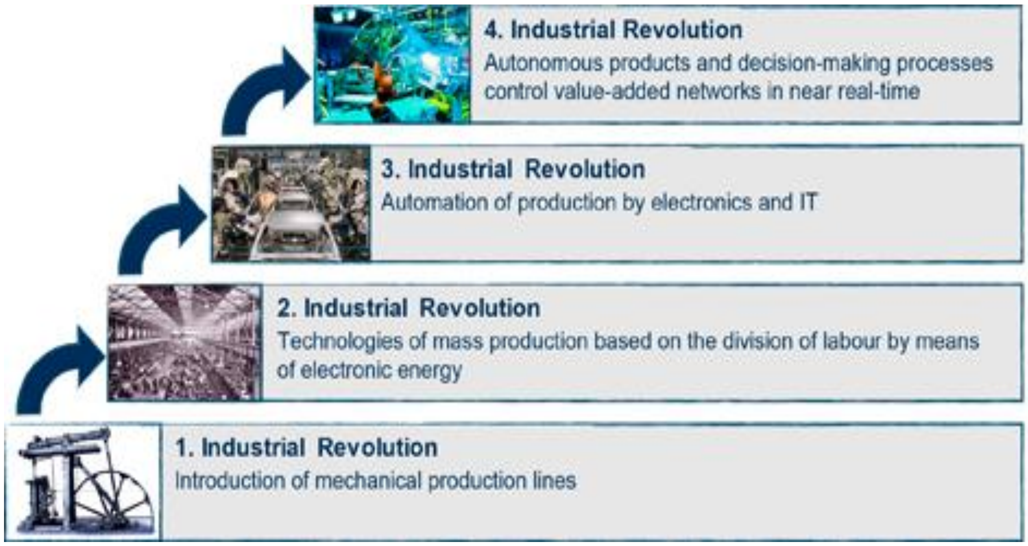


Figure 2.11 Stages of Industrial Revolution [IHPH14]

One important characteristic of the Industry 4.0 according to the committee workgroup industry 4.0 is "*the transformation of all machines, storage systems and resources in production to interlinked cyber-physical systems (CPS)* "[KWH13]. This CPS is, according to Geisberger et al. "*... Characterized by a combination of real (physical) objects and processes with information processing (virtual) objects and processes through open, partly global, anytime interconnected information networks"* [GB12].

Then according to this design paradigm, a new factory type has to be implemented, this is known as the "Smart Factory" which needs this advantages to enhance production flexibility and individualization of products. This new type of factory needs to adapt its production to fast changing costumers' orders while maintaining their efficiency.

Full automation emerges as good solution for reaching high production ratios by increasing the output numbers and reducing the employment of human resources and working time. Leading to economic efficiency but scarifying production flexibility which as explained before is highly demanded by today's industry because of the increasingly short product life and the necessity of developing and launching new products to the market as fast as possible.

Many setups have been developed in order to get closer to the desired productivity and reduce the sacrifice of flexibility i.e. flexible manufacturing cells, flexible manufacturing systems, flexible transfer lines, etc. But their main disadvantage is the lack of self-optimizing ability and leads to the production of low amounts.

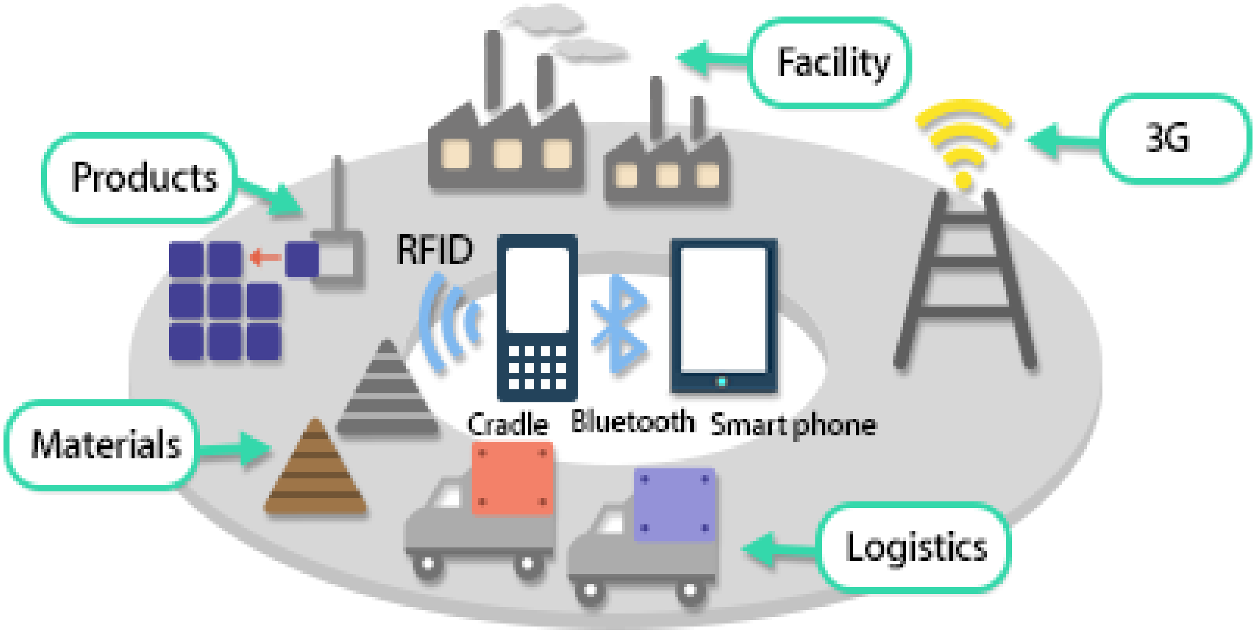


Figure 2.12: An overview of the concept of smart factories [WWW02]

Self-optimizing setups are then requested in order to improve efficiency, making necessary a complete understanding and control of the process flow by the system itself. Task for which becomes necessary to be able to know at any point of the production the status of every involved element in a way that any needed change, adaption or maintenance can take place as fast as possible. With this requirements the machines and products have to be interconnected in a higher level in a way that it is possible to know the status of each one of the components i.e. workstations, robots, assembly stations, products, etc. So the adaptions of either the tools or the products can take place in an automatic way according to the orders without the need of human intervention. The following Figure 2.12 gives an overview of the concept of a smart machine.

Inside the smart factory, as actors of this, several devices that make possible to automate process are given, such as embedded IC's, microcontrollers, PLC's and industrial PC's. Thought this project, several alternatives for the automation tasks will be compared, since the computing power needed can be provided from a wide range of devices and also for the instrumentation, since there exist several third parties that offer ready to install sensors and actuators suitable for the task.

In addition to the instrumentation and control aspects of the project, the communications inside and outside the machine have an important role, since the selection of the correct standard and protocol for the connectivity of the machine can provide advantages for future requirements.

Therefore, the investigation of the different industrial communication standards that are implemented on the controller will be a major feature to consider in the choosing of it. In the world of automation there exist basically 5 levels of communication, Fig 2.11 shows in detail what is the application of those communication standards.

According to this chart and the requirements for the application, the OPC UA (OLE Process Control Universal Architecture) standard is one of the ones that provide communication outside the plant, embedded security and interconnectivity with other devices. This is a non-proprietary protocol allows the transfer of data on a client – server architecture between devices from different suppliers. In addition to this, the OPC foundation has among its members most of the automation device producers this generates a long time lifecycle expectancy.

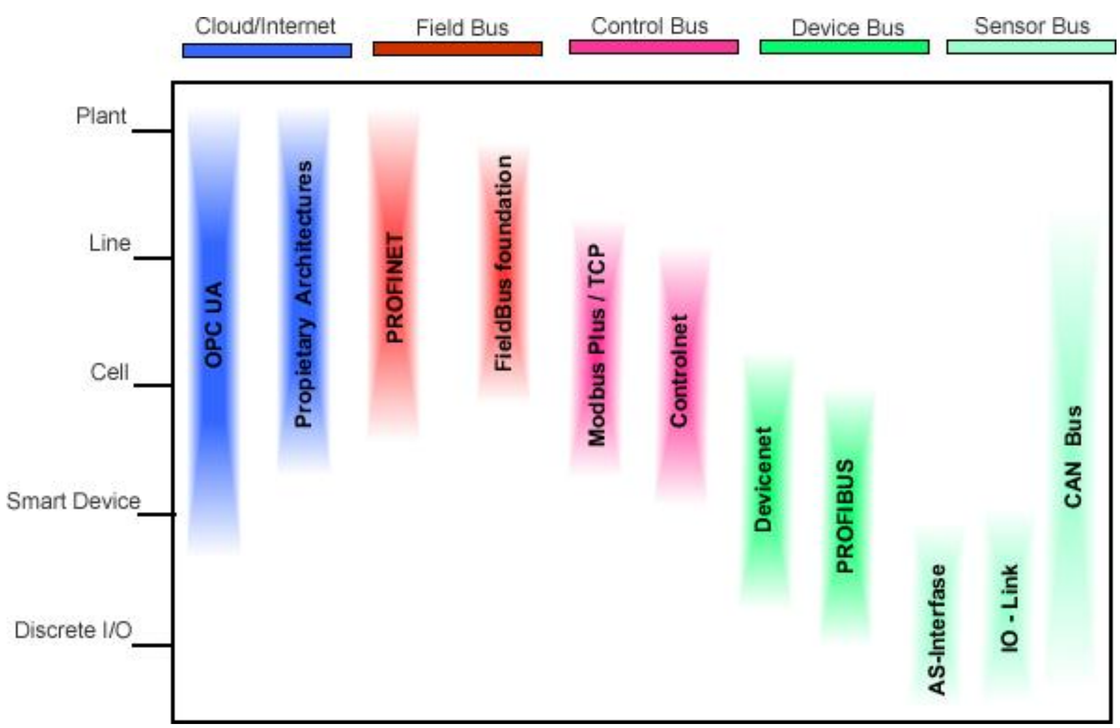


Figure 2.13 Industrial communication standards for automation

Also in the Fig 2.13 it can be seen that the smart devices also have a wide range of protocols can be used for interconnection with the whole process, such as IO-Link, CAN and AS-I communication protocols. Those protocols are mostly for sensor-controller communication; IO-Link is based on the IODD (Input/output device description) that allows the design of complex automation processes with multiple vendor devices by consolidating the IO descriptors with a standard XML file declaration.

Moreover the Controller Area Network Bus (CAN) is related to automotive sensor/actuator and controller communications, this standard has been designed for networked systems that can be applied in a wide range of applications, from small networks to full automated processes with high speed communication (up to 1Mbps) and lastly the AS-i interface that is oriented to distributed IO devices over a network with one central host using only 2 wire data interface.

As well as the control process for the machine, the industry 4.0 is oriented to the tracking of the product along its fabrication. Two technologies have been implemented to do it: Radio Frequency identification (RFID) and QR-Codes, the RFID is a technology based on the use of tags that have embedded information which can be manipulated in a contactless manner by the employment of radio frequency, while the QR-Codes are printed matrixes that assign and store data statically on a product therefore relying on the storage of data inside a central computer; then, selecting which one of these two technologies relies on the following characteristics inside the product.

1. Centralization on the tracking data for the product.
2. Amount of data needed to characterize the product along the process.
3. Cost – benefit balance.

As these points are remarked, it can be seen that the RFID tag is suitable for complex, hi-added value products, since the RFID technology enables the transfer of information in a very effective way, due to the reduced size of the tags, the amount of data that can be stored on them and the speed of the information flow between tags and antennas which can also be manipulated in terms of frequency. There is a wide range of tags offered recently which is divided in three main groups depending on the way they work. In the table 2.1 an overview with the main characteristics of the different types of tags present in the market is shown.

	Passive	Active	Semi-Passive
Power source	External (Electromagnetic field for data transfer needed)	Internal Battery	Internal battery for circuitry. External electromagnetic field for transmission
Range of transmission	Feet	Thousands of feet	Tens of feet
Size	Small	Larger	Large
Data Storage	Less	More	More
Cost	Less	More	More

Table 1 ***Presentation and Comparison of RFID tags [JOER08]***

With these components, the requirements for automate a braiding machine is possible, however not only the knowledge of the process and the automation devices will suffice to complete the project, also a detailed and structured construction method has to be implemented since the machine itself is a mechatronic device, the design has to be planned accordingly.

2.3 Construction Method

In a mechatronic system there is a combination of many different connected elements which are furthermore in separated engineering domains, leading with this to complex and heterogeneous systems that have to be controlled. In order to manage this kind of systems the methods of modeling and model analysis are very important. Complexity is intrinsic in a mechatronic system and leads to 4 main requirements according to the VDI 2206 [GAJÜ03]:

1. “Procedure with changing level of detail and abstraction”: Due to the cross-linkage between a many of elements, during the design phase a reciprocal action between the overall context and the detail focus is needed.
2. “Methods of structuring ”: The systems should be designed structurally in order to reduce the number of interactions to its minimum so as the complexity.
3. “Early modeling and simulation”: Interactions can only be anticipated with the aid of modeling and simulation.
4. “Integration and verification/validation of properties”: The resulted design has to be incorporated to an overall system and to be checked continuously by means of the specified solution concept and the requirements.

These requirements lead to a model for the design and development of mechatronic systems with a specific procedure. It is described by two levels of design support: The Micro-Level and the Macro-Level.

2.3.1 Design Support on the Micro and Macro levels

The design process is divided in two levels; the first one is the micro-level, which focuses on the problem-solving process of the individual designer and the second level, the macro-level, where it is intended to support the design phases and corresponding product states.

The sequence for problem solving on the micro-level comprises 5 steps that are sequentially ordered and give a schematic support oriented to the problem solving of specific situations during the design of the new mechatronics systems. This is a proven "approach to the development and design of mechatronic systems and products" in accordance with the VDI guideline 2206, whose sequence is shown in Fig. 2.13.

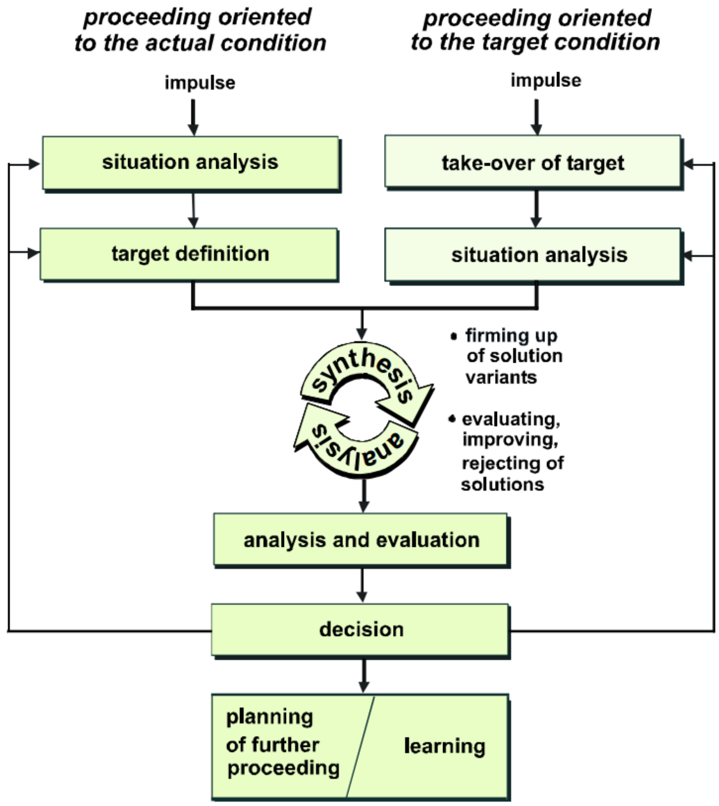


Figure 2.13: VDI-2206: Micro-level (problem solving) [GAJÜ03]

Then the approach VDI 2206 as explained before is divided in 5 steps:

Situation analysis and/or take-over of target: A cycle can start either with the situation analysis, where the actual state of the system given is studied and the setting of the goals follows derived from the analysis or with the take-over of a target where a pre-set target is established and the situation is analyzed.

Analysis and synthesis: this step is intended to work as closed control loop, because first it is intended to find solutions to the problems but most of the times solution variants have to be found due to new aspects of the problem that might arrive after the first attempts to solve the problem.

Analysis and evaluation: The solution variants have to be evaluated on the basis of evaluation criteria defined accordingly to the target formulation. If a solution variant does not fulfill all the goals pretended for that particular problem, it becomes necessary to go back to previous phase of solution search and look for a different solution variant that fits better on the demands of the task.

Decision: It has to be found out if the process of the previous problem solution has achieved all the goals planned satisfactorily. In case it has not it is important to go back to the situation analysis and target formulation phase.

Planning of the further proceeding resp. learning: The further procedure leads to further sequences of problem solutions and thus to an efficient, situation-adapted process. The resulting processes should be analyzed analytically, with the understanding of positive and negative results on the procedures; experience for upcoming designs can be achieved. By helping with this the improvement of future design processes systematically.

Once the micro-level design is completed, the macro level planning and design of the solution can be started, in this level, “The V-shaped model is well-established in the domain of software engineering” [GAJÜ03]. Three main points make it very suitable for the development of mechatronic systems:

1. The v-shaped model shows a downwards approach for the system design which is also subdivided into sub-functions, as well as an upwards one for the system integration part where all the results are integrated in the overall system. Both approaches are given in an obvious way.
2. It permits to highlight the necessity of continuous validation/verification between the requirements/goals on the left side of the model and the actual system status on the other hand side.
3. It has been already proven by the industry in context of mechatronics, giving with this more acceptances to the model.

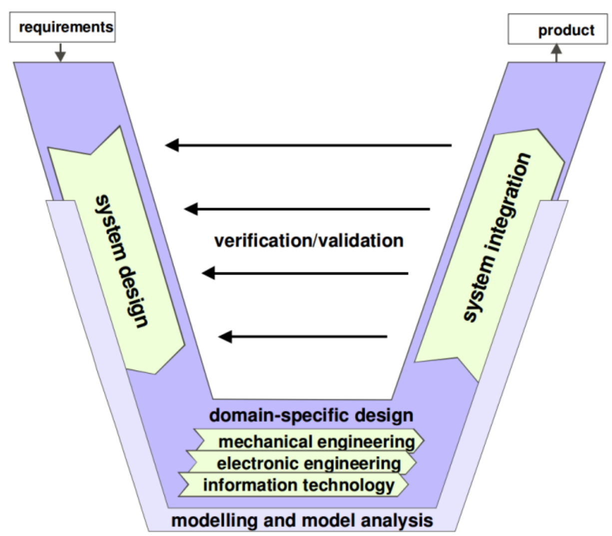


Figure 2.14: V-shaped model for the design of a mechatronic system (macro level) [GAJÜ03]

Consequently the V-shaped model has been chosen and adapted to the mechatronics needs. It clearly describes the steps to design a system accordingly to the requirements of the task involved. An example of the schematic model is shown in Figure 2.14.

As it can be seen on the previous figure, this model is divided in steps and areas of domain-specific design and last but not least a feedback that validates what has been developed in comparison with the design which is derived from the requirements of the task.

Requirements: The first step of this model where the task is defined and clearly described with the help of the requirements needed which will help afterwards to evaluate the outcome at the end of the process.

System design: At this point the object is defined in a cross-domain solution concept that will give an overview of the characteristics of the system to develop. It involves all the different domains presented in the project in a common language with the aim of making it understandable from any point of view. This description will afterwards be divided to its corresponding domain e.g. Mechanical engineering, electronic engineering, information technology, etc.

Domain-specific design: The concept previously defined by the involved domains is now divided and deeply analyzed separately in concern of each area. The singular calculations and designs take place at this point.

System integration: Each outcome from the singular domains is now integrated to an overall system with the purpose of evaluating the interrelations among them.

Verification/Validation: It is important to continuously trace the development of the system and compare it with the concept previously defined in order to be able to identify weak points in an early stage of the process.

Modeling and model analysis: All stages are limited by the modeling and analysis of the conception with the aid of computer-aided tools for simulation.

Product: This is the outcome obtained from the whole design procedure. It doesn’t have to be precisely the finished product, sometimes it can be obtained in different maturity levels e.g. concept model, functional model, prototype, etc.

The presented V-shaped model on the macro level represents only a generic model that works as a guide for mechatronic developments. This means that for complex products it can take more than one macro-cycle. Through the first cycle, for example, a working set-up can be achieved which fulfills the preset working requirements but doesn’t look like the final version of the product, so it is only wanted to be worked out in detail within a second cycle in order to create prototypes. At that point the main phases of the model are not yet specified in detail, it is normally done by the team. Especially design processes can be described in terms of partly predefined procedures modules, which can be organized in data bases. Figure 2.15 gives an overview of how are normally the procedures subdivided.

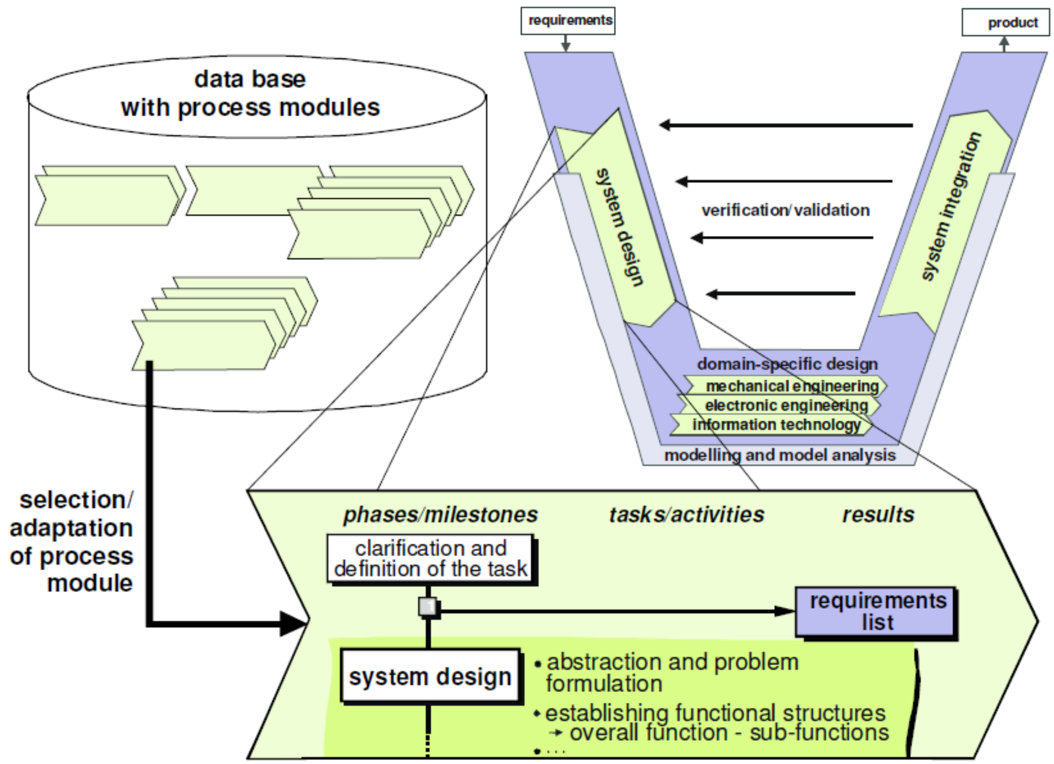


Figure 2.15: Configuration of process modules for individual operation steps [GAJÜ03]

The designer or the responsible of any particular task can choose the appropriate path to meet his requirements; if necessary he can adapt or change them. Figure 2.15 shows an example of this procedure with the module “system design”.

