Department of Precision and Microsystems Engineering

Prototype microwire braiding machine

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Master Thesis Final Report

by

Ioannis Papazoglou

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Preface

I am Ioannis Papazoglou, a mechanical engineer from Greece finishing my Master's of Science in the mechanical engineering department of Delft University of Technology. This Master's Thesis final report summarizes my year long CERN technical student placement and it serves as a documentation to the complete end-to-end design of a prototype machinery purposed to braid microwires for the wire scanners.

This experience is an integral part of my master's education as it gave me real-life, high tech engineering training. There are two reasons I selected this graduation project, the project I undertook and the reality of working at CERN.

The project itself was of extreme interest to me as I had the opportunity to design a complete prototype machine. Meaning that in the beginning of my program I had a loose list of requirements and at the end of it I produced a working prototype. In order to achieve this, many of the engineering and project management skills, obtained during my studying years, were used. The novel nature of the objective of this prototype machine meant that many new problems appeared, that a solution was not known at the moment and not trivial to find and thus I had the opportunity to use and further develop my troubleshooting skills.

I was given the opportunity to interact with remarkable engineers and scientists who have contributed the most to my development as engineer. In addition, my involvement in the machine design phase of this prototype machine aligns well with the education I received during my Masters at. Moreover the engineering applications of CERN's systems aligns well with the education I received during my Masters at Precision and Microsystems Engineering. The machine I designed aims to braid 7 µm wires in a controlled way and the whole accelerator complex controls sub millimeter proton beans at the speed of light.

Concluding, working for CERN has been remarkable. I managed an interesting project and gained valuable experience in using technical as long as system engineering and soft skills. The technical skills obtained relate to the engineering design of a concept and evaluating its performance before manufacturing as well as designing a system following functional and manufacturing requirements. The system engineering done during this project was necessary in order to streamline the design process and design evaluation. Moreover, I expanded my soft skills as I was working as a part of the larger beams instrumentation group. Finally, I am happy to kick-start my career at CERN as I will be continuing working here as a mechanical engineer for the next couple of years.

Ioannis Papazoglou
Geneva, Switzerland, May 2020

Abstract

Micrometer thin, braided wires, is a niche requirement that has applications in beam instrumentation. Due to the rare use-case of extremely thin braided wires there are no established or industrial braiding methods developed. For this reason, a novel method for braiding thin wires was developed. In order to achieve a repeatable result a prototype braiding machine was designed, built and tested. Stainless steel, nylon and carbon wires were tested and evaluated. The aim of this research was to prove that braiding extremely small yarns is possible. Also, the proposed machine parameters have been optimized to ensure repeatability and good quality wires production. By proving that braiding thin wires, in the order of a few tens of microns, we open the way for braiding extremely thin wires for wire scanners.

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Acknowledgments

First, I would like to thank my daily supervisors at CERN, dr. Raymond Veness and William Andreazza for their daily guidance and support during this project. They were always open to my ideas, supportive for exploring new concepts and always provided me with useful feedback. Moreover, the whole team in our section, Mechanics and Logistics section of Beams Instrumentation Group, was always supportive and helped me both to adapt to my new job and life in the area.

Furthermore, I want to thank my TU Delft supervisor, prof. Just Herder from Delft University of Technology Precision and Microsystems Engineering department for always finding the time to virtually meet with me, being open for discussion and new ideas and always contributing with critical thinking points.

Last, but definitely not least, I would like to thank my family for always supporting me during my not so straight path for graduation!

Ioannis Papazoglou
Geneva, Switzerland, May 2020

1
Introduction

1.1. Background

At CERN there is a set of instruments that measures the beam characteristics by passing a wire through it and detecting the scattered particles downstream. Those instruments are the so called Wire Scanners and are widely used due to their high accuracy and precision. Figure 1.1 illustrates CERN's Wire Scanners and its main components. The most critical components of the Wire Scanners are the wires themselves that are comprised of 12 hand twisted 7 μm yarns in a less than 35 μm equivalent diameter package. As the power of the accelerators increases a more repeatable and reliable wire braiding technique is required [29].

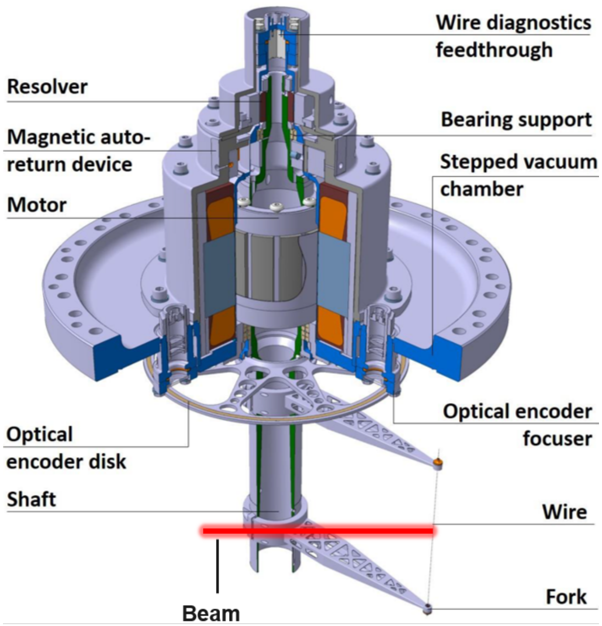


Figure 1.1: CERN's Wire Scanner [28].

In order to tackle the aforementioned issue, a new braiding method needs to be developed to braid the 12 yarns of 7 μm diameter into a wire with a repeatable manner while satisfying the quality specifications. The diameter (7 μm yarns), length (200 mm) and material (carbon fiber or carbon nano tubes) of the yarns required, made it unable to use a commercial available solution as all the up-to-date options are designed for thicker yarns and for long cable production. Moreover, the application of these wires needs as close packing factor as possible, in order to allow measuring thin beams, and all the available braiding equipment for 12 yarns are producing tubular wires compromising the density.

1.1.1. Wire Scanners at CERN

Over the years, CERN has established an impressive number of particle accelerators that enable the research of the fundamental parts of our existence [22]. The main product at CERN are the protons and heavy ions beams, produced and accelerated in the accelerator complex, with the most famous being the Large Hadron Collider (LHC) [6], and the coming power update the High Luminocity LHC (HL-LHC) [10]. In order to keep the beam and its characteristics according to its user's requirements there is a set of instruments used to measure the size, position and energy of the beams in the accelerator lines. One of the most used and reliable instruments currently used in the accelerator are the wire scanners [7, 24, 28].

The wire scanners are one of the few instruments being in direct contact with the beams at CERN and thus their reliability is a matter of paramount importance. The working principle of the wire scanners is described bellow:

A carbon wire is passed through the beam, intercepting it. The interaction generates secondary particles that are scattered from the wire and the latter are subsequently measured by the downstream detector. By having a few measurements along the width of the beam a distribution curve can be recreated resulting in a two dimensional representation of the beam along the moving axis and the direction of the beam. By placing two of those instruments one horizontal and one vertical we can recreate the position and the intensity of the beam in three dimensional space. Those results are then used to calibrate other instruments and to control the position and intensity of the beam.[5, 11]

1.1.2. Current solution

The wire scanners is a popular and very reliable instrument used to measure the profile of the beams at CERN's accelerators. All the operational wires at this moment are manually manufactured, resulting in a high consuming process handled by high qualified personnel. Due to the intrinsic stochastic nature of the manual process the manual twisting results in imperfections. Moreover, due to the wire dimension and the manual nature of the process it is not possible to create customizable wires and there is no ability for braiding, instead of twisting, the wires. There is a clear and pressing need for a new more standardized method.

CERN has been actively seeking for methods to optimize the twisting technique [5, 29] as well as list all quality requirements for building a microwire braiding machine [13]. Moreover there is a move within CERN to make all the knowledge produced more transferable and not susceptible to single points of failure. Also we are currently looking in testing wires of different materials, namely carbon nanotubes [14] which will make the need of fast customizable wires more pressing.

Concluding, creating an automated and standardized method of braiding microwires, via the use of the microwire braiding machine, we aim to improve on the excising solution of twisted wires, tackle the problem of knowledge transfer by having a standard process and adequate documentation, and open the way for future wires testing and prototyping.