In order to illustrate the central task of this work it is vital to give an overview of the environment it was developed in as well as the direction it was intended to follow when the idea was established.

The company Gemini Business Solutions GmbH, Düsseldorf, offers state of the art services and products for the Industry 4.0, where most of the projects are intended for the textile industry. One of these projects is the "Customer-oriented textile manufacturing" which is graphically shown in figure 3.1.

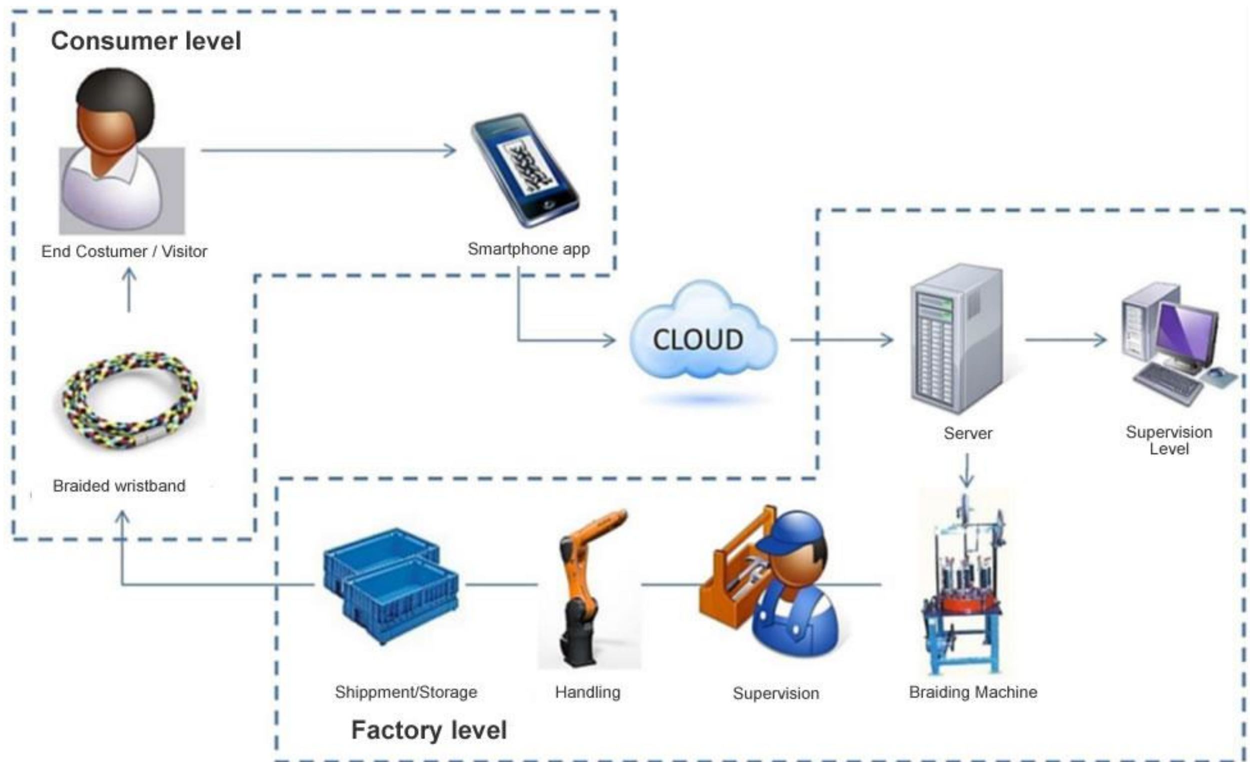


Figure 3.1: Concept customized textile production [Gem13]

This concept is planned to be presented in November at the world-largest textile exhibition "ITMA 2015" in Milan. As an exhibition item, this will be the ideal opportunity to present the visitors with the potentials of Industry 4.0, explained in chapter 2.2, by offering an illustrative demonstration where the interested parties will have the occasion to get directly involved. In practical terms, the goal is to stretch the repercussion a vertical braiding machine for circular braids could have in the manufacturing industry by giving the potential clients the opportunity to see how a braided bracelet can be produced individually in a fully automated way. The production of these bracelets is used here only a "proof of concept" because it results very practical for exhibition purposes to produce small size items that require short time of production, yet it is intended to show that the automation and individualization of braiding processes are possible and can be implemented in many different sectors such as the medical, automotive, etc.

Visitors will be able to take part on the process with the aid of an app, specifically developed for this purpose to be used on either a smartphone or a tablet on which they get to choose from a range of mesh patterns and colors according to their liking and then this order will then be transmitted wirelessly to the machine control following the process shown on figure 3.1. The braiding machine, a model of the company Steeger Flechtmaschinen GmbH & Co. KG with a maximum loading capacity of 16 thread carriers in stock and up to eight 80mm impellers, is automatically set with the required plaiting and then the automated production process initiates. After this production process is completed the visitors then receive custom made bracelets to take away as a souvenir of this stand and more importantly it will serve as an evidence of the production concepts of the company Gemini and the significant impact this technological advances could have in countless industries.

The implementation of this project can be roughly divided into three areas. First, the software configuration of the braiding pattern must be implemented in a mobile app (see. "Consumer level" in Fig. 3.1), which is then transmitted as a compatible data to the machine control. The second area is the braiding process itself where (see. "Enterprise level" in Fig. 3.1), the mechanical concerns take place. Finally, the control stage, where the diverse sensors and actuators such as motors, grippers, antennas as well as the read out sensors values on the machine are to be controlled based on the pre-established specifications without any additional external intervention.

The key objectives of the present thesis are the design, development and documentation of an automated thread changer setup of an industrial braiding machine. This includes the implementation of the mechanical part of the project for the ITMA 2015 from the conception of the idea to the elaboration and assembly of all the required components to ensure its proper functionality. Moreover, it aims to accelerate the manufacturing process swapping from a dated manual labor to a more robust and efficient way. Therefore it becomes necessary to break up the main task into different disciplines and each of them into single subtasks till the point where every one of them can be evaluated in terms of importance and work on them individually leaving room for their future incorporation in the final network.

Two main groups have been identified from the requirements of the project, which initially served as sub-headings of the design procedure. These are the material exchange and the material replenishment in order to allow a continuous production. Company's specifications were established beforehand the beginning of this work and read as follows: "*The braiding machine is designed to be equipped with a maximum of eight carriers, all of which can be loaded with either the same thread color for monochromatic patterns or up to 3 different colors for polychromatic* *and individualized patterns*". The result of these specifications leads to a system of 24 usable tools. For the material exchange, the most important requirement is to guarantee the quality of the final braids as if they were produced manually. A full automation of the process is desirable. Additional required procedures such as, separation of the wasted material, the handling of both yarn ends and the interlacing of the raw material result too complex to be additionally elaborated within the scope of this thesis.

Geometry and ergonomics are also essential features of this system. The space should be kept as compact as possible, in order to be able to continue using the existing structure of the braiding on a working surface of 1000 mm width and 700 mm depth. It is also important to bear in mind the long-term idea of being able to adapt this concept to other braiding machines and commercialize it maintaining the idea of a compact system. In terms of ergonomics, an easy accessibility must be guaranteed, so the material reservoir can be easily replenished, ideally in parallel to the braiding process. About the systems kinematics, it is required that any collision possibility among additional modules should be avoided with the existing actors and these modules may only interfere with the process during standstill of the braider into its working space. Another example of the iterative nature of requirements elicitation is the feature of cost; aspect that was brought to the table by the client, who had not set anything concrete before the main characteristics were processed. From that point a ceiling of €10,000 applies for this work. However, the associated materials and manufacturing costs, should not compromise the quality of the final products by aiming to a maximum cost reduction.

The product life cycle of the apparatus was analyzed by using the scenario technique, which consists precisely in the application of concrete scenarios that are likely to happen. Tab. 3.1 shows a selection of the scenarios that were took under consideration, and the courses of actions associated with each of them. The respective scenarios are accompanied by concrete boundary conditions, from which new requirements of the product to be developed can be derived. The most obvious scenario is the upcoming fair for which this apparatus was designed. However, potential future scenarios such as the use for the manufacture of customized medical technology braids or the behavior of the machine in the long-term operation were examined.

Scenario	Occurring boundary condition	Resulting requirement
Exhibition at a trade fair	• Many prospective customers /crowds • Electricity is the most universal / easiest available energy source	• Safety: strict spatial separation between man and machine in order to avoid the risk of injury by third parties. Design / Ergonomics: visually appealing, professional appearance as a marketing strategy. • Energy: electrically operated actuators are preferable
Production of medical braids	A contamination-free environment is required.	Materials: lubricants and possible contaminants should be avoided. • Also derived from these materials: components that move relative to each other / rub, should have good sliding properties
The machine serial production	Non own production capability / workshop available, restriction on assembling the components	Manufacturing: production-oriented design and design-to-install them as possible components
Long-term operation	Not exclude wear and tear in the long term	Materials: Select a wear-resistant materials. Maintenance: interpret resulting wear parts exchangeable good and reasonably priced.

Table 2: Partial results of the scenario technique for requirements elicitation

3.1 Project Justification

After the explanation of the project seen from the customer point of view, where the goals and requirements of the goal idea are clearly defined, it is important to analyze as well the state of the art of the involved technologies, which has been presented on the previous chapter, and from that point the evaluation of the scope of the idea in the environment where it is planned to be introduced should take place and thus have the following characteristics:

- Fully automated operation.
- Network communication and distributed control interface
- Predictive maintenance purpose data recollection.
- User oriented easy to use interface
- Flexibility and reusability for commissioning in diverse areas.

Because of this a braiding machine that has none of those capabilities is the suitable subject for the development of a system that allows to be integrated on old braiding machines and get the advantages of not only a fully automated system but also a structure that can be monitored and controlled remotely, plus the possibility to make it highly interactive between all the parties involved in a production process.

Then the time saving and the efficiency of the whole process can be improved, by having reliable data on the amount, type and position of the carriers as well as the speed of the braiding subsystem.

Another investigation topic rises from the fact that, once the operation of the braiding machine is automated, then the optimization of the sequence of the carrier change can be researched in order to assure that is made on a minimal set of movements, or a minimal carrier change time is achieved.

So, the automation of the system can be achieved by developing the following systems:

- Mechanical design of a gripper system that allows the manipulation of the carriers.
- The design and development of a rotational system that allows handle the spare carriers for change.
- An identification system that allows controlling the specific carriers in order to get the proper carrier each time.
- A user interface that allows choosing which pattern has to be introduced in the machine.

Once a functional prototype is developed, due to the networking and interaction capabilities previously explained, the next step to think about is the creation of a network of machines that can provide more flexibility to a production system without sacrificing or in the best scenario also improving the processing times plus the possibility to increase the quality of the processes and therefore products because of the opportunity to monitor almost in real time the situation of every tool employed, allowing with this preventive maintenance for the machine tools or in case of accidents faster and more accurate responses.

Chapter IV: Development and selection of the solution

The methodological approach to the development of principles and solutions has already been set out in section 2.3 then is necessary to look for solution variants, evaluate and compare them in order to find the best feasible solution. In this chapter the results of the second phase of the VDI 2206 methodology, the analysis and synthesis, are presented.

4.1 Determination of the functional structure

Along the last chapter 3 the present situation was identified and the wanted goals were settled according to the possible scope of the combination of those two different technologies. The next step in the development is the creation of solution variants to be evaluated.

As a basis for the design of the following steps a black-box concept is presented in figure 4.1 where the requirements of the wanted solution are clearly and synthetically visible in order to be able to understand the input and output variables. This diagram helps to decompose the main goal in smaller targets within different disciplines that have to be achieved in order to accomplish a well-functioning product.

Figure 4.1: Product function structure in a black-box principle.

It can be observed that the main input variables are: the desired thread from the stock that has to be mounted for the following procedure and the replaceable braiding material which is already mounted on the machine and has to be removed. Also the main output variables are given which are the quantities of the used threads that had been incorporated to the stock again.

Based on the known input and output variables, the detailed functional structure can be then designed by downgrading each subset of requirements into the needed steps to obtain it and then joining them together into a functional set-up. The following figure 4.2 gives an overview of smaller and single tasks which depend on each other and are necessary for achieving the wanted goals.

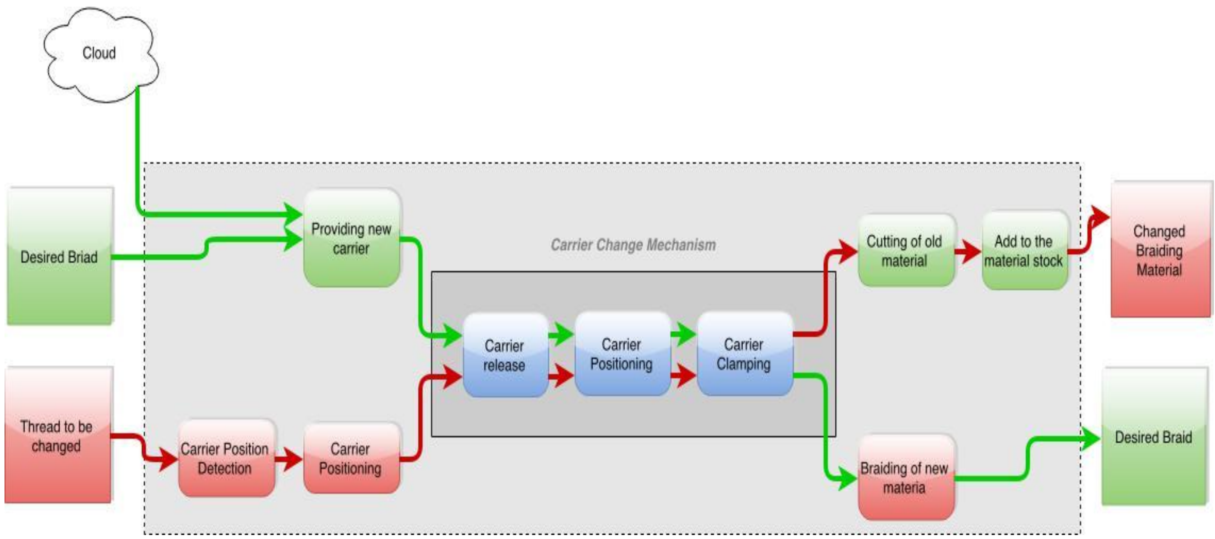


Figure 4.2: Detailed functional structure scheme of the upgraded braiding machine

In the lower part of figure 4.2 the braiding machine is presented as an input variable represented by the braiding thread to be replaced whose procedure to be changed can be followed through the path with the red arrows, which starts with the position detection of the desired carrier in order to move the machine to the right spot where the carrier can be removed and thus later the positioning of a new carrier can take place in order to produce the wanted pattern. This last statement makes noticeable the fact that the detection of the carrier position, as well as the positioning of it, is the first crucial fact for ensuring the proper functionality of the complete system. At the same time in a parallel function an order can be set with the pattern wanted which therefore will include a set of carriers that have to be placed on the machine in a particular configuration in order to produce the order. The exchange process itself consists of three sub-functions: first the carriers are taken from the braiding machine and disposed in to the magazine and for the exchange, afterwards both bobbins are guided to their new place and positioned and finally both bobbins are attached to their new locations before starting the braiding procedure. The way all this changes will take place according to the algorithm derived from the order placed by the customer itself is defined in this chapter after comparing the solutions variants found through research, so a final set-up will be presented at the end of the chapter.

4.2 Determination and systematic development of partial solutions

Within the framework for this thesis all three presented methods were used to find partial solutions for singular problematics. However, the way a classical literature and patent searches was proved as less productive, maybe because of the fact that one of the most important problems to be solved in this project, the automatic change of the bobbins on a braiding machine, is unexplored or at least not documented so far. Some similar patented systems were found but they focus merely on the automatic and continuous bobbin changing and not precisely on the flexibility of changing the needed parts for the wanted procedures. Some suggestions for the supply of the material and the material changing were found in the area of automated tool changing methods on machine tools such as CNC milling, which will be applicable to some of the present problems in a modified way.

4.2.1 Detailed consideration of the partial solutions

It is important to remark that not all the found solutions are going to be shown and explained. Only the solutions variants that at the particular moment were found worth to be developed and actually demanded some extra analysis are going to be presented in the following parts of this work due to the importance they presented during the development of this project.

On the following page, the table 4.1 some of the technologies for specific problems that were taken into account are shown, followed by a detailed explanation in order to give an overview of the way they were analyzed and either accepted or rejected respectively.

Also, the solution variants presented do not include the control and electronic parts of the project due to the way it was planned. The first focus point was to find a viable kinematic solution in terms of functionality and costs. Nevertheless, it doesn’t mean that the possibility to interconnect the elements was not beard on mind during the evaluation and selection processes.

Automation of the changing carriers procedure in a brading machine

Carrier position detection	Carrier positioning	Carrier deploy from stock	Transportation of the carrier	Carrier reléase/fix
•Number of revolutions •Camera visión •RFID system •Barcode reader •Mechanical button •Photocell	•Manual •Stepper motor at handrail •Encoder •Servomotor •Engaging drive •Braking with pin	•Rounded stock •Rounded stock (for each Carrier) •Rigid stock trays •Movable storage compartments •XYZ Gripper arm •Chain magazines •Conveyor belt	•Rotational doublé gripper •Linera slide-out magazine •Robotic gripper arm	•Self locking terminals •Locking pins •Embracing pins •Swallowtail •Electro magnets •Slide plus snapper in foot

Table 4.1: Morphological box for the partial solutions

4.2.1.1 Carrier position detection

The first part of the system to be determined had to be the identification of the position of the carrier that is pretended to be changed afterwards due to the pattern wanted in order to let the following procedures i.e. gripping, removing, positioning, etc. take place as planned. In the following table 4.2 a brief comparison of the solution variants for this isolated problematic is shown.

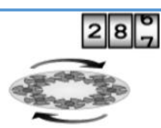
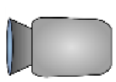
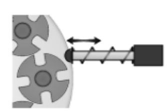
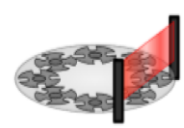
Function	1	2	3	4	5	6
Carrier position detection	 Number of Revolutions	 Camera Visión	 RFID systems	Barcode reader	 Mechanical button	 Photocell

Table 3 **Carrier position detection solution variants**

The first solution shown on the table 4.1 for the carrier position detection is what was called the Number of revolutions because the position of the carrier can be determined by the number of revolutions done by the braiding machine and thus the distance traveled by each single carrier can be calculated. In this case, however, an additional encoder to the currently existing asynchronous motor must be mounted in order to measure the number of revolutions at all. The disadvantage here is that it is only possible to rely on the signals of this sensor and minimal errors during the sensors teaching would be adding up. The information that is mounted i.e. color at each position, length of the threads, etc. could only be managed by a well maintained database in which every change of carriers would have to be recorded continuously, rather than be determined by a direct verification of the carrier. That also demands the usage of a lot of memory for this single step, which has to be added to the memory demanded by the other processes which can result to be a big quantity of memory needed and can have severe repercussions on the processing speed of the system.

Another solution proposed is the use of **Camera vision,** where a camera with a proper image processing algorithm is planned to be fixed on the machine which will be able to detect the carriers and identify them by colors. Once the carrier is identified, a simple function related to the cameras position can provide the carriers position to the system. The main disadvantage found was the possibility of errors during the recognition of the threads derived from a bad lighting or also the confusion between carriers of the same color.

The following two solutions are pretty similar to each other because of the placement of information on the carriers in one hand and on the other hand the employment of a system able to read that information. In the first of these two technologies, the “RFID” is done by electromagnetic field produced by a reading device, causing a within range transponder to transmit a response signal with the information. The information can be managed as wanted in this kind of tags, so it has the advantage of being able to be read and written during the process. The other technology shown is the barcode reading, which can also have up to 32kb [WWW04] of stored data, this one has the disadvantage of not being able to rewrite information on the labels due to the printed form on which they are handled locally.

The Mechanical pushbutton and the Photocell sensor are well suited to determine the position of the moving carriers in a very precise way. However, in addition, an identification of the carrier and the thread color are only possible with the aid of additional solutions.

4.2.1.2 Carrier positioning

Once the proper carrier has been identified for the upcoming exchange, its exact positioning for the exchange is required. So the next solution to be found is the placing of the carriers in to the exact spot where it can be exchanged and for this the following table 4.3 gives an overview of the analyzed variants.

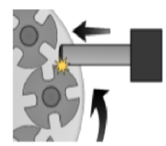
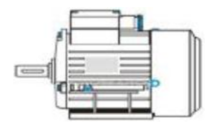
Function	1	2	3	4	5
Carrier positioning					
	Manual	Stepper motor	Encoder	Mechanical brake	Servomotor

***Table 4*: Carrier positioning solution variants**

The "Manual positioning on the trail" should work and could be possible but due to the fully automated process wanted, it doesn't fit with the requirements and makes it unelectable for this partial solution.

As the next solution a stepper motor is proposed to be set on the place of the handrail and encroached on the existing hub for connecting directly to the positioning of the carrier. Because of the given machine, this results to be easy to implement since the handrail is executed separately from the drive and thus it could be directly replaced. Current braiding technologies of leading manufacturers integrate the handrails into the drive motor, so the transferability of this solution for current machines becomes problematic. The variant of the mechanical brake can be accurate and also when blocking the machine, the friction clutch is spinning in view of the drastically increased load. When the outer pneumatic pin acts against a carrier base, an exact positioning of it will be obtained and can be hold for long periods allowing the changing procedure to take place until the pin is retracted back and frees the way of the machine. Nevertheless, this should not be done at full speed of the braiding machine. So the braiding speed has to be reduced, being this a procedural disadvantage.

Among the partial solutions for this particular part of the system still remain the subsequently mounted encoder and the complete replacement of the induction motor by a controllable servomotor. By the employment of the encoder, it is possible to know the number of revolutions done by the motor and with that data and some simple mathematical functions the exact location of every single element that is rotating with that movement at any given time. This technology combined with the existing induction motor and the friction clutch has unfortunately not worked properly in a practical test due to a presence of a variable and difficult to predict lag behavior when stopping. These mentioned problems wouldn't take place in the case of using the servomotor. This type of motors are considered as standard for such positioning tasks nowadays in the industry and are also being used in braiding machines. Even when it seems to be a costly solution, it seems to be the most promising solution from the technical point of view.

4.2.1.3 Carrier deploy from stock

After the not needed carriers are taken away from the machine, it is now necessary to introduce the new braiding elements into the system. The stored carriers have to be taken from the stock and deployed into the right braiding position in the machine. Many solution for storing and providing the carriers were taken into account but only those which resulted more relevant for analysis will be presented. The following table 4.4 shows the analyzed technologies that were taken into account for this task.

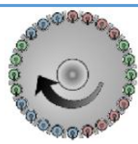
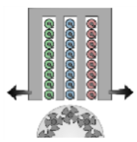
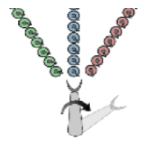
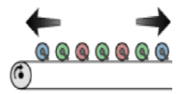
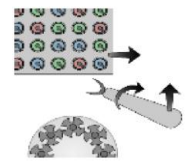
Function	1	2	3	4	5	6
Carrier deploy from stock	 Rounded stock	 Rounded stock for each carrier)	 Movable storage compartment	 Rigid stock tray	 Conveyor belt	 XYZ Gripper arm

***Table 5*: Carrier deploy from stock solution variants**

The first two proposed solutions involve the employment of a rounded stock for the carriers. In these variants the carriers will be placed in the circumference of a rotary ring and stored there till they are needed in the process so they can be rotationally moved to a pick-up position. The difference between them both, is that in the first variant the whole 24 planned carriers will be placed on a ring and by the employment of a controllable motor they will be located on the pick-up position when demanded, which result easy to control and so as effective, the disadvantage found in this variant is the lack of scalability in the number of carriers. The other similar solution works technically speaking faster because all different colors can be waiting in a pick-up position so the step of finding the proper carrier can be eliminated but as a disadvantage it demands the employment of other motors, extra controlling effort and more money so it was discarded.

The following two solutions show a strong commonality, both are based on stock trays. The solution 4 is moved linearly. Variant 3, however, relies on a completely rigid assembly. For each thread color a private compartment is provided, so that the colors have to be always associated with their subject. Therein the clapper is successively lined up and only the front clapper of each compartment can be removed. The clappers are urged by a spring toward the front so that the front receiving position is always stocked. This is a simple but solid technology that can be operated without actuators i.e. goods shelves of some supermarkets / drugstores, vending machines, thus it can move up for withdrawn products directly from the supply. A disadvantage of the solution 4 is that due to the rigid nature of the magazines there is not only one defined point for picking the carriers, a different movement should be planned for each option. Option 3 eliminates this drawback by all subjects juxtaposed are linearly as a unit and thus the tray currently required to be moved to the central receiving point. This active component, this solution is somewhat more complicated, but provides for the selection of the transport mechanism more flexibility.

A random stock principle would be possible with the use of a multi-axis robot arm (6), the entirely arbitrary remote clapper simply can pick out from the camp. For this purpose, a more complex management of individual storage spaces would be needed, but the main drawback is especially the high cost of such a robot arm point, which would exceed the fixed price part of this project.

The conveyor belt which is the solution variant 6 is an example of a classic application of a conveyor system. The question that arises here is about the issue of secure fixation of the carrier to the conveyor belt as well as the horizontal lying position, which makes also needed an additional change in position to the vertical.

4.2.1.4 Carrier Transportation

This part of the setup correspond to the way the carriers are going to be taken in and out of the braiding machine and so as in the magazine and the transportation to their destination according to the production algorithms. As long as this part of the solution depends directly on the previous and following steps, special care has to be taken in order to ensure the well-functioning of all of the parts when joining them together. In the following table 4.4 an scheme of the solution variants that where analyzed and compared at the final stage of this part of the project are presented and explained in the next table.

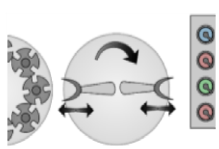
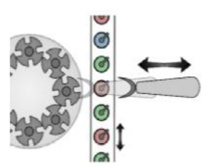
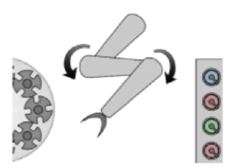
Function	1	2	3
Carrier Transportation	 Rotational double gripper	 Linear slide-out magazine	 Robotic gripper arm

Table 6: **Carrier transportation solution variants**

The first solution proposed in the table is the implementation of a rotating dual gripper, which can be found in principle in a similar form as the so-called pick-up tool changer on common machine tools. The movement here is performed by a rotating plate on which to opposite to each other grippers are mounted in order to be able to grab the tools from the machine and at the same time tools from the magazine so both grippers grab a tool at the same time then retrieve followed by the 180° rotation of the plate and the grippers move again to the grabbing position in order to be able to make the exchange of tools. As the taking off of the tool from the braiding machine and the picking of another tool from the magazine occurs simultaneously, this solutions represents a time saving variant for this task.

For the next solution a linear slide right in front of the magazine is proposed. For this variant the slide should be very close to the braiding process in such a way that the gripper can reach the two spaces, the magazine position space and the braiding machine for locating the carriers in and taking them out of the machine. For this solution it is necessary to leave free spaces on the slide at all times so the gripper can get in the machine by passing through the slide and grab a carrier from the machine to deploy it on the slide on its way back, then it should again go back to let the magazine move to the position of the following carrier that has to be set in the machine and the procedure is repeated once more but in reverse. Here the removal and mounting movements are separated as compared to the previous solution which doubles the required time for this. Anyway this variant is less complex to construct than the one with two grippers and also has the advantage of being possible to set the magazine closer to the braiding machine.

The last analyzed option was the implementation of a robotic arm, which is always fulfills these kind of complex movement tasks, but unfortunately it has a big disadvantage, the high cost of it. Being that the reason why it couldn't had been taken into account furthermore.

4.2.1.5 Carrier fix and release

According to the demand that no changes should be done to the basic components of the braiding machine such as: the impellers or the carrier feet, a solution is sought which allows an easy detaching and re-attaching of a carrier on its base.

The following solutions have in common that they have an intermediate element that is screwed to the base of the carriers and thus take over the task of fixing solution without additional adjustments to the existing components. In table 4.6, an overview of the variants that were taken into account is given where it can also be seen that the variants are either solved vertically by pressing the carriers down and attaching them by different means, or they are pulled laterally in a horizontal direction from the fixing mechanism and reassembled by a lateral slot. Most solutions with vertical mounting direction are the concerns in common that they need a strong locking in normal braiding processes by the largely upward-acting withdrawal forces of the threads, so that the connection cannot come loose by the forces of the current braiding movements.

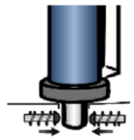
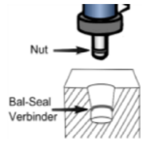
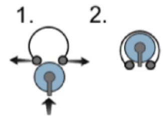
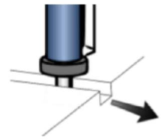
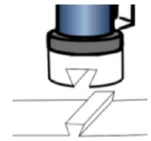
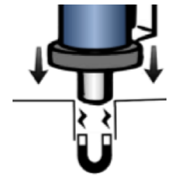
Function	1	2	3	4	5	6
Carrier release/fix	 Self-locking terminals	 Locking pins	 Embracing pins	 Exchange transfer orbit	 Swallow tails	 Electromagnets

Table 7: **Carrier release/fix solution variants**

This is exactly what occurs especially in the first solution, the self-locking clamps, negatively apparent. Here a pin is located below the clapper which is supposed to be inserted into an opening in the base, where it is laterally clamped by spring clips and fixes. A quite simple solution, but a deduction of carriers upward through the withdrawal forces of the yarn cannot be excluded.

This lack of lock is fixed by the lock with pins in solution 2. Here is a located pin below the clapper also introduced into the foot while going through this walk a pin which is guided through slots in the base when it is plugged in and then acts through a short rotational movement of the clapper of a secure locking against vertical slipping. Manually assembled this is an excellent solution, however, is by plugging the subsequent rotational movement so the automation results significantly more complex. In addition to the gripping function to accommodate and transport the clapper, the gripper can still make an additional rotational movement, not to the axle on which the gripper is mounted (which would still be realized), but about the axis of the clapper, that is located between the two jaws.

The third solution belongs to the group in which the bobbin is pushed horizontally onto the foot of the carrier. Here, the clapper or a pin located there below of sprung brackets should be enclosed in the foot and fixed there. These movable and spring-mounted clamps must of course be designed so stable that they have no signs of fatigue or loss of holding force even after prolonged use. At the same time an adequate assurance of the clapper to be given not only in the horizontal plane but also along the vertical should be ensured, this represents a perfectly workable solution.

The so-called "Bal Seal Canted Coil Springs" from the company Bal Seal Engineering Europe BV, Stuttgart, are the starting point of the solution 4. These coil springs are connected to form a ring, obliquely wound springs that exist in various versions for all sealing and connecting tasks (see. Fig. 4.8). Such a spring ring to be inserted into a hub under the clapper and so ensure the fixation when it is attached to a pin on the base of the carrier. The precise centering pin of the clapper would be set on the foot and the spring ring ensures a secure connection since it expands after being plugged in due to the engagement of the inserted pin with the groove (see. Schematic diagram in Fig. 4.3).

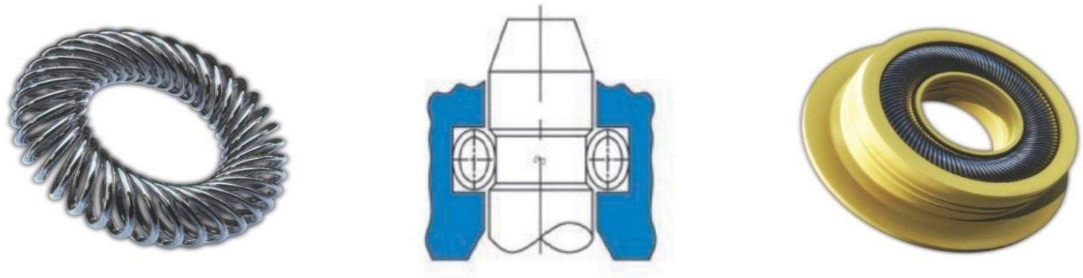


Figure 4.3: Bal Seal Connector [BAL13]

The same principle can be achieved by changing the means of the connecting force, instead of using a snapper for a positive connection, a magnetic force can also fulfill the positive connecting forces as the solution 6 suggests. The principle is the same as in the previous variable but here a set of connector components under the clapper and on the carrier base through the employment of embedded magnets allow the connection of them almost automatically as soon as the bobbin is placed just close enough to the foot. By elements such as a centrally located pins on the foot ensure simultaneous centering of the connection. Only the holding force of the magnets must be adequately dimensioned here in order to withstand the withdrawal of forces of the braiding machine at any time.

Last not least, a purely mechanical form-fitting groove connection is proposed as solution variant 5. Similar to a popular among carpenters in timber Schwal-benschwanz connection is a wedge-shaped spring on the foot. The clapper is pushed sideways with the matching V-shaped groove, ensuring with this that the vertically acting withdrawal forces are countered by the positive connection. This is a simple solution without additional moving parts and provides a degree of accurate positioning and a firm connection.

4.2.2 Controller system selection

After analyzing the solution variants the options, it was possible to think about the controlling systems that could fulfill the tasks and were also available on the market without overpassing the budget.

The controlling devices that were compared by means of the previously mentioned terms at the final stage were: Raspberry Pi, Siemens PLC and Arduino. The three devices can be seen on figure 4.4. It was well known from the very beginning that a PLC can easily fulfill all the requirements of the project in an industrially safe and standardized manner, but presence of a budget limits the list of options, the goal was to reduce costs as much as possible without compromising functionality. Being that the reason of taking into account the implementation of microcontrollers.

Figure 4.4: Project Controller options

As explained before, the first aim was to find if the implementation of a microcontroller was suitable for the proper functionality of the system without forgetting the willingness to give the project the possibility to be upgradable in terms for functionally. This means that the capacity of the controlling system has to be bigger than needed in order to be able to add either hardware or software to the machine in the future without having to change the controllers.

The analyzed model for the embedded solution using a multipurpose microcontroller was the single board Raspberry Pi 2 Computer. With expandable SD card as data storage and a 1 GB as RAM memory, it also has an Ethernet connector that can be used a wired network that can be used to convey the data via OPC server or other Ethernet protocols. It is important to remark that this device works under Linux which is open source, so it allows the users to modify the source code as wanted among other good characteristics like the built in connection for a monitor and USB connectivity.

A board with these characteristics results enough for managing the controlling of a project like this, one of the disadvantages is the development time since the solutions have to be custom made for each project and there isn't a standard platform to make automation projects.

The Arduino UNO is based on an ATMega 328 8-bit microcontroller and according to the datasheet provided by the fabricant, the input level is 0-5V so an interface card has to be developed, also, the implementation of an Ethernet port communication requires the use of an extension shield, thus, the Arduino UNO doesn't represent a good choice on the standardization needed inside the industry.

Once the Arduino microcontroller was discarded it was the time to analyze and visualize an automatic system with the employment of a Raspberry Pi and a PLC and take decision based on the advantages that any case would bring to the set-up.

The picked PLC model for the project was from Siemens, the S7-1200 1214C which is a modular compact controller for relatively speaking automation tasks.

When compared to the selected Raspberry Pi, the board has more memory, processor speed and visualization capabilities (HDMI port), however the PLC has 0-24V embedded inputs, 0-10V analog inputs, expandable interfaces such as IO-Link, RS232-485, RFID-Antennas, etc.

When comparing the prices of the last two options taken into account, it was important to bear in mind the costs of the extra items that are going to be needed besides the main controller. This comes after thinking that the selected PLC is around 6 times more expensive than the Raspberry Pi but when thinking about the other extra devices needed to make the Raspberry Pi have similar characteristics as the PLC in terms of inputs, outputs, connectivity, safety, etc. The difference in price is reduced so significantly that spending that much difference in order to gain roughness, speed and durability is definitely a good call to invest a little bit more and get the PLC.

4.2.3 Reduction of the solution variants

After the whole functioning of the project was divided into smaller tasks and the main solution variants were found for each of the tasks and subtasks, a great number of possible combinations came as a result and it was time now to start eliminating variants until the best combination among all the possibilities was found. The criteria that was elected to either discard or accept a combination is summarized on the following points:

- Within the reach of the firma.
- Scalable for other equipment/applications
- Economically viable

In the previous parts a general overview of each component's weaknesses has been given, therefore, all the components that have not been found viable for the specific task were directly discarded and not analyzed anymore.

4.3 Selection and evaluation of principle combinations

The selection of the partial solutions was divided into 2 main groups as the previous pages of this work suggest, because of the two main disciplines involved in this project: mechanics and electronics.

4.3.1 Presentation of the chosen alternative for the mechanical part

Among the mechanical functionality of the project, electronically working components were also analyzed on the basis of the type of movements that they were supposed to develop. However, as explained before the controlling method was simultaneously evaluated in order to be sure that its functionality was not going to be compromised.

For the partial function “carrier position detection” the RFID technology was chosen, compared to the traditional barcode. Although both solutions fulfill the task, the fact that with the RFID technology the clapper and its position can be identified wirelessly without direct visual contact, the possibility to rewrite data on the tags, and also the greater amount of available memory, made the choice easier.

Likewise, the positioning of the clapper was preferred to be done by the employment of a servo motor, which would replace the existing induction motor. Even when this represents a more expensive solution than the additional encoder or the blocking pin, it outweighs the advantage that always an exact positioning is given regardless of the tracking behavior of the current engine. The braider used is also brought up to date with modern braiding machines, which are also equipped with servo motors as a drive unit.

About the carrier deploy from stock, due to manufacturing costs, material quantity and planned number of different carriers to be shown in this kind of exposition, the choice was the single rounded stock, which fulfills the task’s demands and represent less impact to the budget. Besides the space is better used compared to the option of the carrier provider made from a couple of grippers which are mounted on a circular plate that rotates for doing the exchange due to the unused space in the center between the exchanger and the magazine.

After all the subtasks were partially solved, then a concept of the set-up was made to analyze and evaluate its functionality. The obtained model is presented on figure 4.5.

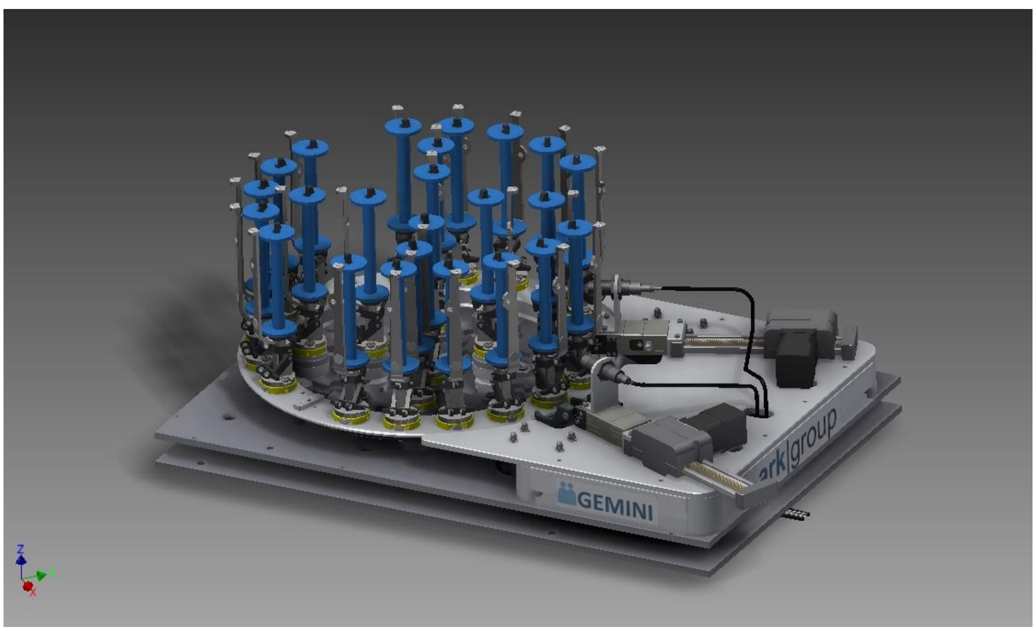


Figure 4.5: Braiding machine with added automation concepts

All the elements previously mentioned are shown on figure 4.5 i.e. RFID Antennas, Grippers, Ring magazine, Linear guides and Carrier holders. It can be seen that all the elements can be joined in the given space without any problem regarding the kinematics of the moving parts.

4.3.2 Presentation of the chosen alternative for the electronic part

After setting a solution for the mechanical part of the project, it was now time to find the best way possible to interconnect these elements in a safe way that can also represent a robust and stable solution for the controlling part.

As explained before, the implementation of a PLC as a central controller of the set-up represents a more robust and stable solution than the other two analyzed options: Arduino and Raspberry Pi. A crucial characteristic that influenced the selection was the possibility to interconnect different levels of automation, like the IO-Link, a new industrial low level network mostly used for sensors and actuators. It allows the employment of different brands or systems in the same controller which can also be expanded to many more elements as needed. Furthermore talking about costs the difference is not very sensitive for the budget and the advantages obtained i.e. uniform wiring and far fewer interfaces at the sensors/actors, continuous communication and diagnostic between sensors/actors, automatic reassignment of parameters when devices are replaced during operation, etc. are worth that extra expense.

As a PLC was decided to be employed as the main controlling device of the project, the whole control cabinet was needed to be designed in order to distribute the power, controlling and inputs and outputs stages. The following figure 4.6 gives a rough idea of the way the things were planned to be mounted in the control cabinet. The electrical diagrams will be given at the end of this work in the appendix.

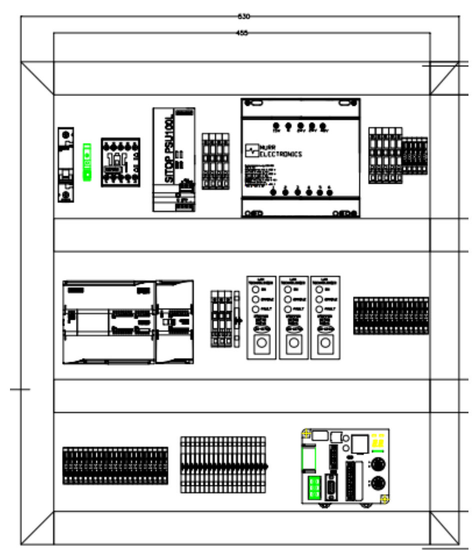


Figure 4.6: Control cabinet distribution

The distribution of the controlling elements was planned to be done in three levels: The power stage (1st level), controlling stage (2nd level) and on the last level the I/O stage. It can be seen in the figure above 4.6.