1.2. Current limitations

Currently CERN uses carbon wires on their wire scanners. There are currently two versions of wires used, a solid 32 µm yarn and a hand twisted set of twelve 7 µm yarns into one wire. A suitable braiding solution is necessary extending the current simple twisting method. The reason is that by braiding the yarns the strength of the produced wire increases [12, 18, 21, 23, 29] and in case of single yarn failure the rest of the braided yarns can contain the faulty wire, reducing the risk of interference with the beam. By reducing the risk of yarns interfering with the beam we can increase the reliability of the scanners and result in fewer shutdowns and interventions to the accelerator complex, in order to change or remove the wire scanners, which has been proven over the years to be extremely time consuming and expensive process.

Additionally, by creating a standardized approach with a use of a machine for braiding the wires we have the ability of obtaining greater quality, more reproducible and uniform wires, as well as being able to change braiding parameters, most notably the braiding frequency and testing new configurations.

Finally challenges for this project pose the extremely thin wires of 7 µm but also the small number of units required and produced per year. This hinders us to opt out of a custom manufactured solution but rather develop an in-house new machine for this specific application. This machine will have the ability to adopt in different wire material, as Carbon Nano-Tubes are investigated for the next generation of wire scanner wires. As well as braid wires of different diameters and braiding topology, allowing strands of yarns as well as single yarns to be braided.

1.3. Research objectives

The main research objective for this project is to produce high quality braided micro wires. High quality micro wires are identified using two metrics, the braiding regularity and the packing factor. The braiding regularity refers to how canonical is the wire braided along its length. The packing factor refers to the amount of space left unoccupied by yarns within the wire. That one may identify a wire as high quality for this application it is required to be both regularly braided and as densely packed as possible. All the methods of evaluating the wires can be found in detail in Section 4.3.

There are three main goals need to be met to achieve the microwire braiding. First, a new standardized wire braiding method, suitable for micro wires, is required. To propose a new microwire braiding method, the optimum yarn material and braiding topology will be investigated so the tightest braiding pattern possible can be established. Second, a working prototype microwire braiding machine will be developed. The prototype will be tested and optimized for micro wire braiding. Finally, highly regular micro wires need to be produced using the microwire braiding machine.

1.4. Project approach

In order to complete this project, the following design approach is considered:

- State of the art review (presented in Chapter 2).
- Braiding topology and material selection.
- Mechanical Design.
- Drawings.
- Controls Design.

To evaluate the project approach as presented above, two main system engineering tools are implemented: the functional decomposition and trade-off tables. Following the design process there are a few additional steps necessary for the implementation of the machine:

- Parts production.
- Commercial parts procurement.
- Machine assembly.
- Machine testing.

1.4.1. Braiding topology and material selection

There are three main challenges concerning the feasibility of a microwire braiding machine: the selection of the braiding topology, the availability of the yarns and the dimension of the yarns. Those three challenges directly impact one another and the quality and performance of the wires. The braiding topology is an indication on how good the packing factor of the braided wire can be and is impacted on the yarns dimension to be selected. On the other hand, the yarns selection is directly impacted by the availability of yarns in the market.

Braiding topology

The braiding topology refers to the shape of the braid itself. It direct impacts the performance of the wire and the design of the microwire braiding machine. This topic is extensively discussed in the Methods chapter and Section 3.2: *"Braiding Topology and material selection"*.

Yarns availability

As the produced wires will be used in a niche application, the availability of the yarns constitutes a very important selection criterion and a considerable limitation factor regarding the design space. Having a limited application means that there is no possibility of a custom yarns solution as it will be extremely costly and hard to justify pulling all the resources in designing a custom solution while there are commercially available similar products. This constrains the yarn selection on only the commercially available diameters, lengths and delivery form and thus the braiding process and topology need to consider only commercial available product as feasible solution.

From the discussion above, it is clear that an important part of this project is the material market research where all the available carbon wires should be listed and then continue on selecting the braiding topology and exact configuration of the wire. For this reason a wide range of carbon fiber manufacturers were contacted early in the project time-line and a list of the available yarn configurations was compiled. During the braiding topology selection process this list was advised in order to create a feasible and realistic design proposal.

Yarns dimension

The yarn dimension closely relates to the previous challenge, the availability of the yarns, as for such a small diameter of yarns the options are limiter. Additionally the dimension of the yarns entails a design challenge. Manipulating such thin yarns makes it very challenging to follow the path of the traditional state of the art braiding machines, as they were designed for rope or even stent production.

Most of the functions of the state of the art braiding machine, presented in Section 2.1.1, are problematic when designing for extremely thin yarns.

1.4.2. Mechanical design

Mechanical Design is a major process for this project and it is closely connected with the literature review and the state of the art research. For a more detailed view of the mechanical design approach consideration please refer to Section 3.3.

1.4.3. Production drawings

In order to produce the parts we need drawings for each part and sub assembly of the machine. All the drawings aimed for production need to go thought the CERN's quality evaluation process to ensure all the parts satisfy CERN's quality and safety regulations standards. The production drawings along with final 3D models are reviewed in Section 3.4.

1.4.4. Controls design

As this machine uses some actuation there is need for controls. The controls used in this project are not going to be in house as this is out of the scope of this project. We are using commercially available motors and controllers and simple controls designed for all the systems to work in parallel.

Moreover the nature of the machine does not require complicated control systems as there will not be any disturbances rejection designed in the guiding systems. A case can be made that more complicated control systems might be necessary for a machine like that but as this is a prototype aiming to produce braided carbon microwires for the first time, such an exercise will not be beneficial for the project's outcome.

1.4.5. Parts production

The design philosophy behind this machine is to use as many commercially available parts as possible. This way we can focus more in the function of the machine and not in the design process. Nevertheless as it is a prototype machine it was bound to have some custom parts. This allows us to expedite the production and better control the manufacturing process. The produced parts are showcased in Section 3.5

1.4.6. Commercial parts procurement

The design aim of this project is to implement a big percentage of the machine machine components as commercially available parts. This means that the CERN procurement processes shall be followed when ordering parts.

1.4.7. Machine assembly

The assembly of the machine is one of the most interesting parts of the project as it is the first time to see in the physical world and not a 3D model using drawing CAD tools e.g. CATIA®. This process can be time consuming especially if there are mistakes in design or manufacturing. The assembly was performed in the labs of the BE-BI-ML section at CERN. The assembly of the machine is discussed in Section 4.1.1

1.4.8. Machine testing

After the initial assembly, dynamic and functional tests are performed. This layering of testing outlooks into identifying issues earlier and solving them before moving with testing more complicated functions. These tests are performed before the wire braiding tests and aimed in testing the functionality of the individual subsystems of the prototype machine. The wire braiding tests initiated with thick and progressed to thinner wires. The testing and evaluation of the machine is presented in Section 4.1.

2
State of the art

2.1. Braiding machines

There are two main areas to focus for braiding machines. First, is the standard rope braiding process which is by definition focused in yarns several orders of magnitude thicker but nevertheless the mechanisms and techniques used can be a useful insight in braiding technology and design approach. Second are the stent and general medical yarns braiding machines: those machines are closer to the dimension of the microwires required for the wire scanners but there are different limitations such as the material. Moreover there is an additional type of braiding machines used for waiving and flat braiding but although evaluated are not included in the current report as they are out of the scope of this project

2.1.1. Rope braiding machines

The design of rope braiding machines is largely unchanged for the last few decades and their key components are quire similar as described from the very old patent, depicted in Figure 2.1 [16].

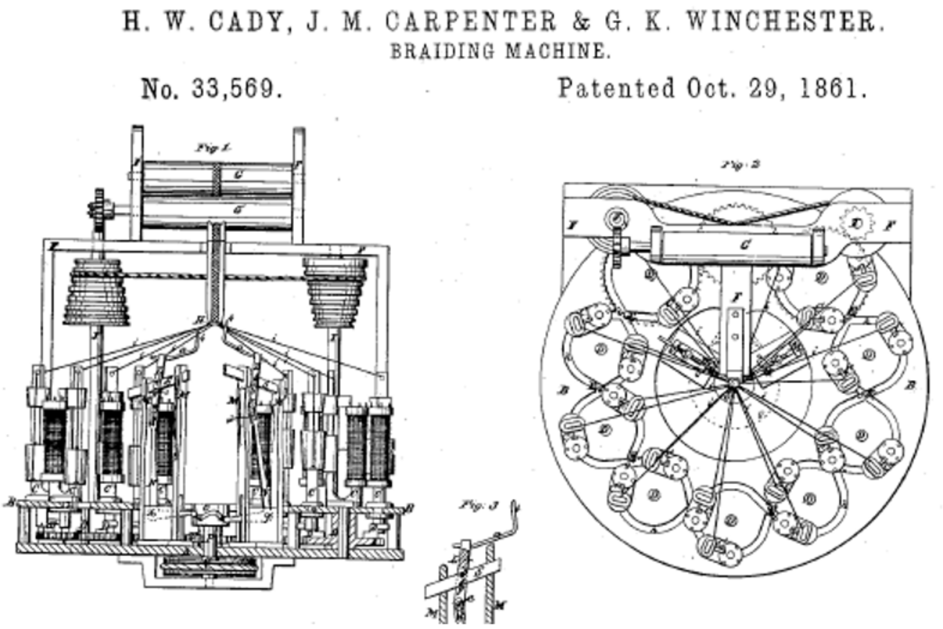


Figure 2.1: Braiding machine patent schematics [16].