The first level, the power stage will work with a couple of security switches and fuses for the security of the system which allow the 230V AC get into the power source that will convert that energy into 24V DC for the PLC and IO-Link which will also feed the actuators and/or sensors accordingly. There is also another transformer that gives as output 24V AC, which is needed to feed the motor controllers of the grippers' stepper motors.

On the controlling stage, the PLC, IO-Link, stepper motor controllers and a couple of relays will be set. The PLC as the main controlling device, which will be managing the execution and working of the other controlling devices, the IO-Link at the moment only for the RFID antennas which use this platform for their communication but also as a future expansion option for the project because of the possibility to add a wide range of components that work under this platform. The stepper motor controllers as its name suggests are intended for the controlling of the stepper motors, they are initiated and stopped by the PLC but the motion control is done by them in a smooth and accurate manner. And finally the relays are only intended to work as a switch between inputs that will never be used in parallel due to its nature or the working principles of the elements that they will be controlling in order to save some inputs on the PLC and leave free room for future expansion possibilities.

The lowest level is reserved for all the inputs and outputs of the system. It is noteworthy that all the cables will be labeled with the same number as in the electric diagrams. This way and by separating the levels of the control cabinet, it becomes easier to identify any wanted cable due to problems, wrong functioning or by any other mean.

Chapter V: Project Development

The construction of the automatic braiding machine has different subsystems that can be designed in a relatively separated way, those subsystems are:

1. Electrical construction.
2. Control scheme design.
3. Host, client and automation applications.
4. Thread change algorithm.

However, those subsystems will be working altogether to make the braiding machine work as stated on the system requirements.

5.1 Electrical construction.

Given the selected geometry for the braiding machine, the conditions of operation, place of installation and the safety measures, the design of the electrical system has to take in account the following restrictions:

- Input: 230VAC, max 25 Amp
- At least 2 emergency stop buttons have to be installed.
- Manual and remote start and stop.
- Two modes of operation Run and Diagnostics.
- OPC connectivity for metrics and further development options.
- The electrical installation has to be easily maintainable and repeatable for further developments.
- A safety switch has to be installed to prevent the user get inside the machine when is in operation.

5.1.1 Inputs and outputs of the system.

Accordingly with the given specifications the following inputs and outputs of the system are enumerated in the Table 5.1.

Component	Electrical Specification.	Type
Stop	Digital 24V	Input
Start Button	Digital 24V	Input
RFID Left Antenna	IO-Link	Input
RFID Right Antenna	IO-Link	Input
Laser distance sensor right	Analog 0-10V	Input
Laser distance sensor left	Analog 0-10V	Input
Open chassis safety switch	Digital 24V	Input
Stepper motor fault	Digital 24V	Input
OPC Server Ethernet port.	Ethernet	Input
Right Gripper open/close switch	Digital 24V	Output
Left Gripper open/close switch	Digital 24V	Output
Left gripper linear guide	Pulse Train / Direction	Output
Right gripper linear guide	Pulse Train / Direction	Output
Carrier ring motor	Pulse Train / Direction	Output
Braiding servomotor	Modbus TCP	Output
ON-OFF Indicator	Digital 24V	Output
Fault indicator	Digital 24V	Output

Table 8: **Inputs/outputs of the system**

With this I/O map The installation of the sensors and actuators can be prepared.

5.1.2 Stepper motor installation.

For the sectioning the motors, the plausible control mode has to be taken in account, since the movement of the grippers and the ring has to have enough speed, torque and precision in order to be viable to change the carriers in an acceptable time and without errors.

In order to get 5 second cycles either for retrieving or placing a carrier using the gripper, the minimal speed of the lineal guide has to be 20mm/s, simultaneously the resolution for the placement for the motor has to be at least 1 mm in order to guarantee the well-functioning of this device. With this requirements , the selected linear guide for the gripper is the “Schunk 100mm guide with stepper motor model : GRW-0630-A-80-110-17-L-S-000” that has the possibility to move up to 35 mm/s and a resolution of 0.1 mm, the specifications of the motor are shown in the following table 5.2:

Torque: 0.28 N.m.	Full step angle: 1.8°
Bipolar phase current: 0.7 A	Phase resistance: 6.3 Ω
Phase inductance: 8.9 mH.	Total weight: 0.24 Kg.

***Table 9*: Specifications of the stepper motor**

Accordingly to the electrical and control specifications of the device, a stepper motor driver is proposed to handle the operation, the selected driver is a *"DS1041A"* from LAM-Technologies, this stepper motor driver allows micro-stepping, this control technique consist in exciting the coils of the motor with a fraction of the current during time which improves the resolution and ease of the movement the functioning principle is shown in the figure 5.1.

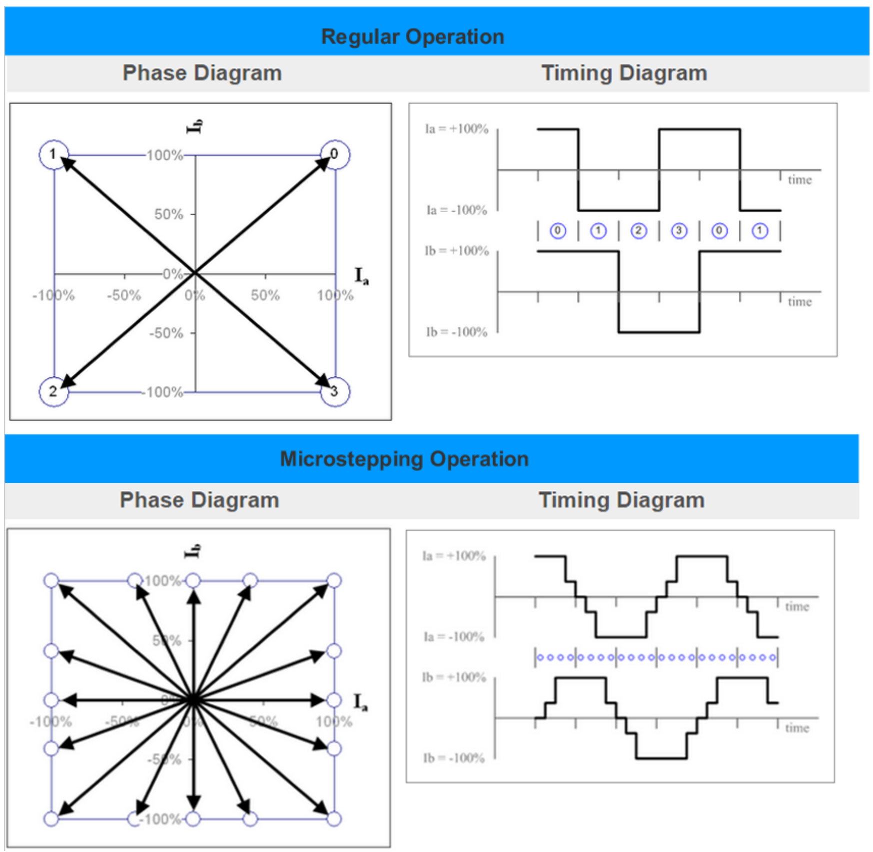


Figure 5.1: Micro-stepping operation

Other of the advantages of using a stepper motor driver is that it works as a power interface simplifying the installation and maintenance of the system. The operation of the driver works with two outputs of the controller, one for pulse and other for direction, the feedback of the controller is a digital fault signal, with these devices the installation should be done as shown in the figure 5.2.

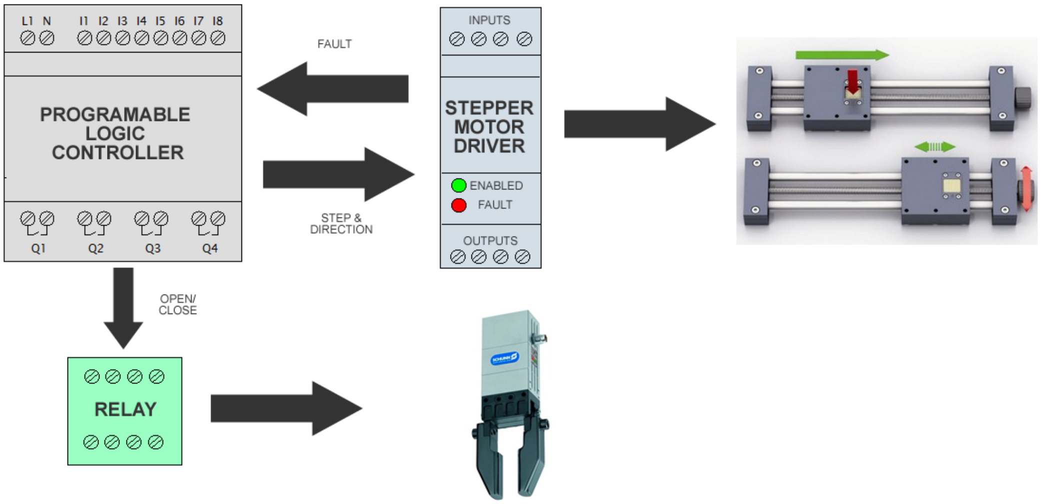


Figure 5.2: Gripper installation

The detailed schematics for the electrical installation can be found on the appendix.

Similarly to the gripper installation, the motor selected for the carrier ring is also a stepper motor; however, more power is needed for it, so a NEMA 34 motor has been selected to be installed in that position. The electrical specifications of the motor are shown in the following table 5.3:

Torque: 4.4 N.m.	Full step angle: 1.8°
Bipolar phase current: 5.6 A	Phase resistance: 0.26 Ω
Phase inductance: 1.5 mH.	Total weight: 2.1 Kg.

Table 10**: Electrical specifications of the carrier ring motor**

In contrast to the gripper, the carrier ring has a pulley attached, so the transmission ratio has to be taken in consideration for its setup and operation, the diameter of the carrier ring is 442mm. and the pulley attached to the motor is 62mm with this data the next transmission ratio is given:

$$\frac{442mm}{62mm} = 7.1\ 3$$

Equation 1

This ratio means that 7.13 revolutions of the motor are needed to get 1 revolution on the carrier ring, and 200 pulses are needed for one revolution of the motor, so with the transmission, the number of pulses per revolution for the carrier ring is:

$$7.13 * 200 \frac{p}{rev} = 1425 \frac{p}{rev}$$

Equation 2

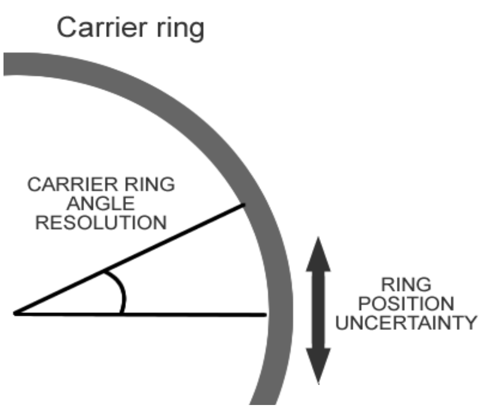
(EC 5.2)

With the direct driving of the motor a resolution of 0.25° per pulse is given. This resolution can be improved with the micro-stepping feature of the driver. Nonetheless the accuracy of the motor has a detrimental effect on the angular speed since the maximum pulse frequency is 10 Khz with this limitation the maximum rotary speed for the motor are described on table 5.4.

Resolution carrier ring	Micro stepper setting.	Max. Motor speed.	Max. ring speed
0.25°	200 p. / rev.	314 rad/s.	44 rad/s
0.125°	400 p. / rev.	157 rad/s	22 rad/s
0.0625°	800 p. / rev.	76 rad/s	11 rad/s
0.0312°	1600 p. / rev.	35 rad/s	5.5 rad/s

***Table 11*: Ring properties**

With this dynamic data for the ring can the configuration that allows getting the best speed and a permissible uncertainty can be choose, given that the closing distance of the gripper is 5 mm, the maximal uncertainty for the system should be 2.5 mm.



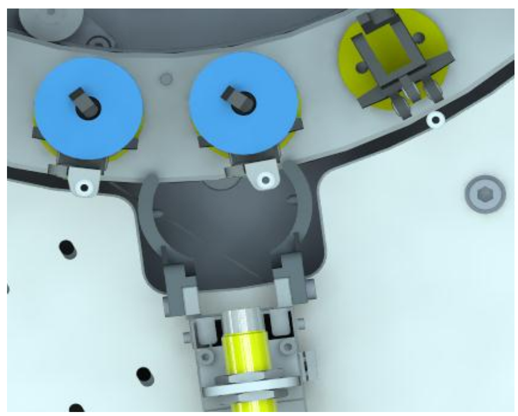


Figure 5.3 Carrier Ring resolution

$$Gripping\ tolerance = \left(carrier\ resolution\ angle * ring\ radius.* \frac{\pi}{180}\right)$$

Equation 3

Carrier ring resolution	Gripping tolerance.
0.25°	0.96 mm
0.125°	0.46 mm
0.0625°	0.23 mm
0.0312°	0.11 mm

***Table 12*: Ring position uncertainty**

From this data, is assured that the uncertainty of the carrier ring positioning system will not interfere with the gripping, the configuration of 200 p./rev. will be selected, since the overall speed of the process is the highest priority. With this configuration, maximum speed for the carrier ring can be reached, however, the dynamic speed control has to be regulated for a smooth operation, this controller will has to be implemented in the PLC.

5.1.3 RFID Antennas and analog distance sensors.

The selected RFID antennas, were the *"Balluff BIS L-409-045-002-07-S4"* which are connected via IO-Link with the controller, the technical specifications for this devices are enumerated in the following table 5.6-

Current: 150mA	Sensing rage: 24 mm.
Device interface: IO-Link Rev 2.0	Typical read tag time: 10ms.
Operating voltage: 24 V	

***Table 13*: RFID specifications.**

This antennas work together with RFID tags that have up to 32 bytes storage, with this capacity the following data can be stored inside each carrier tag as in the following table 5.7.

Unique carrier ID: 2 - 4 bytes.	Estimated thread left: 2 bytes.
Thread color: 1 byte	User data: 20 bytes.
Last used timestamp: 4 bytes.	

***Table 14*: tag memory organization.**

According to the design the antennas are installed on top of each gripper in order to read the data on the tag placed on the carrier. Figure 5.4 gives an overview of the antennas and the tags placed on the carriers.

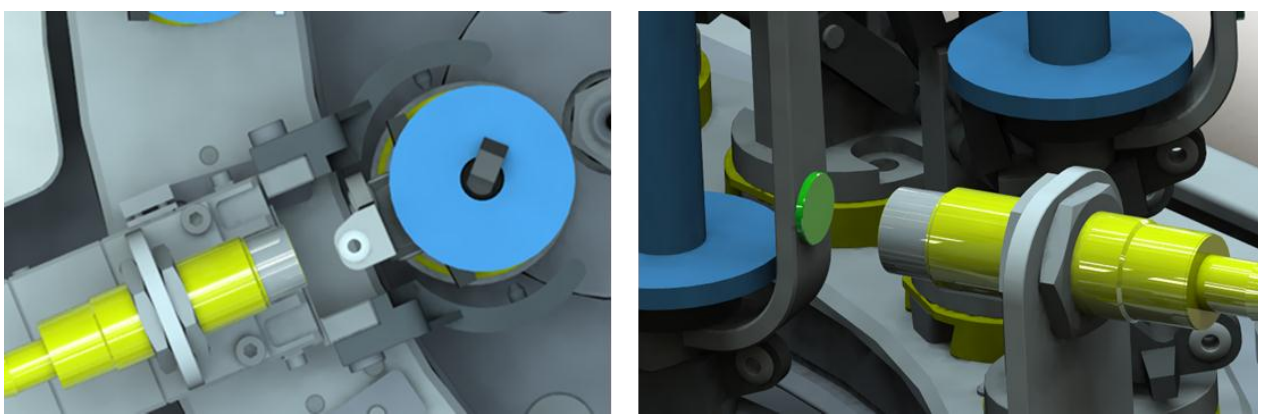


Figure 5.4: RFID reader installation

One of the possible areas of improvement found on the RFID sensor placement is that for each reading the machine has to stand still because the mechanical design of the gripper. A further analysis of this issue will be addressed in the results chapter.

The analog distance sensor selected was the "Balluff BOD001L" that operates with red light and has the following specifications specified on table 5.8:

Operating Range: 20 – 80 mm	Sensing principle: Red Light
Switching: PNP Transistor	Output: 1 – 10 V
Resolution: 20 micrometer	Input: 24VDC

***Table 15*: Analog distance sensor specifications**

An important aspect of the installation of this sensor is the fact that a highly reflective surface is suggested for proper working, for that reason, the placement of the sensor is above the RFID antenna, together these two sensors provide feedback in thread identification and carrier positioning, the sensor has to be placed as shown on the next figure 5.5.

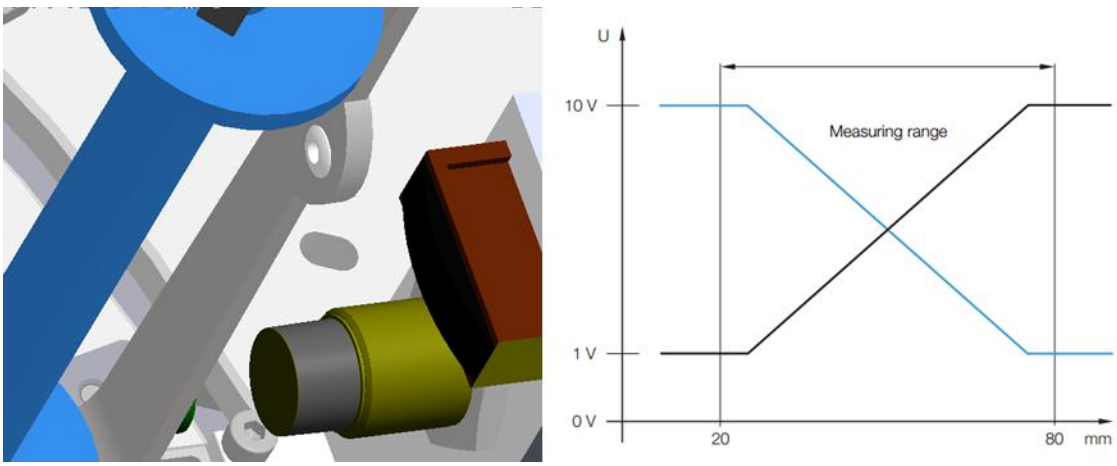


Figure 5.5: Analog sensor positioning and electrical behavior

According to the specifications on the PLC, an analog digital converter (ADC) 16-bit resolution is used to read the output signal on the sensor, providing a real resolution of:

$$Resolution = \frac{9V}{2^{16}}(60mm) = 0.008\,mm$$

Equation 4

Which is lesser than the 20 micrometer that the sensor is providing, therefore a dead-band of 12 micrometer will exist in the measures, which is ignored for the purposes of the project because the least resolution of the actuator is 0.1 mm, then the resolution of the sensor is superior to the resolution of the actuator, therefore, the sensor is correctly selected.

5.2.4 Electrical installation and safety devices.

The electrical installation of the project was made using the IEC 60446:2007 standard for installation and safety principles. Therefore the wires and conductors had proper identification, and color. Also the entire wiring schematics were developed using AutoCAD electrical 2012 student version. A short version of the electrical schemes is shown in the following figure 5.6.

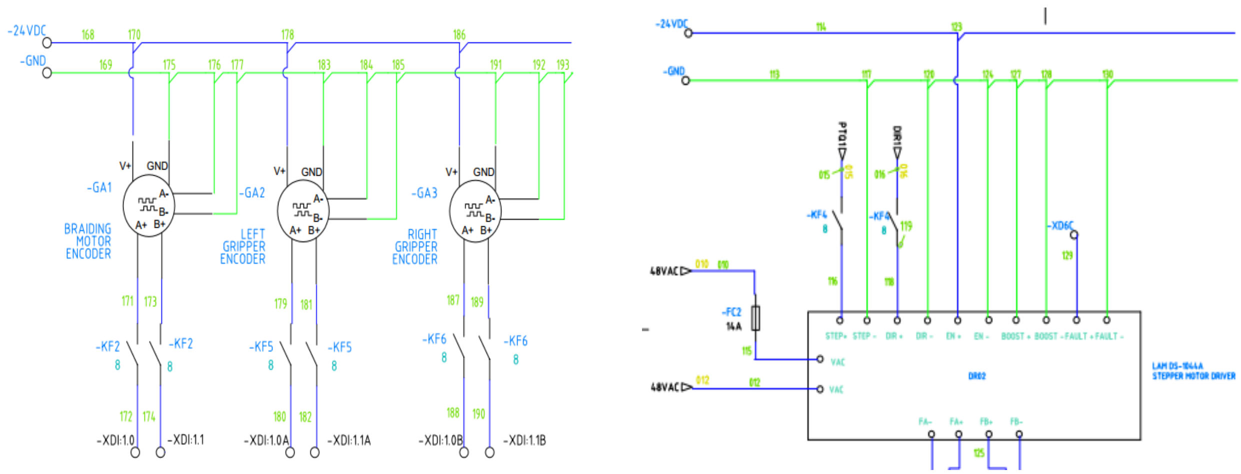


Figure 5.6: Sample of electrical wiring diagrams

The complete version of the schematics can be found on the appendix. Lastly the installation of the electrical circuit was designed to be mounted on an IP67 electrical case, and thus, the distribution of the components will be the following.