The last few years there is a modernization to the classical design by adding additional motors and sensors and thus having the possibility of faster changes in the settings of the machine and more customization of the braids produced, better control and faster braiding, but the core of the machine is still largely unmodified.

Generally a rope braiding machine can be subdivided in a series of subsystems, each responsible for a specific function of the braiding process. The main subsystems can be seen in Figure 2.2 and are:

- Motion System (actuation)
- Carriers (better shown in Figure 2.3)
- Braiding Point
- Take-off
- Collection (not pictured in Figure 2.2)

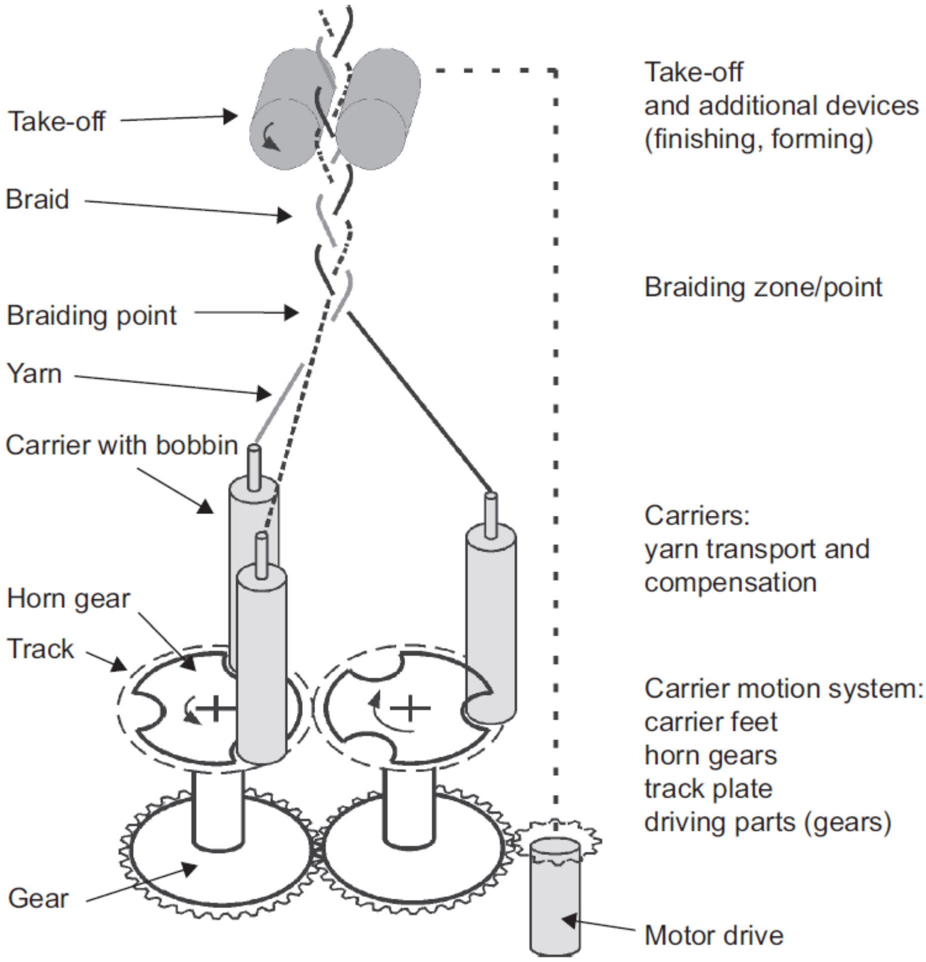


Figure 2.2: Main components and functions of a braiding machine [1].

The main components of a braiding machine are described in Figure 2.2 [1]. The motion system, or actuation system is responsible for the motor displacement of the machine. It is comprised by an electric motor that is connected to a set of driving gears, seen in the bottom of Figure 2.2 [1]. Those gears transfer the drive force to each other and are connected with a shaft to another set of gears. The second set of gears are called Horn gears and are the ones with a cut on the side in order to transfer the actuation to the carriers. All this system is mounted on a guiding path that guides the carriers around the appropriate braiding shape.

The classic carrier design is better illustrated in Figure 2.3 [2]. It is one of the most complex and most important part of this braiding machine design. The carrier is responsible for holding the bobbin with the yarn reserve and ensure the yarn is under constant tension and feeding the correct amount of yarn for braiding using the braking mechanism (shown on the top of Figure 2.3, the part with the teeth is a step by step braking mechanism).

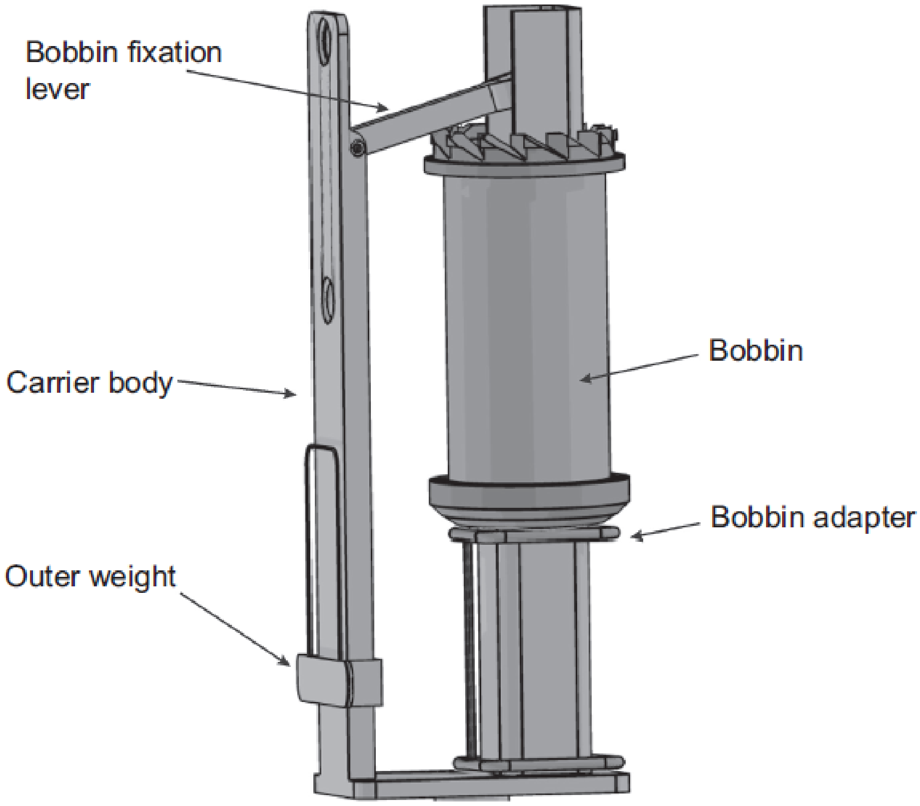


Figure 2.3: Carrier design with weight balance [2].

In addition, the Braiding point is controlled by the guiding mechanism that dictates the exact braiding point by physically forcing the yarns to converge where it is desired. The take off mechanism is usually a friction based mechanism that rolls the finished wire towards the collection mechanism. The take off mechanism together with the motor speed aim to control the braiding frequency by adjusting their relevant velocities. Finally the collection mechanism, which is not shown in Figure 2.2 is usually an additional spool where the finished product is collected when the braiding process is completed.

2.1.2. Medical yarns braiding machines

There is a range of braiding machines used for stent braiding applications [9, 9, 25]. These machines operate with the same working principles as the aforementioned rope and wire braiding machine with the difference they use thin metal wires but thicker than 7 μm.

A notable braiding machines manufacturer is the Steeger company [27]. Their machines can braid wires closer to the size required for the wire scanners but are compromised in the sense they braid metal wires and those machines are also based on the same method described earlier using bobbins with very long yarns.

2.1.3. Carbon yarns braiding

Although there is a lot of literature in carbon production and carbon nanotube production, braiding carbon fibers is not a popular research topic. Park et al [20] showed promising results, as shown in Figure 2.4 but as highlighted in the aforementioned paper, the proposed technique is not useful for this application as they only twisted manually one yarn in Figure 2.4, B and a set of two yarns shown in Figure 2.4, C. It has to be noted, although one might have the impression that one braided wire is needed for the microwire machine, it is just a manually twisted carbon yarn. Moreover, the described effect is only localized and not along the length of the hundreds of millimeters we require.

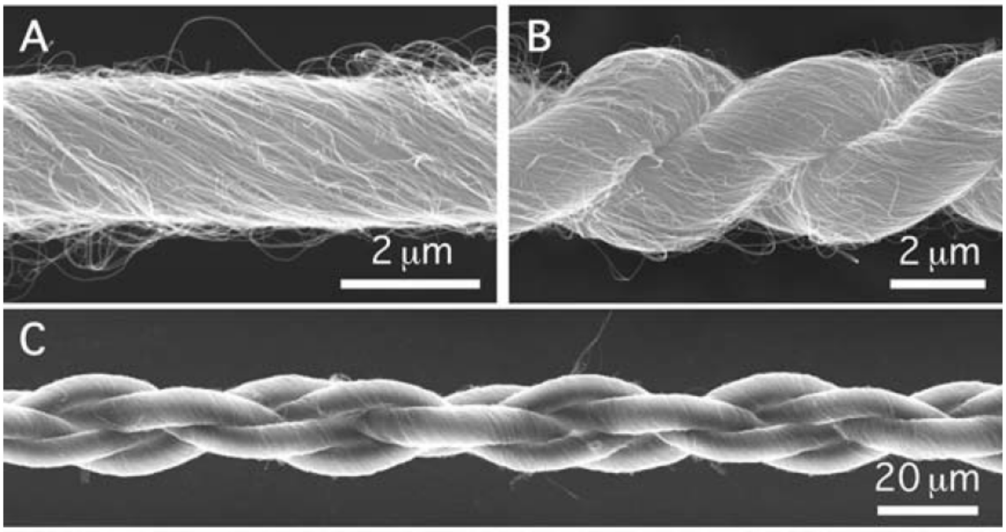


Figure 2.4: Twisted carbon nanotube yarns from Park et all [20].

One additional promising technique was introduced by 3TEX [3, 4]. They developed a machine that can braid multiple yarns but as can be seen in Figure 2.5 it is a manually operated machine and the yarns used to produce the wire are thicker compared to the 7 μm yarns we require.

2.2. Limitations of the state of the art

Concluding the research on the wire braiding machines and techniques, there was a set of limitations towards the application that is necessary for this project, namely densely braiding 7 μm carbon yarns. Those limitations are imposed by the limited length of yarns needed.

More specifically we cannot obtain very long carbon yarns on bobbins making all the excising options unfeasible or necessary to invest more resources for designing new processes for separating long lengths of the shipped multistrand yarns and rolling them to bobbins before using it for braiding. This solution appears straight forward but the very small dimension of the yarns and the fact that they are shipped pre-rolled with 12000 yarns bundled constitutes it a formidable task.

Additionally, all the carriers investigated comprised by heavy duty mechanisms that require excessive force to be applied in the wires and there is friction applied in the yarns for the tension and feeding control functions, an effect that is not desirable for the carbon wires. The same applies for the tensioning mechanism that is mostly based on pulling the wire through friction force and it poses danger for damaging the wires. Finally, the collection mechanism requires long braided wires to justify its existence.

Concluding the state of the art, available machines available at the moment cannot cope with carbon microwire braiding. There are two main reasons of the incompatibility of those machines, the length of the initial yarns and the potential damage on the braided wire. Thus, a new solution for microwire braiding is needed in the form of a new microwire braiding machine that takes into consideration all the aforementioned shortcomings of the excising solutions.

2.3. Additional uses for braided microwires

The application that drives the design of a new braiding method is CERN's wire scanners. Nevertheless, the current proposed braiding machine design can be extended from the CERN wire scanner application to different particle accelerators across the world in need for more reliable wire solution.

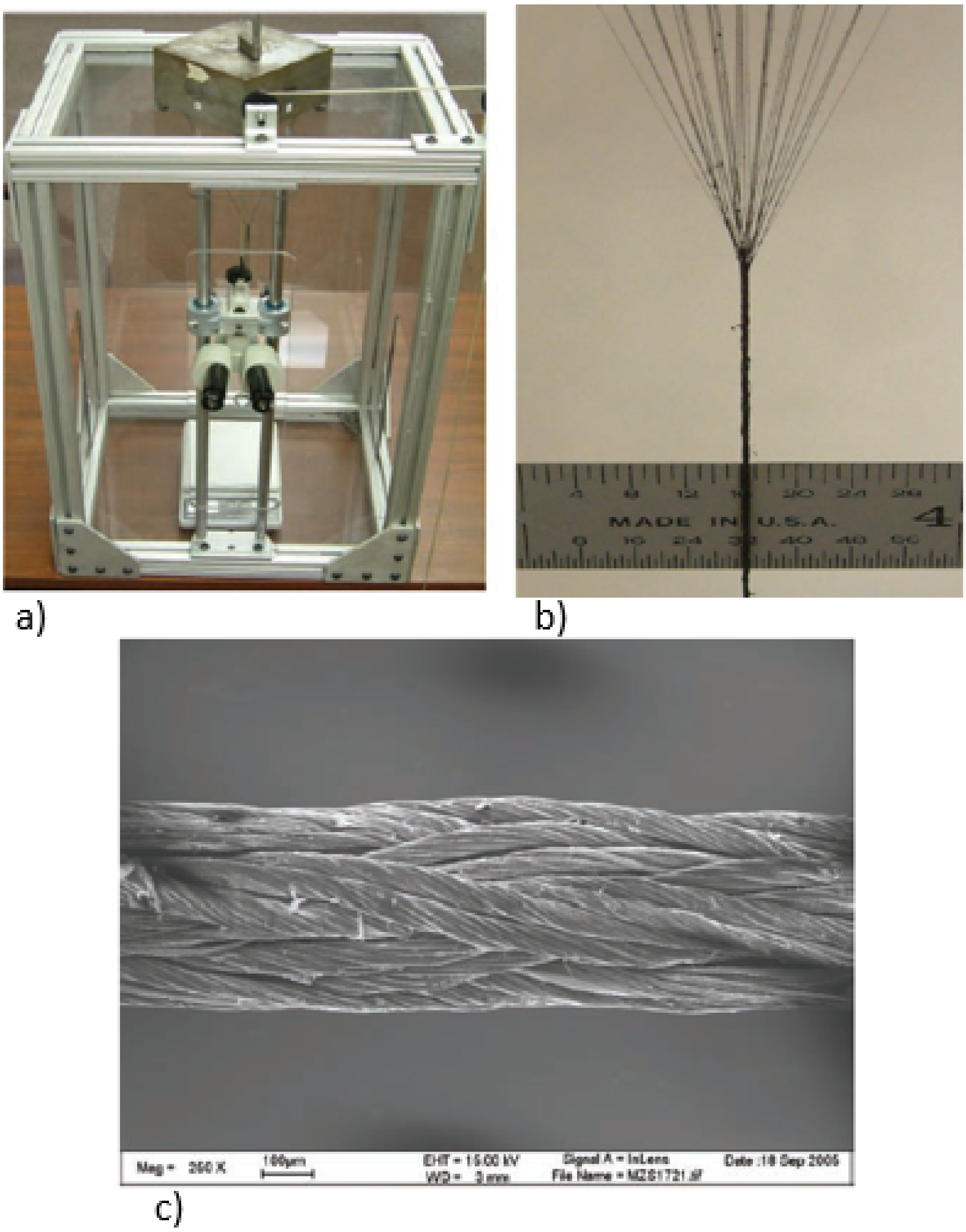


Figure 2.5: 3TEX carbon braiding. a) braiding machine, b) braided wire and c) SEM imaging of the braided wire [4].

3

Methods

3.1. Wire assessment

In order to verify if all research objectives are met and the listed requirements satisfied there is a list of measurable criteria introduced to allow the evaluation and improvement of the machine's product, the wire scanner wires. Those criteria are:

- Braided length.
- Braiding packing.
- Uniformity of the braids.
- Mechanical properties of the wire.