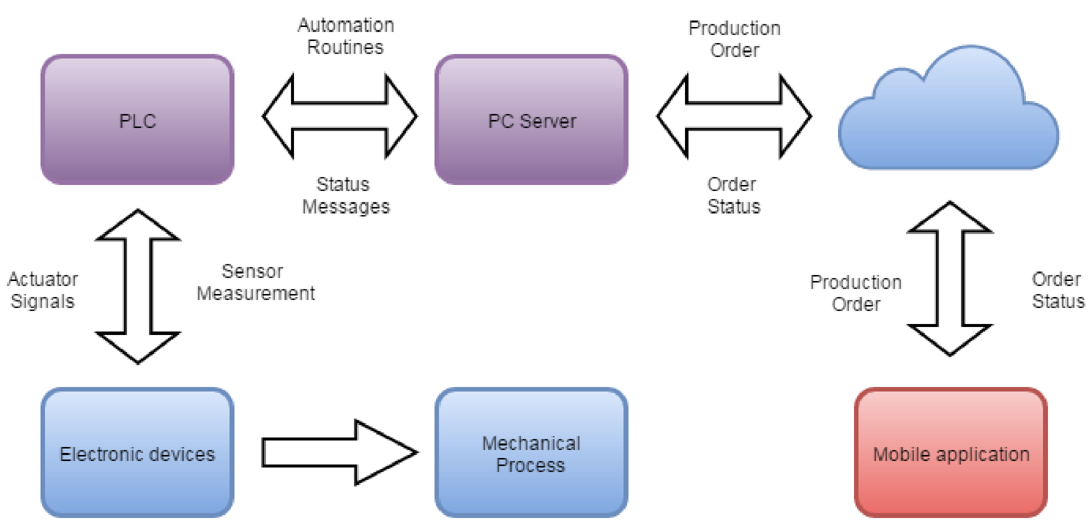


Figure 5.7: Electrical connection diagram

Once the full list of components is selected, the following electrical requirements were calculated for the startup and steady state operation of the machine:

- Max startup current: 12 Amp
- Steady operation current: 2.5 ~ 4 Amp
- Input voltage: 230VCA
- Output voltages: 24VDC & 24VAC
- Overcurrent DC source fuse: 3A
- Overcurrent AC transformer: 16 Amp
- General protection fuse: 16 Amp

According to the specification, two emergency stop buttons have to be installed as well as one start button. The stop buttons are in series with the electrical sources because the operation of the motors of the system has to be stopped and there is no element that in emergency needs to be in a special state (i.e. a pneumatic or hydraulic valve).

The installation of the signal lights is wired directly to the controller in order to have software control of them. Those signaling lights are 24VDC led indicators, a small portion of the electrical diagram is shown on the figure 5.8.

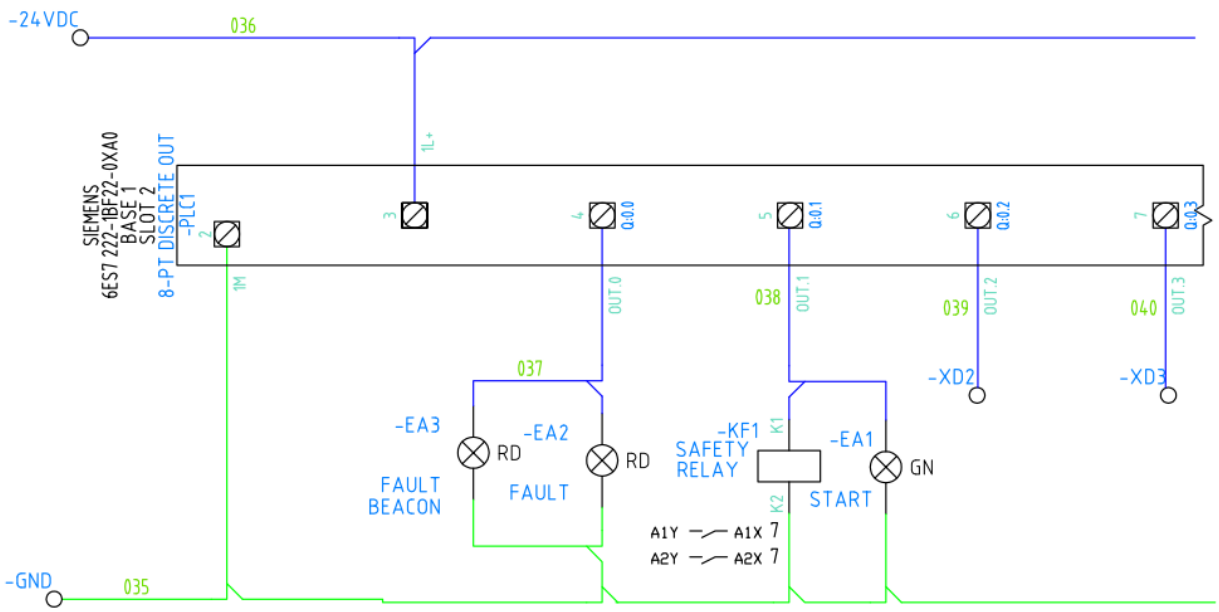


Figure 5.8 Wiring of signaling lights

5.2 Control design

The control of the system is related to three user roles, a customer role can ask for a braided product using a smartphone application, a personnel role is able to change threads and get basic reporting from the system and an administrator role that has the possibility to make maintenance tasks, the following figure 5.9 gives an overview of the different roles.

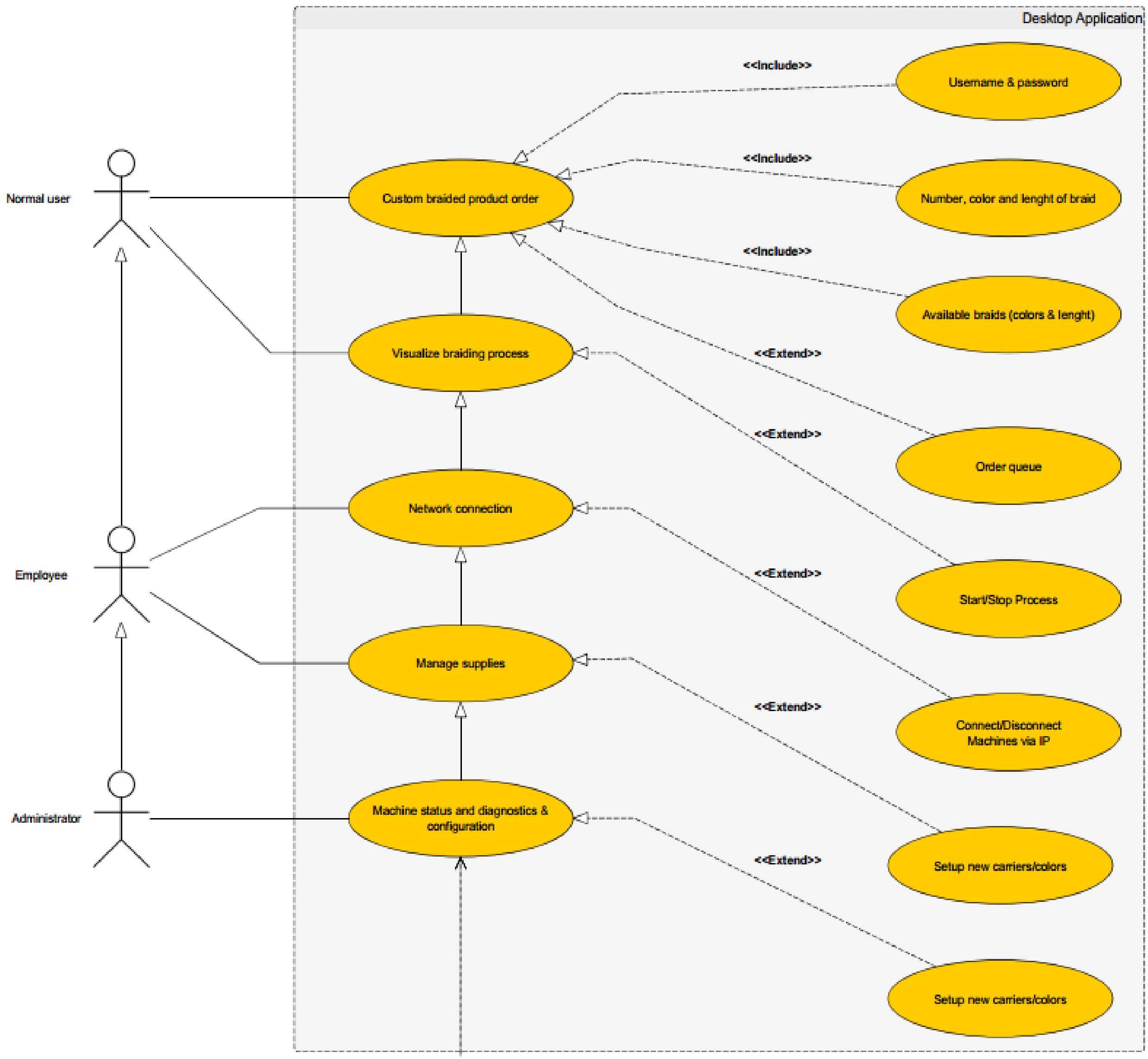


Figure 5.9: Use case diagram

With this use case scenario for the system, the most important task is the "*Braid production"* this task involves all the systems and the other tasks and roles can be extended from it, therefore, this is the first task that is designed and then, the other tasks will be extended.

The braid production process starts when a client enters a request for a new product, after that, the data for the previous machine state is loaded and compared with the requested configuration to produce the thread changing route, in this two steps, the user validation and the resources quantification will be performed, however, those two sub processes will be developed separately and extended to this one once the machine is fully implemented. Then, the braid production process will have the next sequence. A block diagram of the sequence is given on figure 5.10.

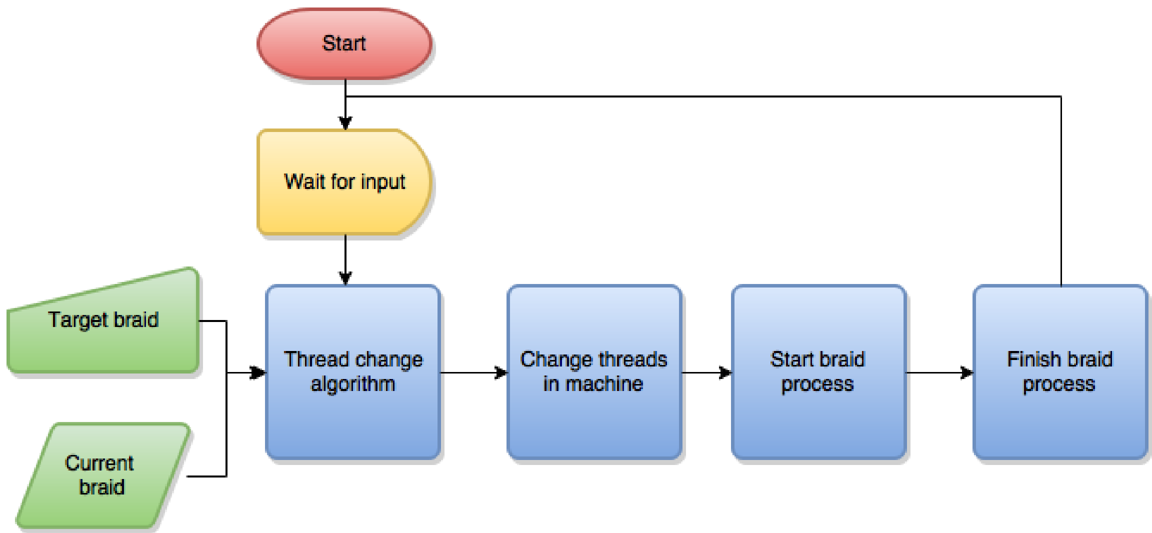


Figure 5.10: Braid product sequence

In this high order view of the process the *"change threads in machine"* sub process can be observed, this process is the critical process in the entire application because it contains the movement of the grippers and the ring. The process of changing a thread it's completely managed by the PLC and its inputs are the ID of the thread that will be replaced and the ID of the replacing thread, after that, the gripper will get inside the moving ring and wait to read the ID of the thread that will be replaced, then stop the braid motor, grip the thread, get the thread to the ring, rotate the ring to until the target thread is found, get the thread inside the machine, check that the distance between the gripper and the placed thread is correct, retract the gripper and wait for the next thread change be issued by the server.

Several mechanical features of the machine have impact on how the thread change is performed, the principal geometrical aspects that the controller has to avoid are:

- Carrier falling inside the machine.
- Error on gripping carrier.
- Carrier misplacement on the ring or inside the machine.

Those errors, are avoided by the use of the Analog sensor placed on the gripper, the method is to place a distance range on each step of the thread change, this way if the sensor at any moment gets outranged, the controller will send an error message to the server and will stop the operation; giving the user indications to check and correct the malfunction, after that, the user will resume manually the operation of the controller.

The error handling and error solving protocols are developed in such way that the braid that is being made at the time of the error is not scrapped.

Also, according to the expected data inside the server and knowing that the carriers can be misplaced the algorithm to change a thread will poll the ID's of the carriers that are inside the machine and ring instead of moving the ring in an absolute manner, this is to avoid errors on the placing of carriers and rely on the order of those.

However, this approach to solve the problem can be time consuming, that is why the algorithm to know which the shortest way to change threads is important. Then, the diagram of the implemented process is as follows on figure 5.11.

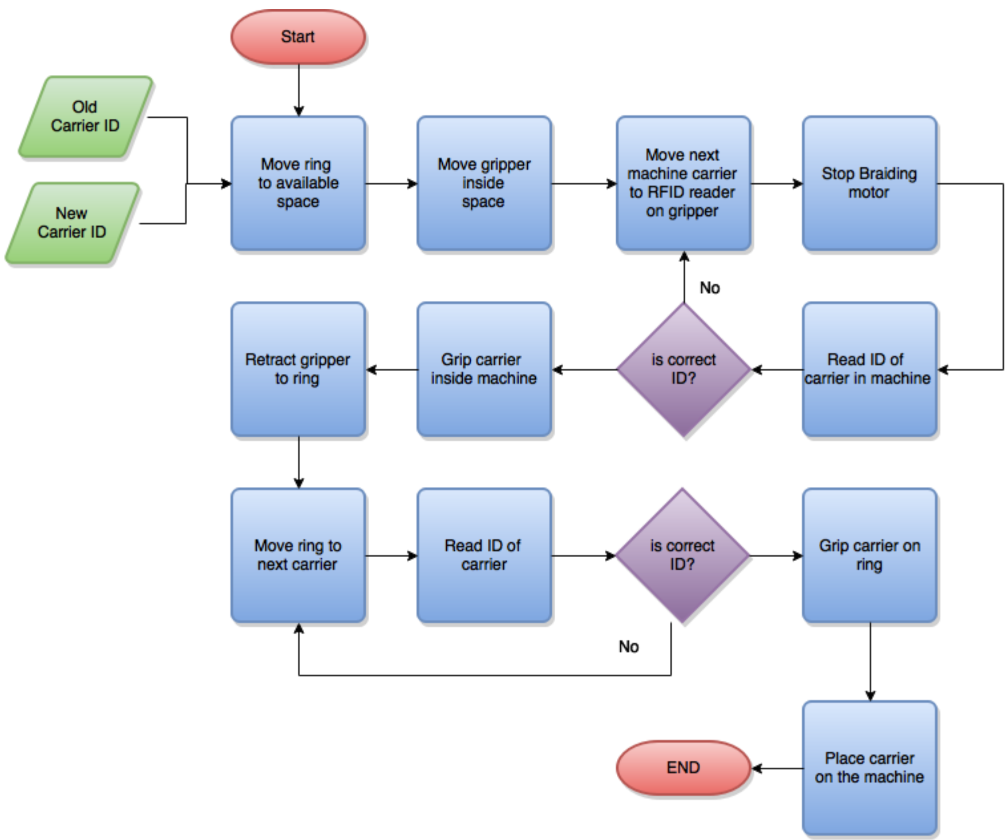


Figure 5.11: Process diagram for changing the carriers

It is expected that each one of the states have a distance tolerance that will be measure by the analog sensor at all time, this process can be interrupted in every step by triggering an error interrupt.

After all the threads have been changed, the controller will send a start braiding signal, that signal will trigger a message that has to be transmitted via "Modbus –TCP" to the braiding motor. The braiding motor supports the parameters: Start, Speed and turn.

Therefore, the start braiding parameter has to be configured whether is going to be clockwise or counterclockwise. Also, the speed of the braiding motor has to be changed when a thread change is made because of the reading of the carriers' ID.

5.2.1 Gripper and ring stepper motor speed control.

The second important task for the controller is to generate the pulse train that is needed to control the stepper motors installed on the carrier ring and each gripper. The motion control is made via pulse train frequency control. The parameters that are controlled in each stepper motor are given on the following table 5.9:

Pulses per revolution	Maximum speed
Acceleration time.	Maximum acceleration.
Last used timestamp: 4 bytes.	Position limits.

***Table 16*: stepper motor control parameters**

With these parameters an open loop speed controller can be produced, that allows absolute positioning for the grippers and the ring, the main restriction is that the maximum output frequency from the controller is 10 Khz, as shown on figure 5.12.

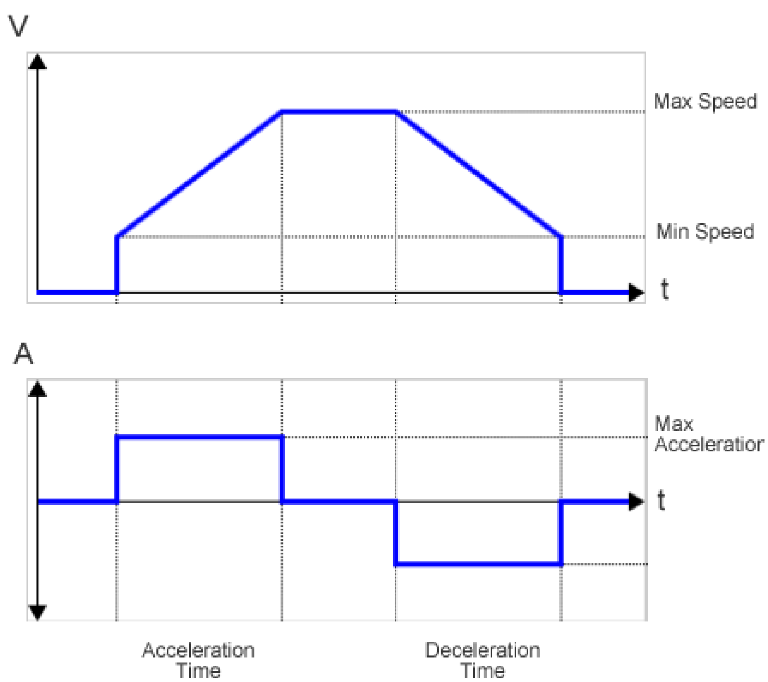


Figure 5.12: Speed and acceleration profiles for stepper motors

Having that in mind, a class is generated using these parameters, this way the constructor will have the dynamic parameters of each motor, and the methods that will be implemented on the class are given on following table 5.10.

Constructor parameters:	Implemented methods.
Steps per revolution.	SetParameter(ParameterID, Value)
Maximum speed	MoveAbsolute(Position)
Minimum acceleration	MoveRelative(Position)
Maximum acceleration	
Acceleration/deceleration time	

***Table 17*: Stepper motor controller class implementation**

Since 1 pulse represents 1.8° at full resolution (this parameter can be changed on the stepper motor driver) this is the base of the calculations to get the frequency functions for the controller. An example of a train pulse can be seen on figure 5.13.

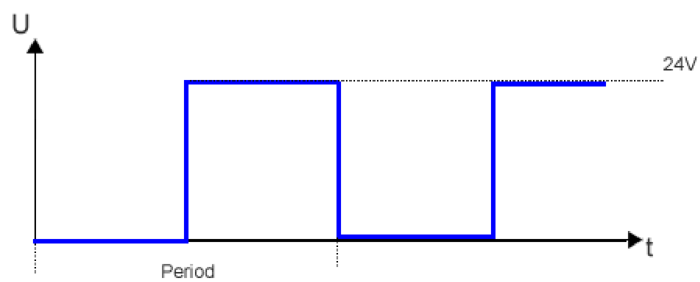


Figure 5.13: Train Pulse

Since it's easier to use the period for calculations instead of frequency, the equations for period are:

$$\tau = \begin{cases} k\left(\frac{V_{max}}{a_t}\right)t, \forall t < a_t \\ kV_{max}, \forall\, t > a_t \\ k\left(\frac{V_{max}}{d_t}\right)t, \forall t > d_t \end{cases}$$

Equation 5

Where a_t, d_t and k are the acceleration time, deceleration time and the proportional constant between pulses per second and rad/s respectively, the proportional constant can be calculated once the amount of pulses per revolution is set, for example for 200 pulses per is:

$$k = \frac{200hz}{2\pi \frac{rad}{s}} = 31.84$$

Equation 6

Lastly, to implement the third part of the function, 2 cases arise, the first when v_{max} is not reached and when it is, in order to know in which case the system is at, the compare of the minimal distance to reach the max speed, and that is:

$$D_{min} = \int_0^{a_t} k\left(\frac{V_{max}}{a_t}\right) t = k\left(\frac{V_{max}}{2 * a_t}\right)(a_t)^2 = \frac{kV_{max}a_t}{2}$$

Equation 7

And if the distance is bigger than $2 * D_{min}$then the estimate of the time for the complete movement profile that will be:

$$t_{total} = a_t + d_t + \left(D_{total} - \left(\frac{kV_{max}(a_t + d_t)}{2}\right)\right) * V_{max}$$

Equation 8

Where D_{total} is the user given distance, and then, the distance needed to decelerate:

$$D_{decel} = \int_0^{d_t} k\left(\frac{V_{max}}{d_t}\right) t = k\left(\frac{V_{max}}{2 * d_t}\right)(d_t)^2 = \frac{kV_{max}d_t}{2}$$

Equation 9

However, if the distance isn't bigger than $2 * D_{min}$ a symmetric acceleration deceleration profile will be calculated with a slope of $\frac{V_{max}}{a_t}$ then the profile should be:

$$D_{total} = \left(\frac{V_{max}}{a_t}\right) t^2 \xrightarrow{yields} t = +\sqrt{\frac{D_{total}a_t}{V_{max}}}$$

Equation 10

And with that, half the time the acceleration will be positive and the other half negative. This way a method named MoveAbsolute(position) can be created as shown on figure 5.14.