3.1.1. Braided length

There is a series of wire scanner machines in CERN's accelerator complex that can use the produced wire. Those machines are not all the same as there are used in different accelerators, with different beam energies, and there are multiple versions of wire scanners developed along the years of its commission that are currently active. Thus the braided length should be within a range of 100 mm to 200 mm. To ensure a future proof design and the uniformity of the braids, the machine should be capable of braiding longer wires. The braided length consists the part of the whire where regular braiding is present only, meaning that all the mounting of the wires or loose yarns are excluded from the braided length of the wire,

3.1.2. Wire packing

The wires application dictates as tight packing as possible and regular diameter along the length of the wire. The wire packing can be defined with the use of the packing factor where the volume of the wire occupied by material (the braided yarns) is divided by the total volume occupied by the wire, the wire envelope. A tight packing factor is crucial as it translates to smaller braided wire diameter compared to a loose braided wire. A tight packing factor can be defined individually for each wire and braiding topology. A theoretical attempt to identify the optimum packing for different wire typologies is presented in Section 3.2.2.

Obtaining a wire with high packing factor in is important in order to obtain measurements using the wire scanners as the wires occupy less area for equivalent diameters and thus more measurements can be taken while crossing the proton beams. The method of calculating experimentally the braided wires packing factor used in this report is explained in Section 4.3.2.

3.1.3. Uniformity of the braids

The uniformity of the braids, also mentioned as regularity of the braids, refers to the canonical frequency of the braids along the length of the braided wires. In order to determine the uniformity of the braids, two measuremnts are used, the braiding wavelength of the wire and the outer diameter of the wire. By obtaining a small standard deviation of these measurements along the braided wire, the wire is deemed uniform. The measurements performed for to determine the regularity are explained in Section 4.3.1.

Uniform cables allow for more reliable measurements from the machines as the cross section is constant across the wire length. Additionally, the change of the braiding parameters allows the manipulation of the braiding frequency and to perform tests with different wires and thus ensuring an optimum braiding.

3.1.4. Mechanical properties of the wires

As the wires are in constant tension and are subject to rotational acceleration their mechanical properties will be tested. The wires are under 4 N of tension and due to the rotational acceleration of 1760 m s^{-2} it is equivalent to just 2.3×10^{-6} N due to its small weight.

In principle, the braided wires should be able to meet and withstand all the forces exerted to them and additionally any additional CERN strength requirements. In order to identify the strength of these wires, a series of strength tests need to be performed.

3.2. Braiding Topology and material selection

The currently used multi yarn wires at CERN consist of twelve yarns twisted together. The initial proposed idea, before the beginning of this project, was to come up with a solution that braids twelve wires in a circular pattern.

In order to determine the wire topology there was valuable input from the users of the wire scanner machine within CERN. This input was useful to identify the design requirements of the cables and then move on with the machine development within a better-defined design space. Moreover, there were three design requirements necessary to proceed with the machine development, the number of yarns, the thickness of each individual yarn and the braiding pattern desired.

For the correct measurements of the beam profile, the most important parameter is the diameter of the wire. This diameter needs to be less than 35 µm for LHC operation but it can be greater for other accelerators such as the Super Proton Synchrotron (SPS). The reason that the diameter of the wire is the major point of interest is the measurements performed from the Wire Scanners. As mentioned in Chapter 1 the scanner passes the wire through the proton beam and recreates a normal distribution based on measures from the scatter particles downstream. Thus, the diameter of the wire needs be smaller than the diameter of the beam in order to obtain sufficient measurements to ensure a Gaussian distribution.

Furthermore, it is not necessary for the yarn numbers to be twelve, for the braiding to be hollow and the yarns to be 7 µm in diameter. This realization prompted a step back on the braiding machine development in order to investigate other braiding techniques, amount of yarns and yarn thicknesses. Moreover, the most important conclusion is the one of the packing of the yarns consists of the most important parameters in the wire design as it allows a lower diameter wire and thus contributing to better quality measurements.

Finally, there are three strict requirements regarding the final wire design:

- The external diameter should be less than 35 µm (radius of 17.5 µm).
- The braiding geometry should be circular, not flat.
- The wire should withstand the pretension applied (about 0.45 N).

3.2.1. Yarn packing investigation

In order to investigate the close packing of the wires a two-dimensional study is performed. There are two parts in the study: first, the packing factor investigation of circular braids and two-stage braiding and second the optimum packing of circles in a circle.

The packing factor is defined as the fraction of the total area (envelope circle) occupied by the circles (yarns), as seen in equation 3.1

$$F_p = \frac{\sum A_{yarns}}{A_{total}} \tag{3.1}$$

Circular packing

The circular packing refers to the amount of circles that can fit within an envelope circle and being tangent to it and tangent between circles. It is not the most efficient packing but it is a good representation in the 2D space of a braided tubular wire. Moreover, Figure 3.1 demonstrates some examples for the circular pattern braiding for better visualization of the geometry.

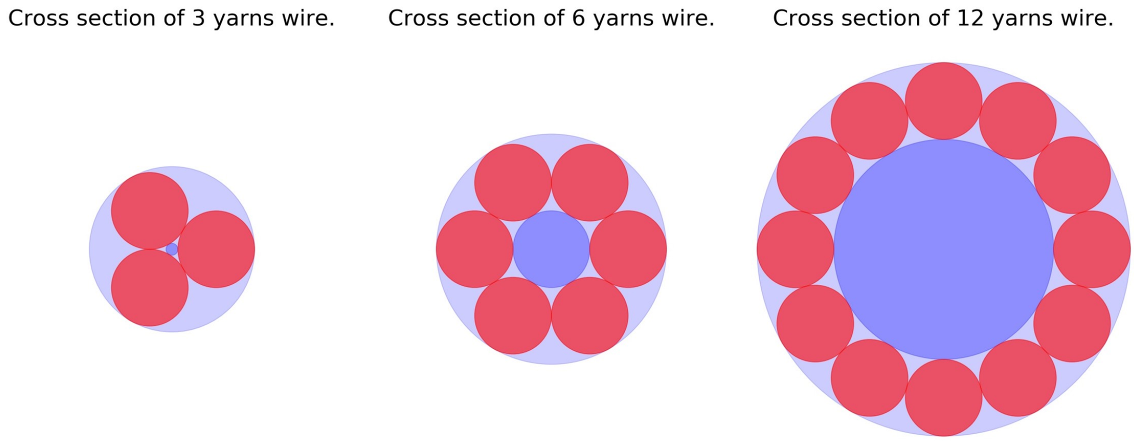


Figure 3.1: Circular braiding pattern examples.

Table 3.1 lists the results of a study about the circular braiding packing factor. As expected while adding more circles the void space in the middle increases and the packing factor of the structure decreases.

Circular packing		No of Circles [-]	
Packing factor [%]	**Yarn Radius [μm]**	**Circle Radius [μm]**	
2	50	3.5	7
3	64.6	3.5	7.54
4	68.6	3.5	8.45
5	68.5	3.5	9.46
6	66.7	3.5	10.5
7	64.1	3.5	11.57
8	61.3	3.5	12.65
9	58.5	3.5	13.73
10	55.7	3.5	14.83
11	53.2	3.5	15.92
12	50.7	3.5	17.02
13	48.5	3.5	**18.12**
14	46.4	3.5	**19.23**
15	44.4	3.5	**20.33**

Table 3.1: Circular braiding pattern investigation. The options marked in red are unacceptable for our application.

Bundled yarns packing

Moreover, an additional investigation was performed on breading bundles of three or four yarns. Table 3.2 lists the results of an investigation on the bundled braiding pattern. It can be seen that for higher amount of yarns the packing factor is greater than the equivalent circular pattern option which is logical as there is not as much empty space in the middle.

Additionally, Figure 3.2 demonstrates some examples for the bundled pattern braiding for better visualization of the geometry.