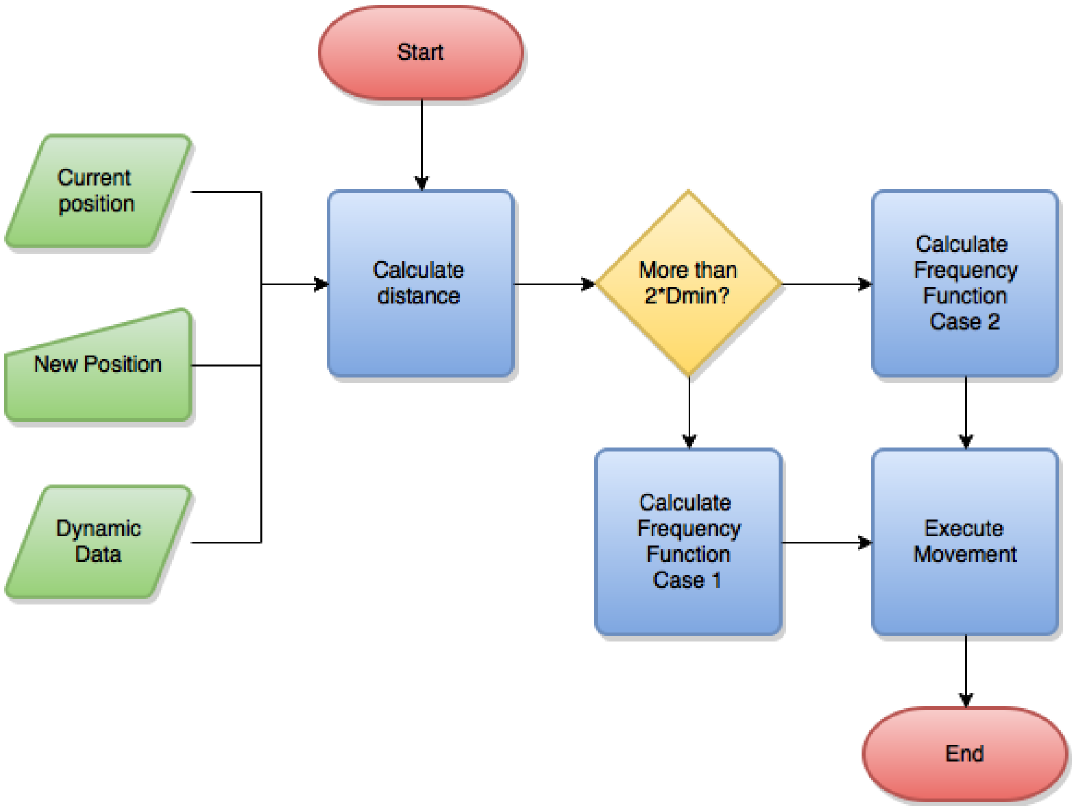


Figure 5.14: Stepper motor MoveAbsolute method implementation

This kind of movement is known as spline interpolation as explained on [ERKR03]. And the SCL code implementation of the class can be found on the appendix.

The **MoveRelative** method only differs on the *"Calculate distance"* process, instead of being a subtraction is an addition.

5.3 Thread change algorithm:

In order to avoid unnecessary movements and assure a smooth operation of the system, a thread change algorithm has to be created. That's because the geometry decided for the outer carrier ring the change between two states can be optimized by designing a cost function and then, finding the less amount of energy and time spent for changing the machine configuration.

The statement to design this algorithm is as follows:

"Design an algorithm to find the minimum amount of steps to change between two 8 circular sets with 4 different kind of members"

However, some other aspects of the thread change process have to be taken in account for the successful design of this algorithm. An approach to the braid state is 5.15.

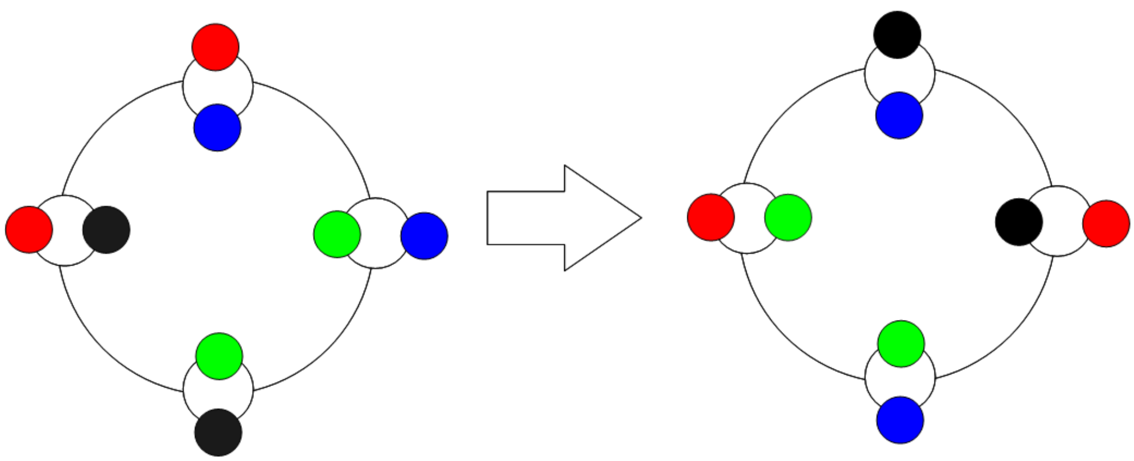


Fig 5.15: Two different states of the machine

The first step to find the algorithm is to find the constraints for it. The amount of different colors is 4 and the amount of carriers of each color is also four, therefore the simplest state that exist consist of two different colors with 4 threads each.

The second step is to know how a configuration is made, for each thread set they are separated in two cycles, one clockwise and other counter clock wise, each one of the threads has a sequence of intersections with each one of the other cycle members, so if a configuration can be named as, $\{R_1,R_2,R_3,R_4,L_1,L_2,L_3,L_4\}$ "*this creates an equivalency class that has as members all rotations and reflections of the configuration*" [SAKA10] consequently for every configuration at least the next number of equivalent configurations is created, as shown on the figure set 5.16.

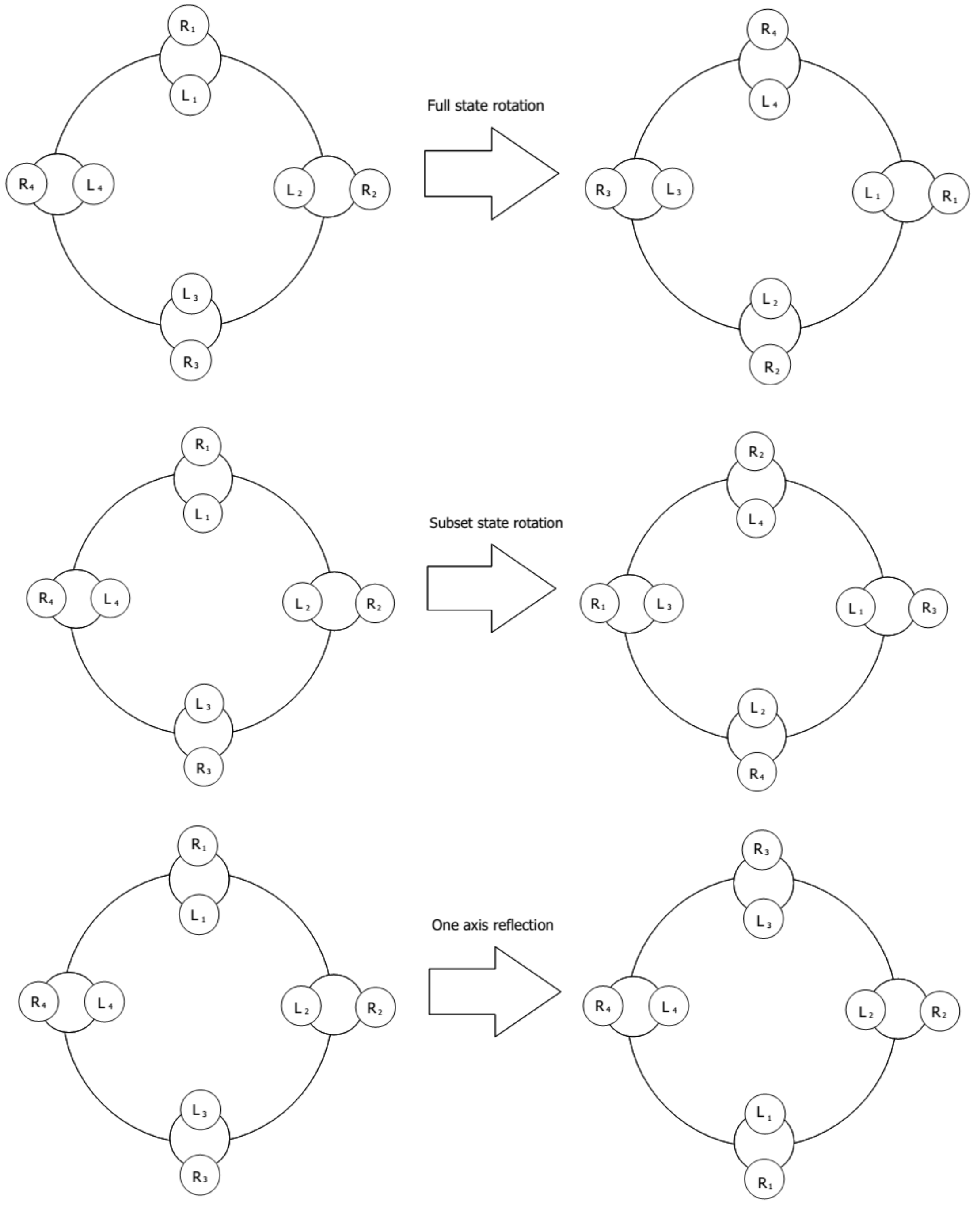


Fig 5.16: Rotation and reflection invariance in steps

So given the property of rotation and reflection and using the multiplicative to calculate the amount of equivalent braids to a state "A":

- Full state rotations 3 for each state "*R*".
- Subnet rotations 3 for each state "*S*".
- One axis reflections 4 for each state *"T"*.

- Two axis reflections 4 for each state *"V"*.

$$|Z_A| = \mathbf{R\ x\ S\ x\ T\ x\ V = 144}$$

Equation 11

So there exist a set of 144 of equivalent configurations that will produce the same thread assuming that each color is different. However the size of the set is increased if repeated colors are part of the configuration [SAKA12].

Since the purpose of this algorithm is to minimize the amount of steps needed to change form any starting state to another arbitrary state. A cost function has to be designed.

Let $A = \{a_0, a_1, a_2, a_3, a_4, a_5, a_6, a_7\}$ be the initial configuration of the machine and $B = \{b_0, b_1, b_2, b_3, b_4, b_5, b_6, b_7\}$ the target configuration of the system, it can be said that one thread change is needed if, $a_i \neq b_i$ so, the result of the operation A – B it´s equal to the number of occurrences of $a_i \neq b_i$, and since there is a set of all equivalent machine states of A and B named $\mathbf{Z_A}$ and $\mathbf{Z_B}$ another operation called A x B can be developed that is the set of the equivalent states (A_i, B_j) that produces the minimal difference index.

$$\{AxB\} := \{(A_i, B_j)\,|\,A_i - B_j\ is\ min\}$$

Equation 12

So to calculate the set {A x B}, it take the steps shown on figure 5.17.

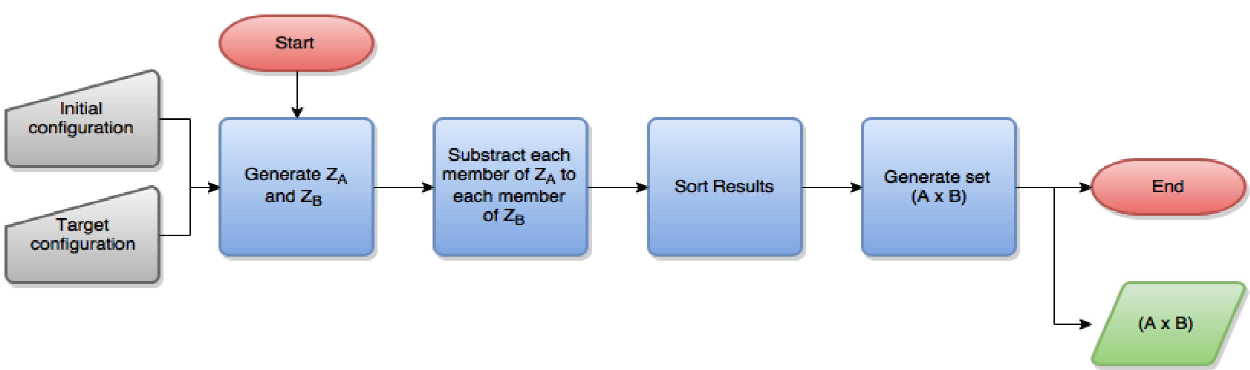


Figure 5.17: Minimal change set generation

Once the set *{A x B}* is produced, the addition of the cost for moving the carrier can be done to make all the movements needed to change the state, and then an estimated time of the change of configuration can be calculated, in order to do so, it is assumed that two different sets exist, A that is currently on the braiding machine and B that is in the outside ring.

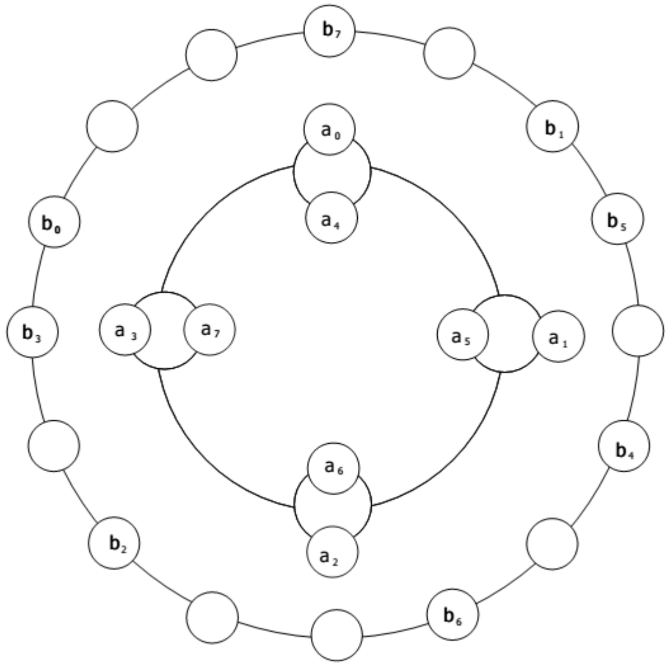


Figure 5.18: Usual thread arrangement

By knowing this information is possible to estimate the time that will take to change every member of the (A x B) and thus the thread change order is calculated. As shown on the figure 5.19

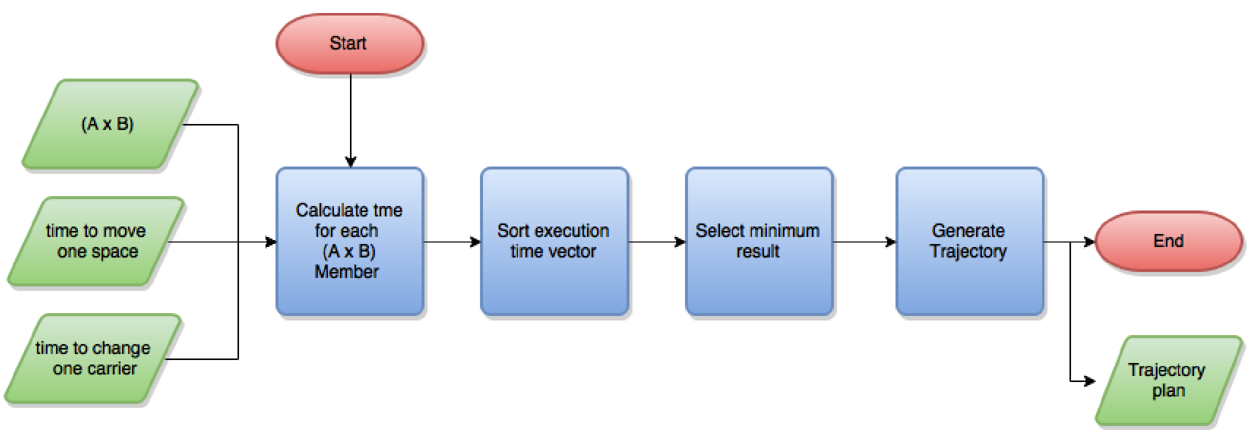


Figure 5.19: Trajectory planning process

Finally the trajectory that is planned should be put in a sequence of commands that will be interpreted by the Host application.

Since not all the thread colors in any given thread are different, a penalty coefficient can be created that conglomerate factors such as remaining thread in the carrier and have different strategies to choose which the best trajectory is.

Lastly the selected trajectory can be stored in a data base or in an indexed file for further program reading. The source code of the trajectory planning algorithm can be found on the appendix 3.

5.4 Application and network development

Since the complete software solution of this project has 4 different applications, each one will be documented separately even though the development was concurrent. Every piece of software involved in the project will be connected via OPC UA server to exchange information and provide further expansion capabilities. Also the OPC UA provides embedded user/password validation that helps to the authentication and role assignment inside the desktop and mobile application.

And since every exchange variable can be stored in the OPC server, the monitoring can be expanded to other stations without compatibility issues as described previously, the development of this project is oriented to Industry 4.0 type applications.

Hence, the appropriate topology for the application is clearly shown in figure 5.20.

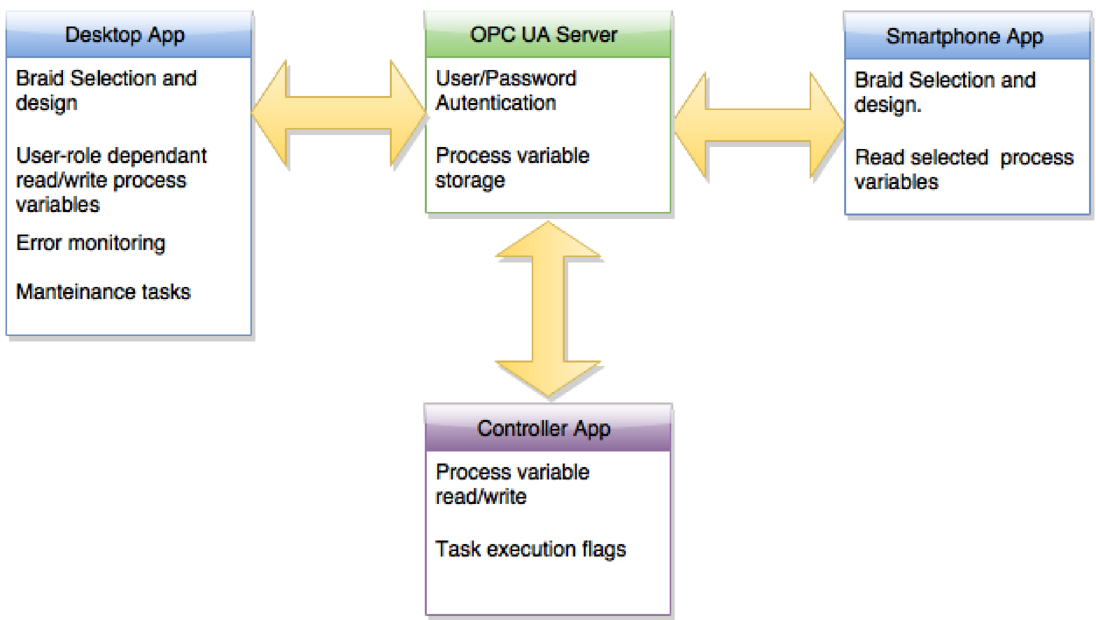


Figure 5.20: OPC UA network

5.4.1 Programmable logic controller.

The controller selected for the task was a *"Siemens S7-1214 DC/DC/DC Ver 4.1"* this controller provides the features explained on the following table 5.11.

Programmable using SCL & FBD	14 digital inputs, 2 analog inputs.
100 KB program data	10 digital outputs (transistor) max 0.5A
Programmable interrupt subroutines.	Ethernet communication (Multiple protocols)
Expandible I/O ports.	I-O Link module expansion available.

***Table 18*: PLC Features list**

The application of the controller centers in the creation of a group of classes that allows the information exchange and manage the thread change process. In addition to that task, the safety and status message has to be composed by the controller and transmitted to the server, this message is sent in a synchronous way, and therefore a cyclic execution object is added to the program.

And lastly, because of the installation of this particular unit, the status lights will have a particular blinking code, then the safety class is designed in a way that allows to operate those blink states and extend them as seen fit. An overview of the actual class model on the PLC is shown on figure 5.21.

In the selected programming language, the term class doesn't exist as in other languages such as C++ or JAVA, however the entity Function Block (FB) exists, and with this entity, a class model can be abstracted.

Figure 5.21: Class model on PLC

The way to abstract the class model is to take the member variables and methods and convert them into constants, variables and functions inside the block, and asynchronous calling to other blocks is also possible. This way the class model can be represented in SCL (High Level Structured Text) as shown in figure 5.22.