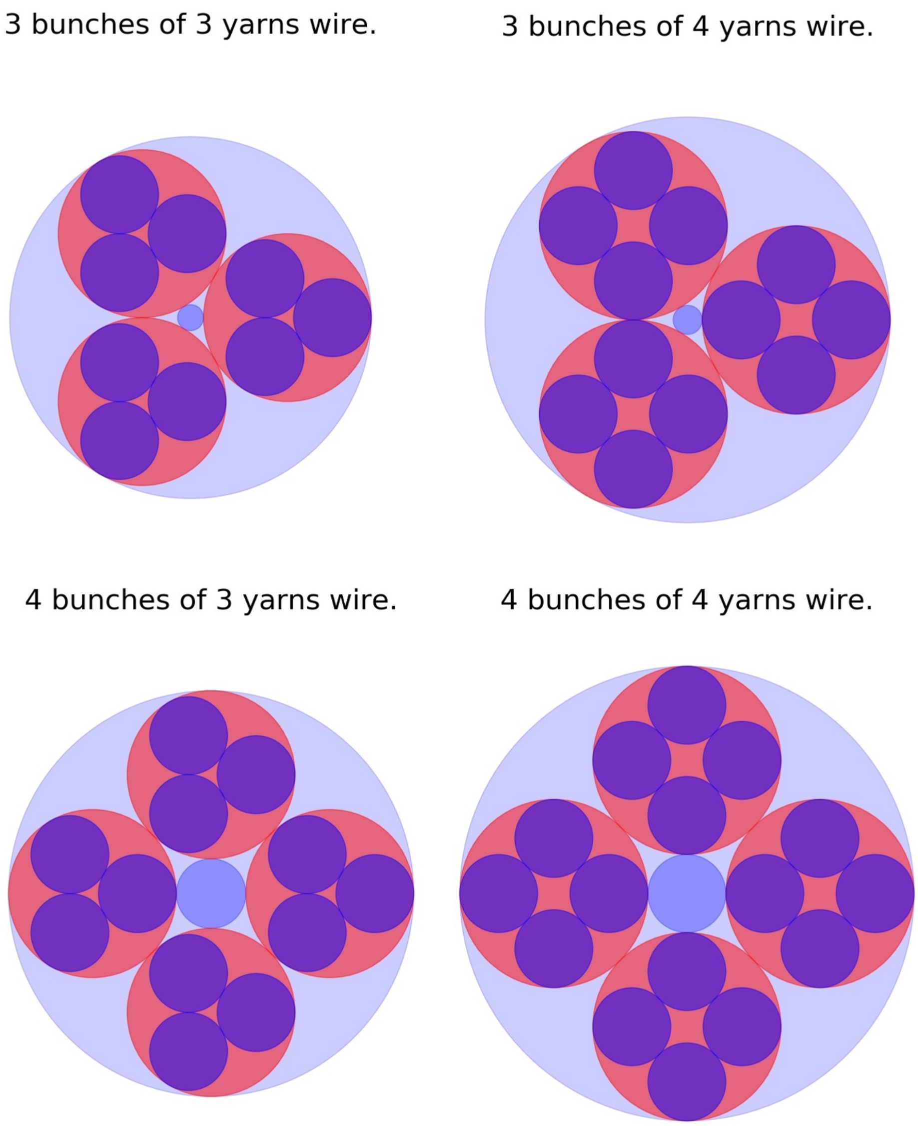


Figure 3.2: Bundled braiding pattern examples.

		Bundled yarns		
Number of Bundles [-]	Yarns in bundle [-]	Total Yarns [-]	Packing Factor [%]	Package Radius [μm]
2	2	4	25	14
2	3	6	32.3	15.1
2	4	8	34.3	16.9
2	5	10	34.3	**18.9**
2	6	12	33.4	**21**
3	2	6	32.3	15.1
3	3	9	41.8	16.3
3	4	12	44.8	18.2
3	5	15	44.3	**20.4**
3	6	18	43.1	**22.62**
4	2	8	34.3	16.9
4	3	12	44.3	18.2
4	4	16	47.1	**20.4**
4	5	20	47	**22.8**
4	6	24	45.8	**25.4**
5	2	10	34.3	**18.9**
5	3	15	44.3	**20.4**
5	4	20	47	**22.8**
5	5	25	47	**25.5**
5	5	25	45.7	**28.4**
6	2	12	33.3	**21**
6	3	18	43.1	**22.6**
6	4	24	45.8	**25.4**
6	5	30	45.7	**28.4**
6	6	36	44.4	**31.5**

Table 3.2: Bundled braiding pattern investigation. The options marked in red are unacceptable for our application.

3.2.2. Optimum packing

Finally, the optimum packing arrangement for circles inside a circle was investigated in the literature. This way the optimum distribution of circles is determined. Even though the optimum distribution is not always possible for braiding applications, some similar geometries could be designed and investigated.

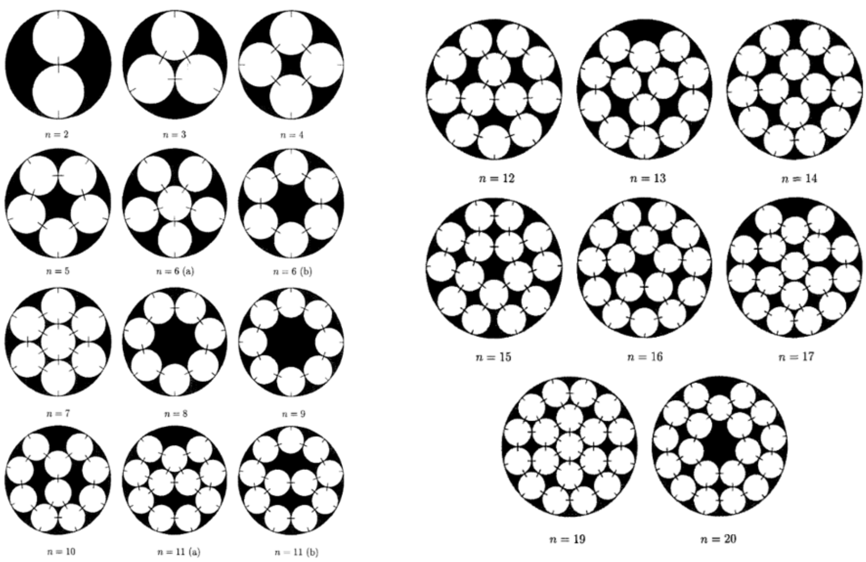


Figure 3.3: Optimum packing of 2 to 20 circles [15].

According to Melissen et al.[15] the densest circle packing can be seen in Figure 3.3 optimum packing of 2 to 20 circles[15]. As mentioned earlier some geometries are not available for braiding, for example 12 yarns. In order to be able to create a circular braid the number of yarns in the perimeter should be even. This means that the optimum configuration of 12 circles is not available for braiding. The next step of this study is combining the three investigations presented and using the optimal packing as a starting point. Finally, as can be seen in table 3.3 the packing density for the optimal case is in most cases way better than the circular braiding or bundled braiding investigated earlier.

n [-]	Packing Factor [%]	Circle Radius [μm]	Envelope Radius [μm]
2	50	3.5	7.00
3	64.6	3.5	7.54
4	68.6	3.5	8.45
5	68.5	3.5	9.46
6	66.6	3.5	10.51
7	77.7	3.5	10.51
8	73.2	3.5	11.57
9	68.9	3.5	12.65
10	68.8	3.5	13.34
11	71.4	3.5	13.74
12	74	3.5	14.09
13	72.4	3.5	14.83
14	74.7	3.5	15.15
15	73.4	3.5	15.82
16	75.1	3.5	16.16

Table 3.3: Packing density for the optimal case

3.2.3. Optimal packaging available for braiding

From the optimal packing options showcased in [15], only the options with even number of circles in the outer shell are available for circular braiding. One option is using the options with central yarns as a core and braid around it. This can be seen for example in the options for n =7, n=10, n=11, n=14, n=15, n=17 etc.

Moreover, it is seen that by removing some circles more combinations can be made. For example by removing one circle from the diameter of the n=13 optimum circle one n=12 option appears with eight circles in the perimeter. The same applies for n=16, where by removing one circle in the perimeter one n=15 option appears. Those options are not as closed packed as the optimal configuration but they are available for braiding applications with a core. Finally those two options have a packing factors of 66.8% and 56.3% for n=12 and n=15 respectively. As expected the packing factor is decreased from 74% and 73.4% found on the optimum packing.

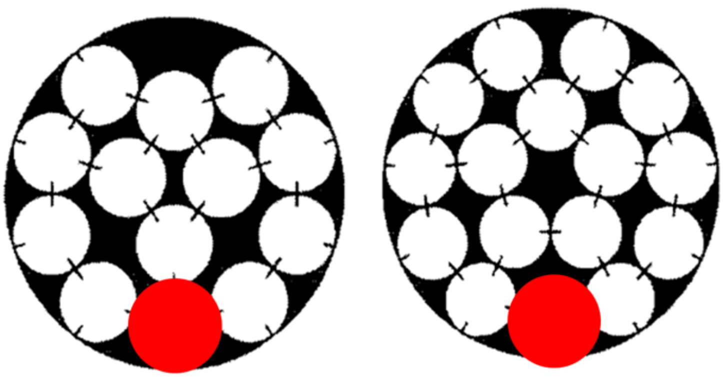


Figure 3.4: Packing modifications for dense packing. Left n=12, right n=15 [15].