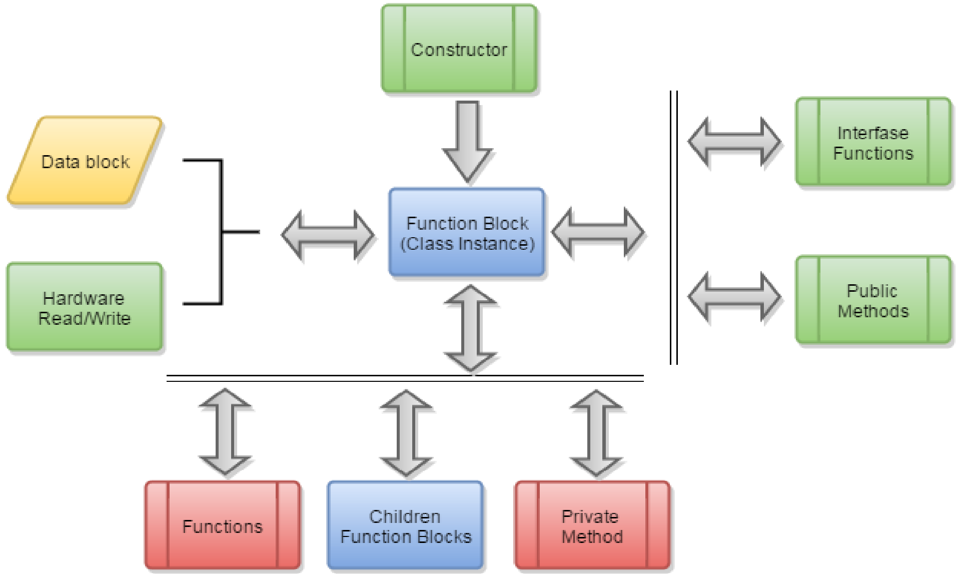
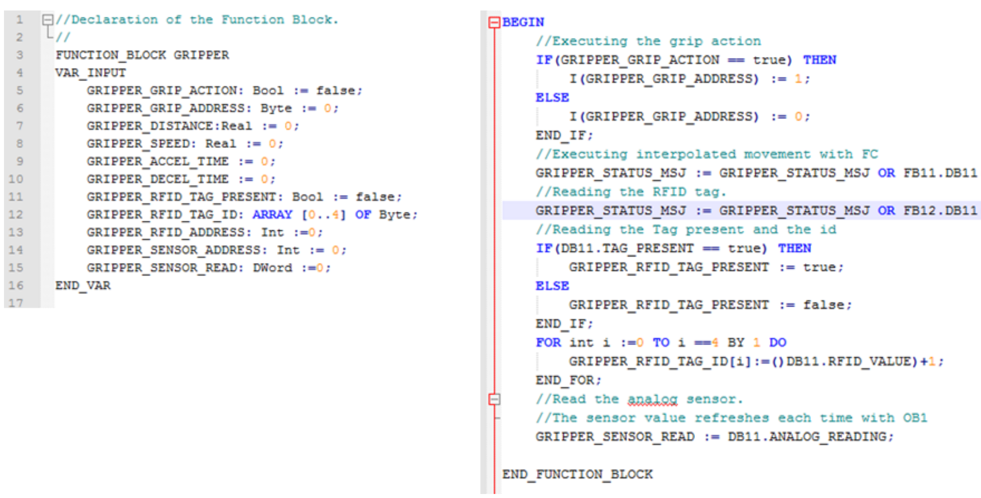


Figure 5.22: SCL Class implementation diagram

This way for example a class such as the Gripper that contains children instances of other classes such as stepper motor or RIFD reader can be implemented as the example given on figure 5.23.



```
//Declaration of the Function Block.
//
FUNCTION_BLOCK GRIPPER
VAR_INPUT
    GRIPPER_GRIP_ACTION: Bool := false;
    GRIPPER_GRIP_ADDRESS: Byte := 0;
    GRIPPER_DISTANCE:Real := 0;
    GRIPPER_SPEED: Real := 0;
    GRIPPER_ACCEL_TIME := 0;
    GRIPPER_DECEL_TIME := 0;
    GRIPPER_RFID_TAG_PRESENT: Bool := false;
    GRIPPER_RFID_TAG_ID: ARRAY [0..4] OF Byte;
    GRIPPER_RFID_ADDRESS: Int :=0;
    GRIPPER_SENSOR_ADDRESS: Int := 0;
    GRIPPER_SENSOR_READ: DWord :=0;
END_VAR
```

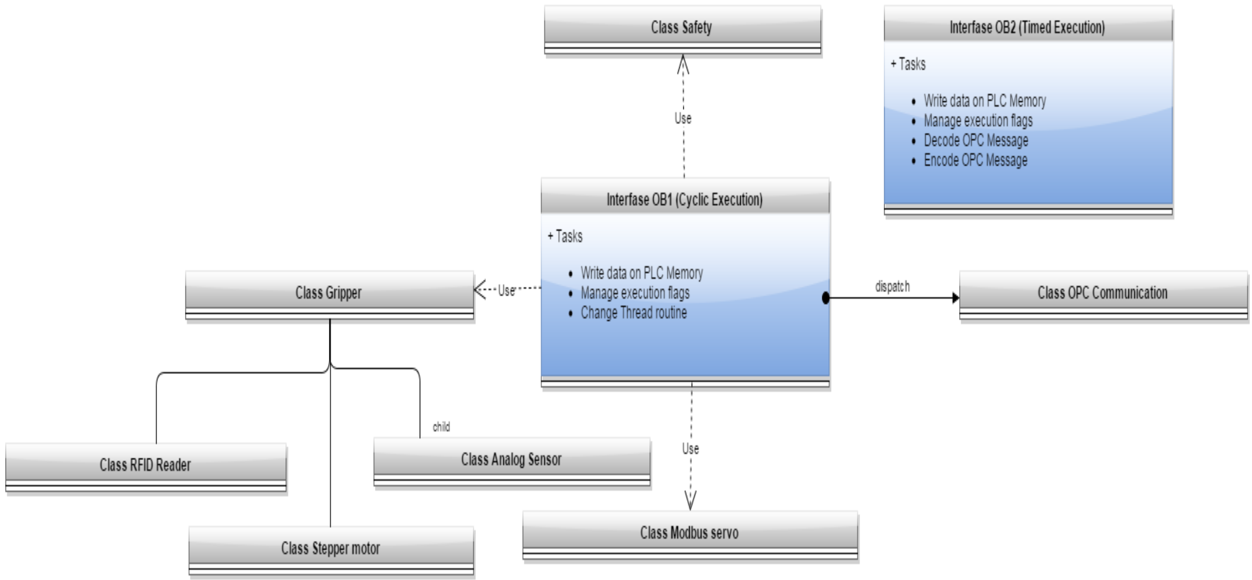
```
BEGIN
    //Executing the grip action
    IF(GRIPPER_GRIP_ACTION == true) THEN
        I(GRIPPER_GRIP_ADDRESS) := 1;
    ELSE
        I(GRIPPER_GRIP_ADDRESS) := 0;
    END_IF;
    //Executing interpolated movement with FC
    GRIPPER_STATUS_MSJ := GRIPPER_STATUS_MSJ OR FB11.DB11
    //Reading the RFID tag.
    GRIPPER_STATUS_MSJ := GRIPPER_STATUS_MSJ OR FB12.DB11
    //Reading the Tag present and the id
    IF(DB11.TAG_PRESENT == true) THEN
        GRIPPER_RFID_TAG_PRESENT := true;
    ELSE
        GRIPPER_RFID_TAG_PRESENT := false;
    END_IF;
    FOR int i :=0 TO i ==4 BY 1 DO
        GRIPPER_RFID_TAG_ID[i]:=()DB11.RFID_VALUE)+1;
    END_FOR;
    //Read the analog sensor.
    //The sensor value refreshes each time with OB1
    GRIPPER_SENSOR_READ := DB11.ANALOG_READING;

END_FUNCTION_BLOCK
```

Figure 5.23: Gripper function block code sample

However, implementing object oriented programming in Siemens SCL is not completely possible since the language does not allow making symbolic instances of a Function Block, and the addressing inside the PLC is usually direct, the Data blocks that contain the member variables of the object are statically expressed in the code.

Finally two Organization blocks are needed in order to manage the functionality of the automation inside the machine. One being the cyclical routine that runs all the time inside the controller and the communication routine that has a timed execution to refresh all the variables



from the server, then the structure of the program is constructed as shown on figure 5.24.

Figure 5.24: Object execution structure of the PLC program

Furthermore, the OB2 Interface is composed for the OPC data exchange, and has a latency of 50ms which provides of 20 samples per second giving a good performance for the variable change in the project.

5.4.2 Desktop application development.

The host application development was made using the framework QT that allows multiplatform compilation and C++ syntax, first it is develop a simple data exchange client for OPC server that perform read and write variables and submit messages. This application has the reading of all the data variables existing on the server that are related to the PLC.

A class structure was also made for the application that allows to make more than one instance of the machine and has methods to submit direct orders to the PLC and read message data, that's why classes that manage the objects inside the PLC have been made as suggested on the following figure 5.25.

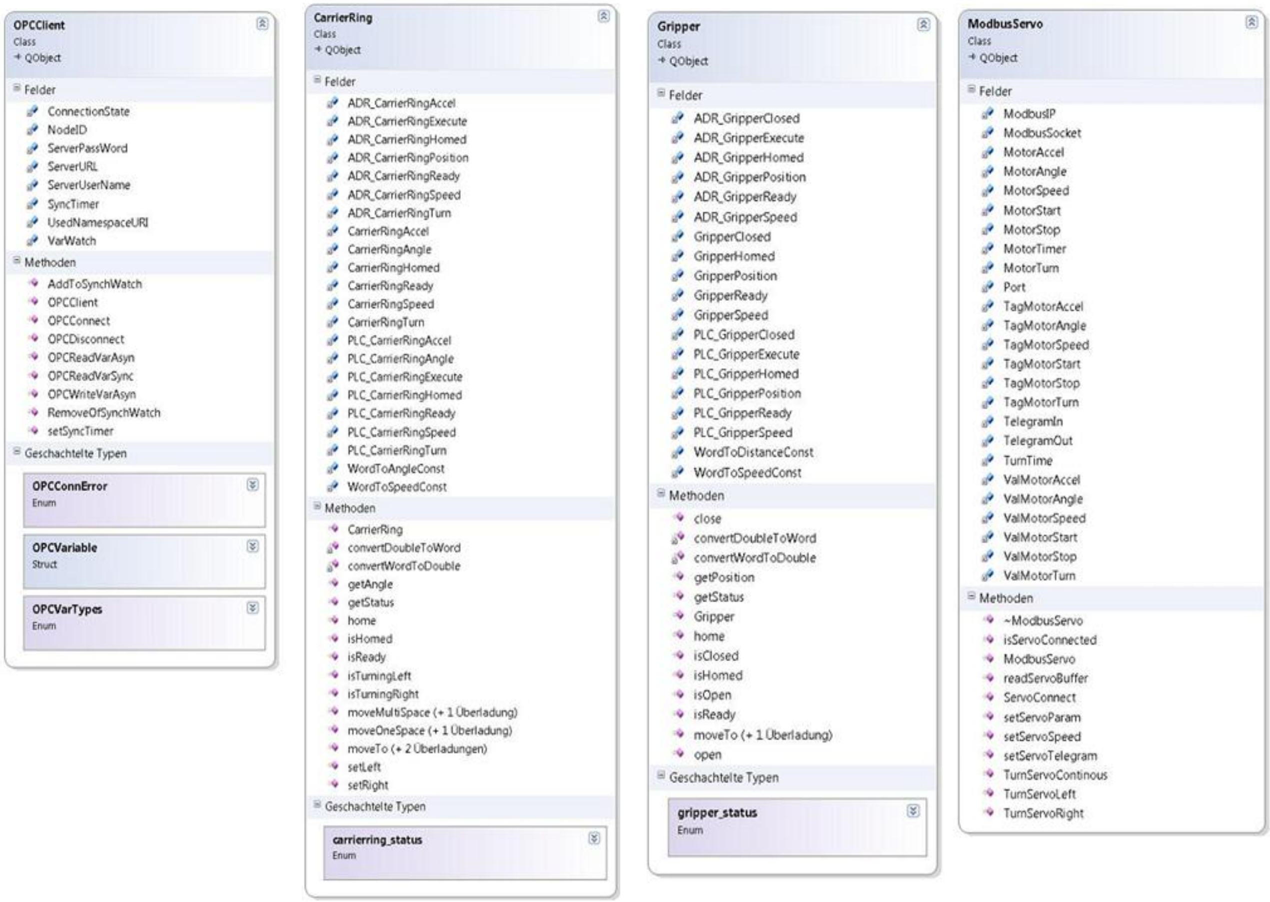


Figure 5.25: Child members of BraidingMachine class

This classes together form the super class BraidingMachine that inherits all the methods from those and allows an easy to use interface that can be reused by the portable application by just eliminating the methods that the developer doesn't want to make available.

From this, a graphical user interface was made for testing purposes, which are to get the process time, the process sequence and detect possible failures on the application.

Other features are planned for the desktop application such as a database that stores the ID and status for each tread inside the process, the runtime and various parameters.

Then, after the requirements of the desktop application are stated, the Braidingmachine class can be extended to manage them, however, those extensions are not covered by this work. An overview of the class and desktop interface is given on figure 5.26.

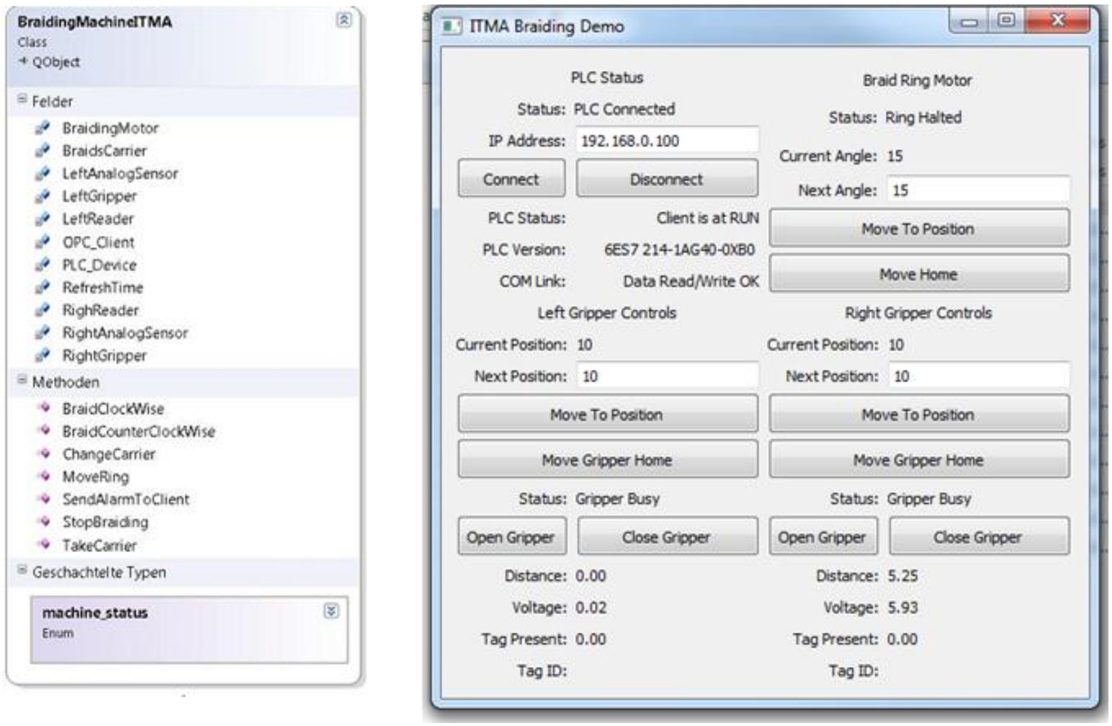


Figure 5.26: Braiding Machine class and minimal desktop interface

Currently in development is the full desktop interface with the database, the final methods for changing carriers and the optimization algorithm. The desktop application is still in development as the scholar period of the project ends, regardless, the current state of the development can be seen on the following figure 5.27.

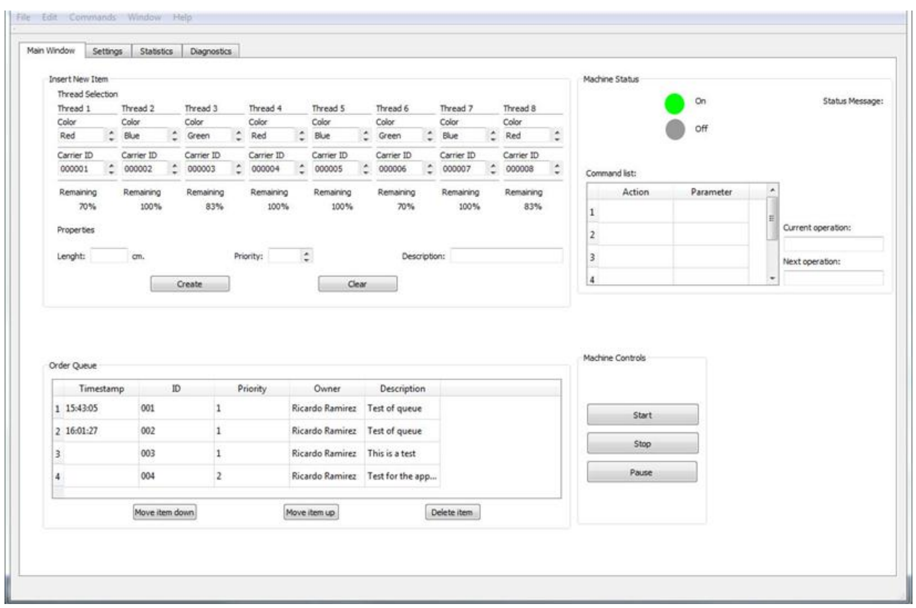


Figure 5.27: Desktop application braiding machine

5.4.3 Client application development

The client application was designed to run in Android devices, and the development of the application was made simultaneously with the desktop and PLC application by the development team. An overview of the development of the android app so far is shown in the following figure 5.28.

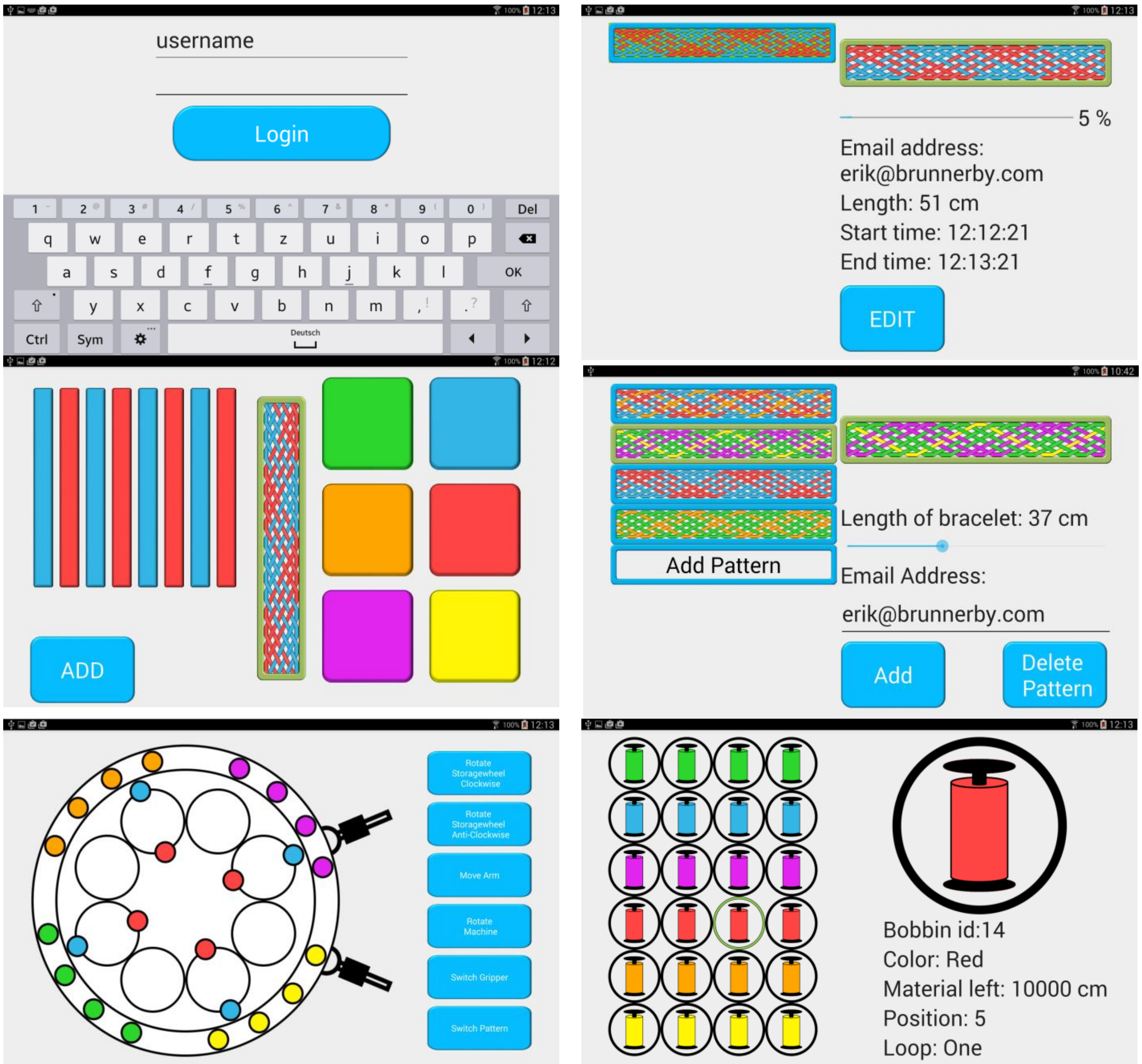


Figure 5.28 Android application design

Chapter VI: Results.

In this chapter the results obtained at the end of the work are going to be compared with the previously achievable set goals. It is important to remark that the goals were being continuously changed through the development, due to unseen obstacles or new ideas that were found on the way. So the summarized goal pretended is to reduce the time for changing the threads because of the help of the automation and to be able to work with the machine on the cloud.

6.1 Thread change time and performance.

The implementation of the machine isn't yet finished, however, with the current development state the measure of an approximate time needed for the changing the final product can be calculated, the braid, as long as the dynamic properties of the grippers are given and can be even tested and the developed optimization algorithm, then, the only parameter that is missing is the amount of braid per minute.

The dynamic parameters for the machine are given on the following table 6.1.

Gripper.	
Maximum speed: 50 mm/s	Acceleration time: 0.25 s
Minimum speed: 5 mm/s	Deceleration time: 0.25 s
Carrier Ring.	
Maximum speed: 35 °/s	Acceleration time: 1.5 s
Minimum speed: 10°/s	Deceleration time: 1.5 s

***Table 19*: Dynamic parameters of the braiding machine**

With this parameters the average time to change any given carrier depends only on the carrier ring movement since the gripper time is already fixed. Movement whose characteristics are also known and therefore can be calculated in an approximated manner. The following table 6.2 gives an example of the approximated times needed for the changing procedures of any single carrier.

Gripper Action.	Time needed.
Check ID carrier on ring	3.5 s.
Check ID carrier on machine	4.5 s.
Grip carrier.	0.2 s. (Gripper works at full voltage)
Carrier Ring Action.	Time needed.
Move to next carrier space. (18°)	1.2 s.
Move to opposite carrier.(180°)	4.8 s.

***Table 20*: Action performing time**

The average amount of movements needed to change from one state to another is shown on table 6.3.