3.2.4. Packing factor study conclusion

It is very important to mention that the final wire design has still many unknown parameters. Firstly, the 2D design presented here is not completely accurate for the real 3D braiding of wires as many parameters, such as the braiding angle and the interbraiding of the yarns are not considered for this study. Moreover, the yarn selection is strongly dependent on the commercially available carbon nanotube and carbon fiber yarns. Meaning in a case of selecting an option with no available yarns the process needs to be revisited.

3.2.5. Final braiding topology selection

The conclusion on braiding topology considers all the aforementioned packing factor investigations and the complexity of the machine required for fabrication. Initially a set of five prototypes is created out of rope in order to visualize the braiding geometry. The braids selected are shown in the Figure below and they are:

1. Three single yarns.
2. Four single yarns.
3. Six single yarns.
4. Three bunches of four yarns with twelve yarns in total.
5. Four bunches of three yarns with twelve yarns in total.

Additional braiding patterns of interest are six bunches of two yarn for a total of twelve yarns, twelve single yarns and a core of four yarns with eight yarns around them for twelve yarns in total.

Figure 3.5: Prototype yarns created for better shape visualization. 1) 3x1, 2) 4x1, 3) 6x1, 4) 3x4 and 5) 4x3

The final selection was done between 4x3 yarns, 6x2 yarns, 12x1 yarns and 8 in circumference with four in the core yarns. The options of 3 and 3x4 yarns were disregarded due to the flat nature of its geometry, making it unfit for the wire scanner application and the few yarns for the 3 single yarns and 4 single yarns. For further reduction of the four available concepts we considered the complexity of the machine we need and the achievable precision. In the case of 12 single yarns, the machine requires 12 moving parts, making it very complicated and all the yarns need to be tensioned very precise making the operation even more complicated, thus, it is disregarded. The option of 4 yarn core and 8 yarns in the circumference is also disregarded due to the complexity of keeping the 4 yarns in the core and tensioning them appropriately for the rest yarns. The final two concepts considered is the 4x3 and 6x2 configuration. The selection topology is the 4x3 due to the less parts required and the simpler geometry. Moreover the packing factor for the 4x3 version is greater (44.3 compared to 33.3 for the 6x3) and the envelope circle smaller and acceptable from the machine users and the beam size. In all cases above we are referring to 7 μm in diameter carbon wires that are available for purchase.

3.3. Mechanical Design

For the mechanical design process three main system engineering methods are used, three step design process, functional decomposition and trade off tables. The design process kickstarted with the conceptual design, with brainstorming and following it closely with the literature review and the state of the art research. Following the second phase, preliminary design where the options are narrowed down to three main concepts that are further evaluated and concluding with the best concept going through detailed design process where all the machine was created in CATIA® in a big 3D assembly.

Complementing the three phase design process are the other two systems engineering tools, the functional decomposition and the trade off tables design evaluation. For the functional decomposition method the necessary parts of the machine were identified and more concepts were generated. Finally in order to evaluate all the generated concepts the trade off table method was used where for each function a set of criteria were selected and a weight factor was assigned to them. Those criteria are used for concept evaluation and design selection.

3.3.1. Functional decomposition

Functional decomposition is a widely used systems engineering tool [8, 17, 26]. It aims in identifying the most important functions of the machine's operation and it can be used to generate concepts that satisfy the necessary functions.

For the microwire braiding machine design it was necessary to have a two step functional decomposition. The first functional decomposition, can be seen in Figure 3.6, was performed after the state of the art and the literature review part of the process.

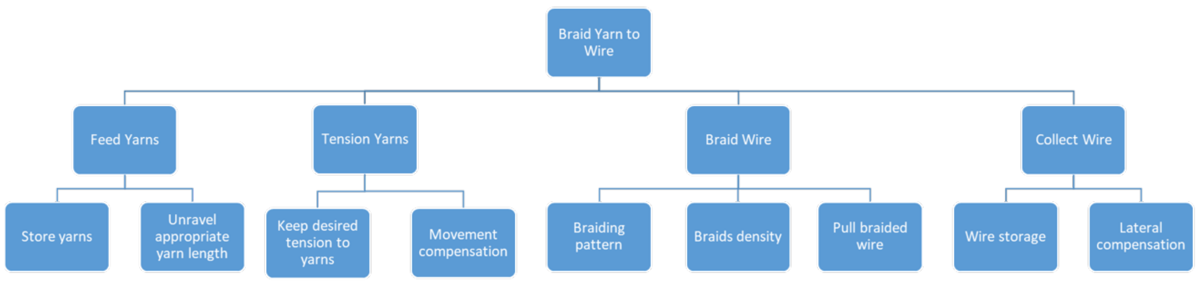


Figure 3.6: First version of the microwire braiding machine functional decomposition.

Using the decomposition illustrated in Figure 3.6 the conceptual design was started and most of the concept explored during that phase of the design was linked to this decomposition. By further examining those functions and evaluating the designs that generated it became apparent that all those functions and thus subsystems are not necessary for designing a microwire braiding machine. Moreover, by eliminating some of the functions we could reduce the design complexity without having any impact on the final product. Thus, a new version of the functional decomposition was done as demonstrated in 3.7. It can be seen that this version is way simpler that the initial (Figure 3.6). This means that it leads to a much simpler design for the final machine.

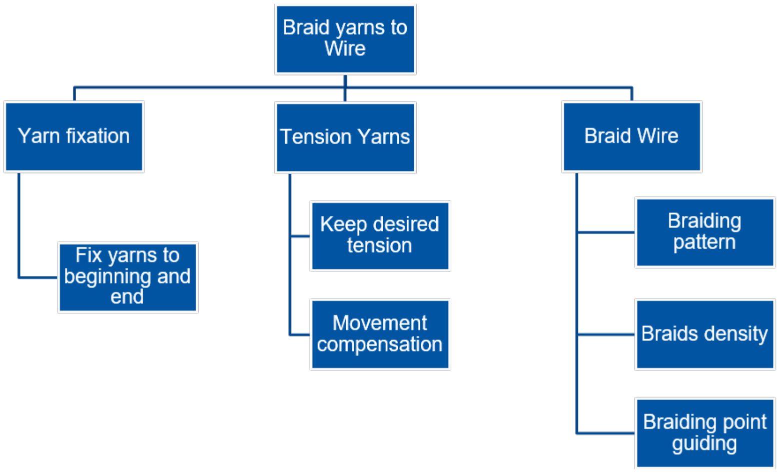


Figure 3.7: Second version of the microwire braiding machine functional decomposition.

3.3.2. Trade off tables

Trade off tables is another widely used systems engineering tool. It is very useful for making justifiable and logical design decisions. For a trade off table a table is created with all concepts in a column and all the selected design criteria in a row and all concepts are judged based on the design criteria. The criteria are be ranked from 1 to 5 with 1 being bad and 5 good for the final design. Moreover, a weight factor is added to each of the criteria related to their importance to the design objective, the function that the part satisfies.

The most important part while designing the trade off tables is selecting the trade off criteria. Those criteria should be in line with the design objectives but also they should be easily quantifiable. Meaning that every criteria should either have a measurable quality that can be identified or be well defined. For example one criteria can be the weight of a subsystem; in this case something that is heavy can be assigned a score of 1 and something that is lighter can be assigned a score of 5. The reasoning behind this is so the results are reproducible and every other person that might work with this set of concepts and criteria should select the same final design.

Finally, the weight can be selected a little more arbitrarily than the criteria. It reflects what is more important between the criteria. For example cost and complexity could be two criteria. If by making something simpler so more people can assemble it or operate it is more important than the cost we can have a higher weight to the simplicity than the cost and thus we can come up with a design that is simpler but more expensive as the best choice.

3.3.3. Three step design

The process designed to braid microwires is going to be in a form of a complicated machine. For this reason a three step design process was selected. During this process I am trying to narrow down the wide design space and select the final version of the machine for development. The three steps used are:

- Conceptual design
- Preliminary design
- Detailed design

By using this process we have distinct milestones for the design process and clear goals in the end of each phase so the design process is streamlined and structured.

Conceptual design

The conceptual design phase is basically a brainstorming session accompanied with the literature review and functional decomposition that aims in the generation of multiple concepts. It is oriented in generation of high quantity of concepts and it is important to stress that the quality of the concepts is not an issue at this stage. After generating multiple concepts we started evaluating them and better understanding the project and problems with different subsystems.