Actions.	Amount.
Carrier changes.	5
Check ID carrier on ring	8
Check ID carrier on machine	16

Table 21: **Average actions per change of state**

Then the average time can be calculated as:

$$Change\ state\ time = (1.2 + 3.5) * 16 + 8 * (1 + 4.5) = 97.2\ s$$

Equation 13

However, the optimization algorithm can have a strong impact on the change state time since usual patterns only need 3 ~ 4 thread changes. Then the time will be reduced in 20% on average.

6.2 Machine assembly and operation.

Simultaneously with the development of the applications, the installation of the electrical components was made, only one adjustment to the original footprint was made because the inrush current needed to magnetize the transformer was too high, then, a new smaller transformer was installed in order to avoid the inrush current problem.

As it can be seen in the image, the electrical installation for the control cabinet has the intended PLC, sensors and controllers.

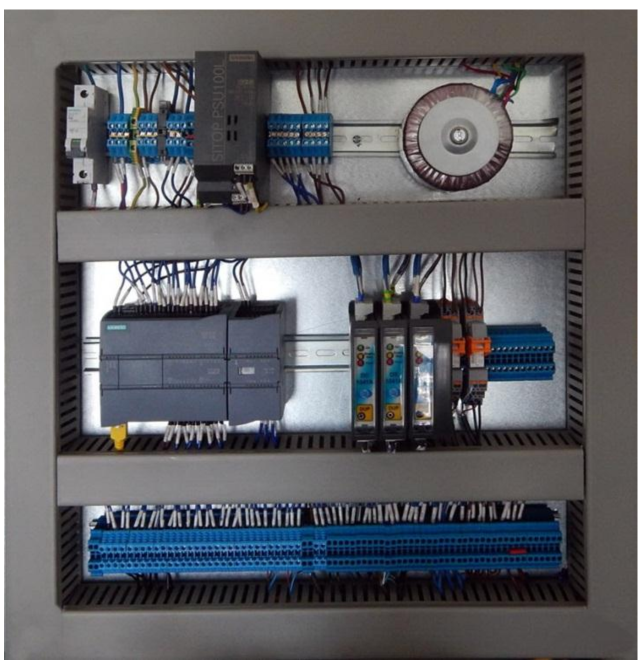


Figure 6.1 Control cabinet installation

Then as is shown in the next image, the stepper motor for the ring is installed in the braiding machine plate. Also the ring is installed in a concentric relation with the braiding machine to allow the correct operation.

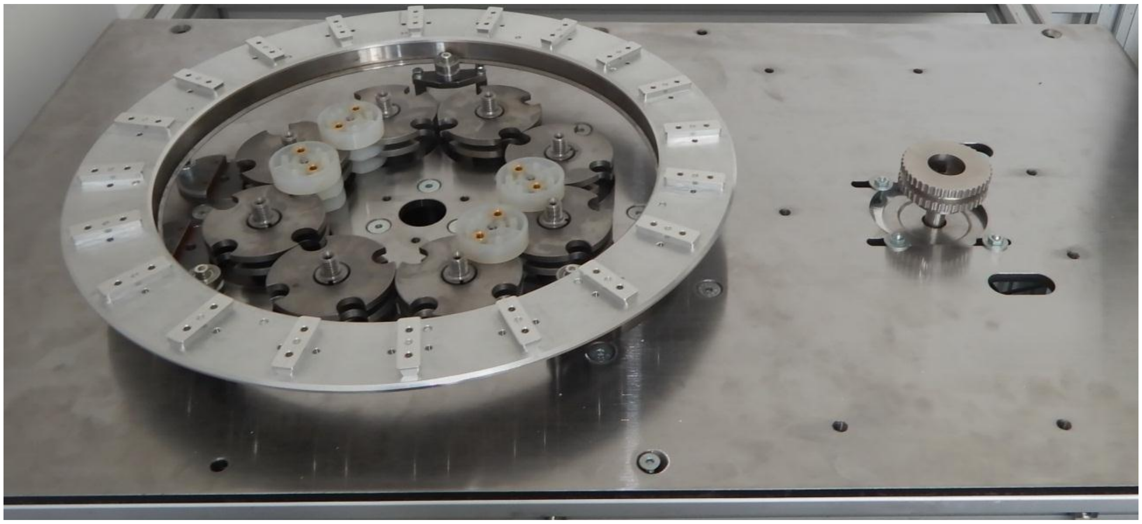


Figure 6.2 Stepper motor and carrier ring installation.

After the installation of the ring and the stepper motor, the grippers had to be installed in a specific way to allow the correct operation to change the threads.

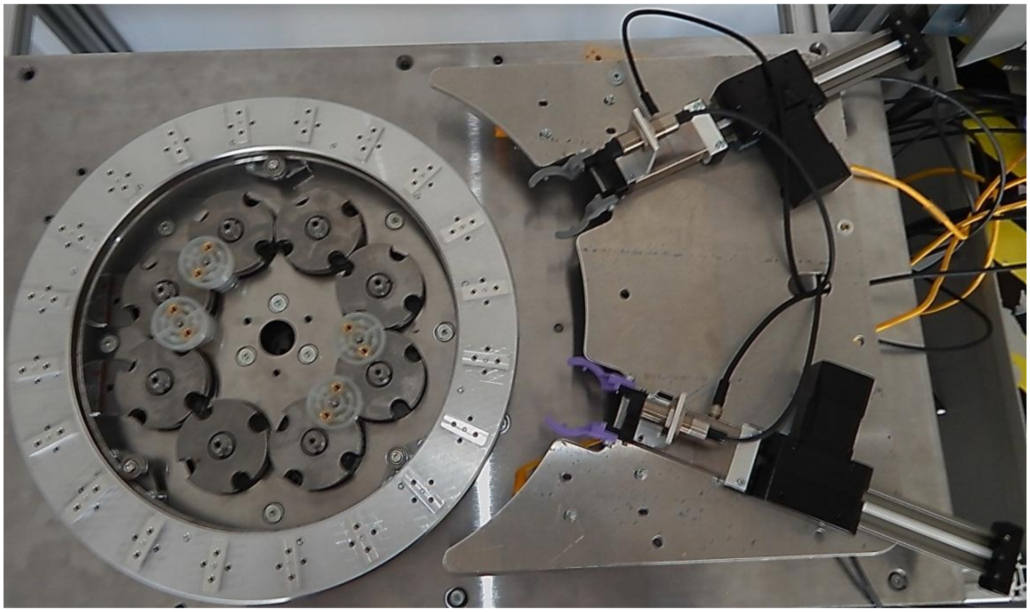


Figure 6.3 Parallel gripper installation.

Each gripper has a RFID sensor on top that allows to know which thread ID is currently in front of it.

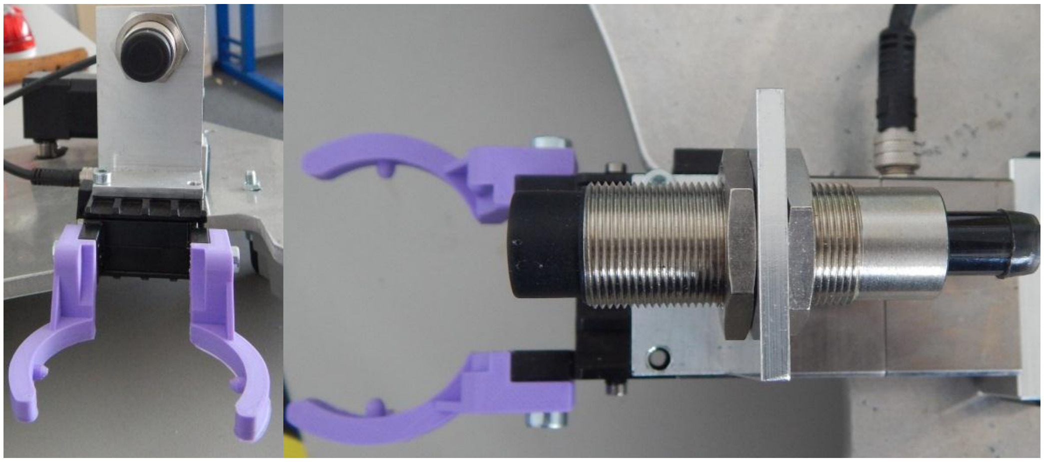


Figure 6.4 Gripper RFID Antenna setup.

The setup allows for the whole system to be adjusted in case of being necessary, in the next picture the gripping step is shown.

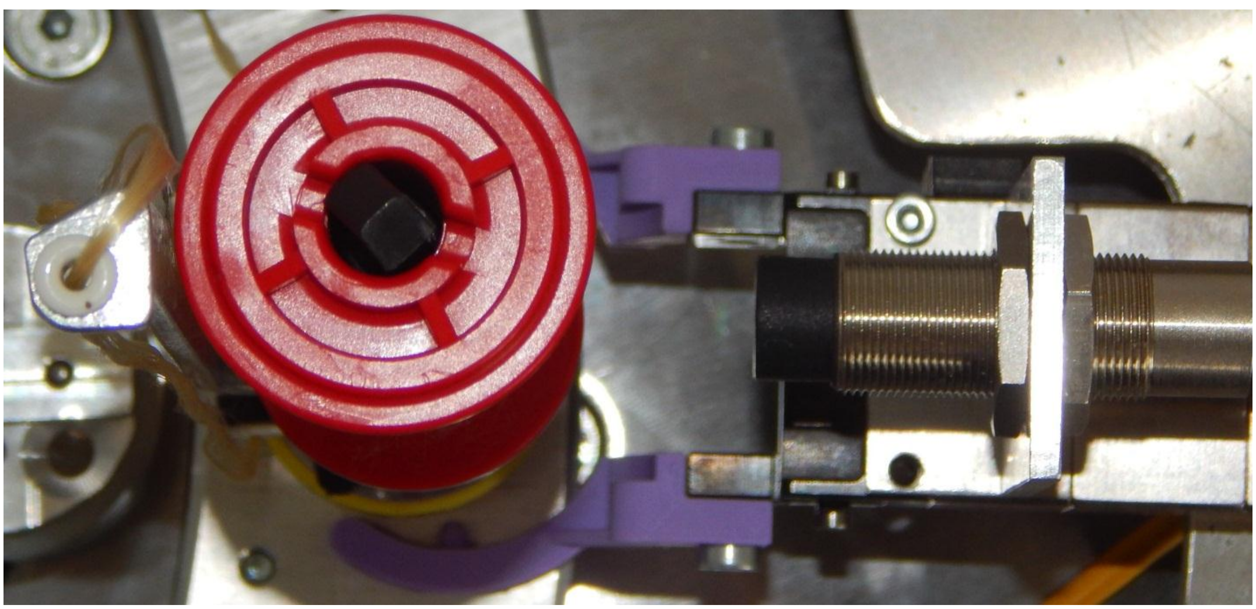


Figure 6.5 Gripping step.

After adjusting the gripper setup, the fixtures for the carriers are installed. The fixture consist in a piece of aluminum and a POM (Polyoxymethylene), these two parts slide onto each other to allow for the carrier to be inserted whether in the machine or the ring. The next figure 6.6 shows the geometry of this fixture.

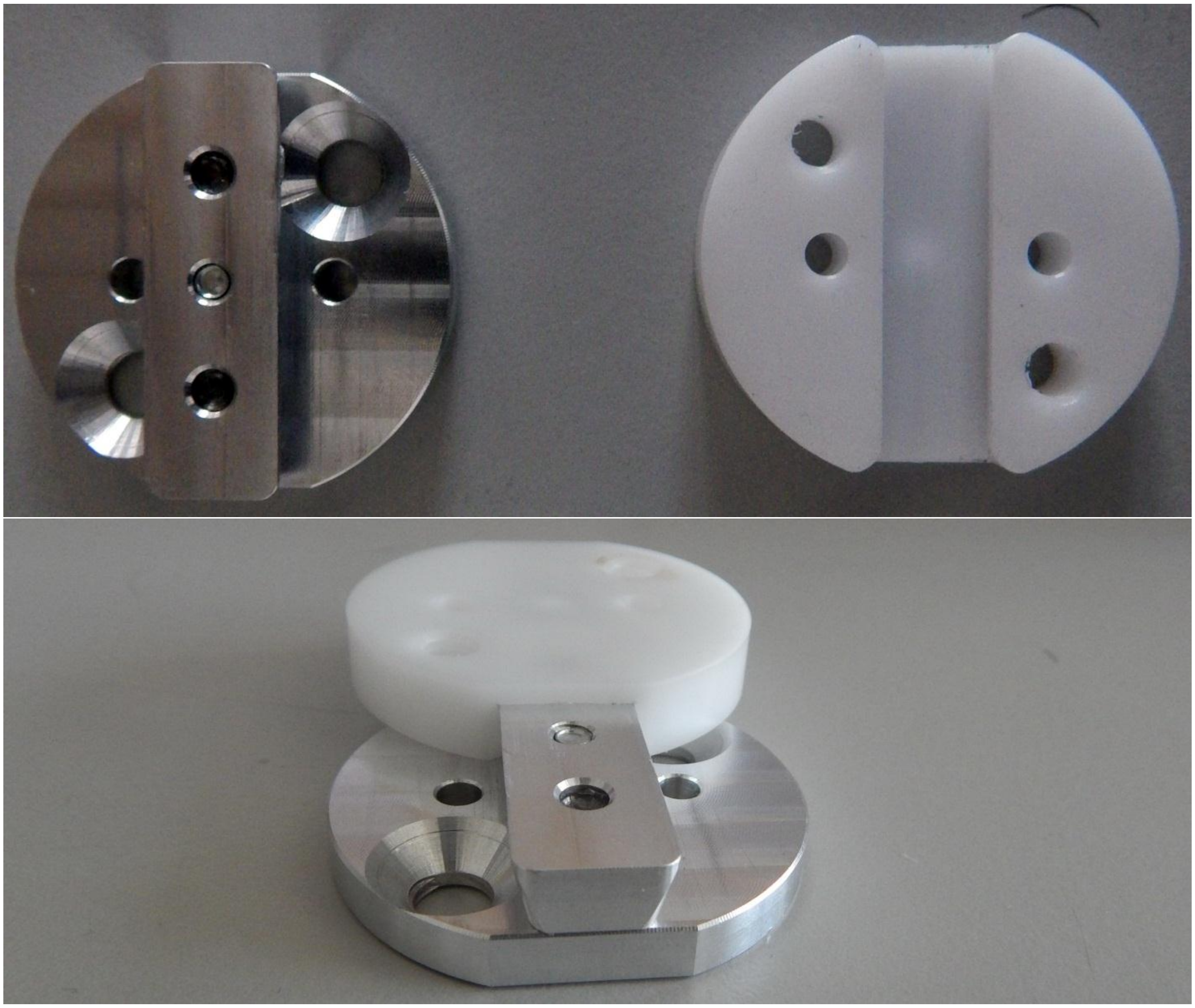


Figure 6.6 Carrier fixture.

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The main feature for the fixture is that it's easily modifiable and the materials offer a good lifespan therefore, the replacement of one piece due to wear isn't a factor to take in account within the normal operation of the machine.

The gripping mode has shown that a new feature has to be added to the POM element since the gripping grove allows rotation on the carrier and that can lead to operational problems. Then a modified POM element was designed and manufactured.

Then the installation for the fixtures in the machine is made as shown in picture 6.7, the thread state can be configured with at least 4 threads.

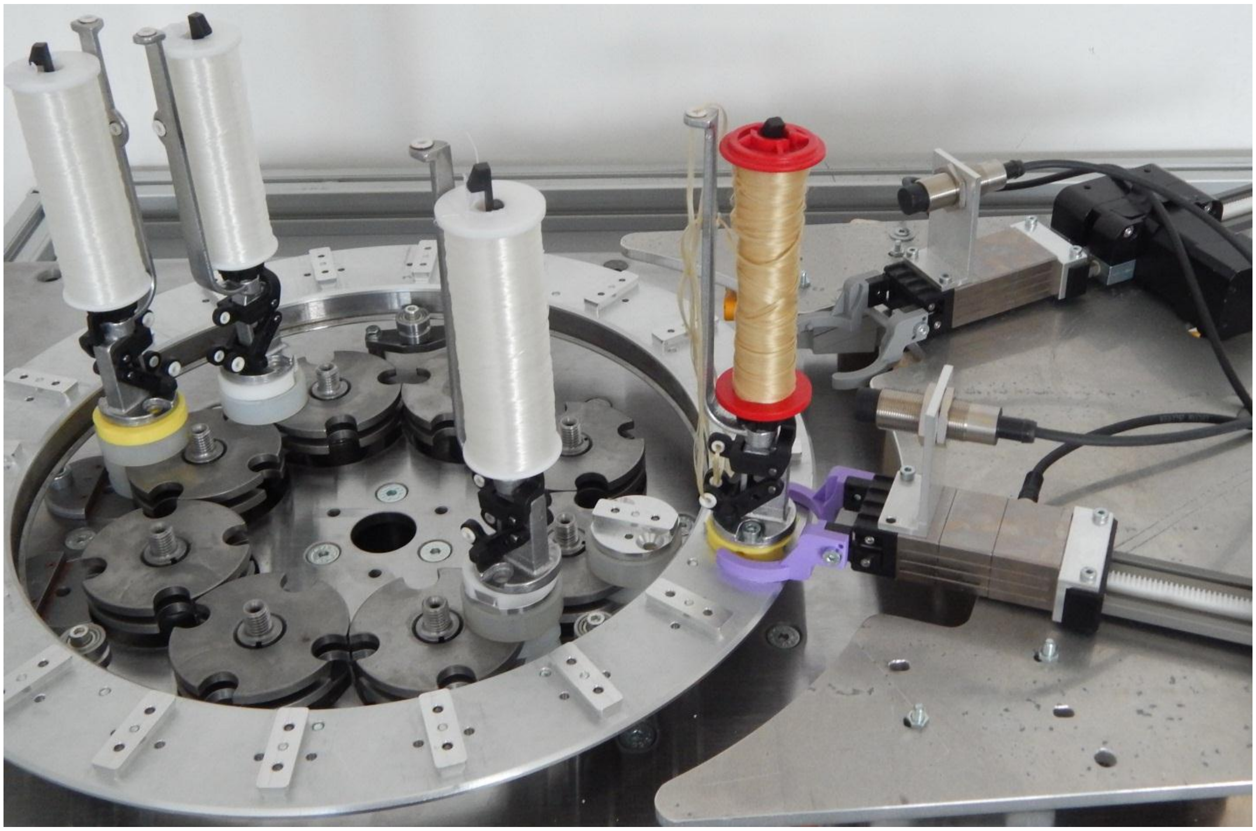

Figure 6.7 Braiding machine basic setup.

There are two remaining installations that have to be made in order to complete the machine, one being the servomotor that powers the mechanism and the pulley that takes the finished braid from the machine.

Chapter VII: Conclusions

The aim of modern production systems is to increase their efficiency as much as possible; that means that it is expected to obtain the largest probable output with the minimum input possible. Nevertheless, in recent times it is important to possess the ability to react promptly to the needed changes in the production in order to react correctly to the market's launch speediness of new products producing a continuous reduction of the products lifespan.

The capability of joining materials with different characteristics in order to obtain better adapted products for specific tasks has been an ongoing research topic for the industrial sector. Braiding, an ancient technology, has been gaining importance to different sectors i.e. medical, aerospace, automotive engineering, etc. during the last decades because it provides those technological needs. Therefore, it is essential to continuously seek for improvements to this manufacturing technology in order to produce better quality products and avoid the slow-down process of developing such innovations.

The idea of developing innovative products should be accompanied by the development of innovative production systems. "Industry 4.0" is a new philosophy that gives the opportunity to the industrial sector to transform the way things are produced with an innovative system which makes the production more effective and flexible.

Industry 4.0's goal is to modernize the actual production systems and to improve their productivity and flexibility. Braiding is a manufacturing process that represents a potential candidate for this kind of industrial revolution; it can be sensibly improved by the adding of the new philosophy of the Industry 4.0. The optimization of the most time-consuming processes and the increase of this type of technology connectivity with an economic approach are the main focus of this new technology; of course without compromising the quality of the final products.

It can be concluded that it was a clever decision to follow a project development guidance; in this case the VDI 2206 guidance was used during this project's improvement because of its tactics, which are based on a structured way of developing projects that involve different disciplines and to keep the attention focus because when a great number of possibilities is open the important objectives of the project can be easily lost and a lot of time can be wasted majorly on looking for solutions that are actually not important for the project's means. It can now be said that this guidance, which is related to the adaptation of mechatronic setups to already working systems, provided a structured way of thinking and an organized working path to be followed by all the parts implicated in the project; and at the end this made an easier linking of the different disciplines involved.

The results represent a big step forward in the optimization of this kind of manufacturing technology besides from the automation, which sensibly reduces the process idle times and the need of man power in a production facility, the possibility of networking many similar machines and even further, being able to control the network from the cloud because of the working principle under it was designed, the Industry 4.0, the scope of this development is largely extended. As said before, it is important to maintain an ongoing research process to find new developments in any type of technology, especially if the aim is to stay competitive in a fast-changing sector; therefore some space to future improvements was left.

Some improvements have already been thought as potential changes for the following steps, like the incorporation of another RFID antenna for writing any new information wanted on either the tools or the products, which will allow an easier handling of the tool's maintenance. Another potential improvement is to opt for an automatic logistics system, among many others. In addition to those improvements the idea of aggregating an extra mechatronic system for cutting the final braids produced at the end of the setup could be useful in addition to an individual packaging system.

It can be concluded that for the development of technology based on the integration of new technologies it is vital to have a path to follow and stick to it at all times; it must be either designed or adopted because the lack of it can lead to time waste and therefore extra costs for the project.

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Appendix

Due to the nature of the appendixes, they are enclosed within a DVD on the back cover of the thesis, and they are organized as follows:

Appendix 1: Complete electrical schematics. Within the folder “Electrical Schematics”

Appendix 2: Datasheets for the electrical components used in the project. Within the folder “Product documentation”

Appendix 3: Detailed and full sized use case diagrams, class structure and flowcharts for the software. Within the folder “Software planning”.

Appendix 4: Source code for the PLC as TIA portal V13 SP1 project with dependencies, server interface and Braiding machine class. Within the folder “Software development”