As the conceptual design phase consists mostly by disregarded ideas that didn't make it through the next steps and selection process, the rejected designs are not presented in this report for reasons of clarity. Nevertheless Figure 3.8 illustrates a combination of some of the concepts generated during the conceptual design phase. During the conceptual design phase and from the concepts generated is when we realized that some of the functions listed in the initial functional decomposition are not necessary for the design of the microwire braiding machine. This resulted on a the second version of the functional decomposition and filtering out many of the initial designs.

From the initial designs three were selected and proceeded to the preliminary design phase.

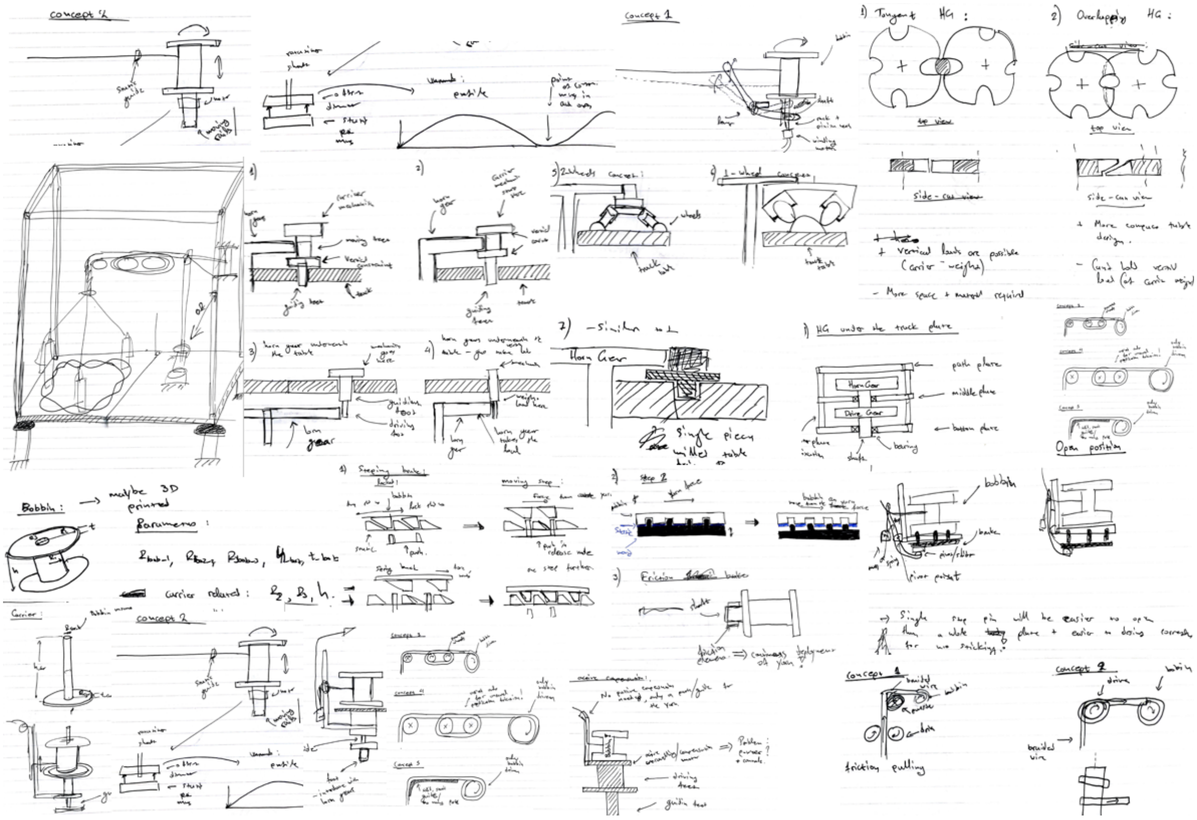


Figure 3.8: Collage of some conceptual design concepts that did not move to the preliminary design phase.

Preliminary design

The preliminary design phase is an intermediate phase in the design process. During this stage, the three most promising designs from the conceptual design were investigated and developed further with aim to select the final design. In order to select the best designs the trade off table method was implemented. The trade-off criteria selected are the wire quality, the overall design complexity, both for assembly and maintenance, and the ease of design or manufacturing, The wire quality refers to the produced wires, as the ranking is in something that has not been tested yet, the expectation on wire quality is ranked. For this reason, in Figure 3.10 the established circular path is ranked as perfect, 5, but the new concept, the rectangular path is ranked at 4 as it is expected to perform good but is not tested. Moreover, the complexity refers to the number of components needed for each concept. The concepts that require many components are ranked as bad, 1, and the ones with few as good, 5. The last criteria is the difficulty in design and manufacturing. Again the concept expected to be difficult in design or manufacturing are ranked with a low score, 1, and the ones that are expected to be very easy at 5.

Furthermore, weight factor is implemented for the trade off tables used. The factor is implemented in the form of a percentage weight. The wire quality is weighted as the most important selection criteria with weight factor of 50%, then the design and manufacturing difficulty with 30 % and finally the machine complexity at 20%. The reason these weights are selected is that the wire quality is the most important characteristic of this machine and sacrificing some ease of design or complexity to gain in wire quality is acceptable. Further, the complexity of assembly and manufacturing is not an issue as CERN has a lot of experience in complicated machinery so handling a more complicated design is acceptable.

There were six best concepts from the end of the conceptual design and can be seen in Figure 3.9.As some of the designs shown in Figure 3.9 are similar they are represented all together by circular pattern 1 and circular pattern 2 in the trade off table, Figure 3.10. As it can be seen from Figure 3.10 the best two solutions are the simple rectangular path and the circular pattern 2, thus those two were the concepts selected for design during the preliminary design phase. It is interesting to see that the traditional part idea ranked last with the selected criteria but it was selected as well for further development as during the initial development steps of the other two designs it became apparent that they might not be as simple and easy as initially projected.

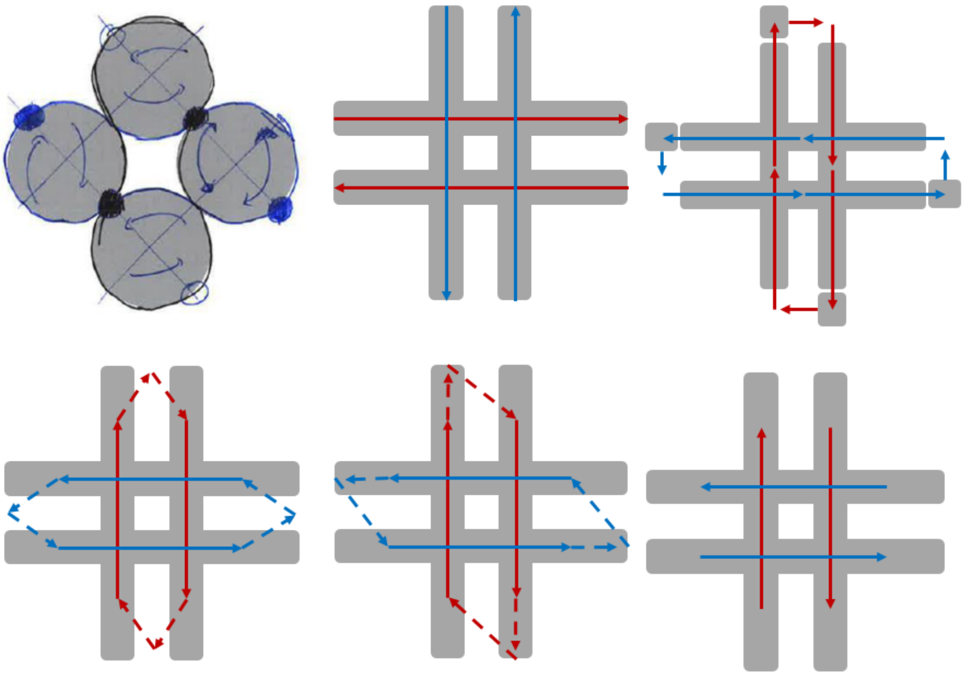


Figure 3.9: The six best concepts from the conceptual design.

Concept\Criteria	Wire Quality	Complexity/ Ease of assembly/ Maintenance	Design/ manufacturing difficulty	Total
Weight Factor [%]	50	20	30	100
Circular (traditional) path	5	1	1	300
Simple Rectangular path	4	5	5	450
Circular Pattern 1	5	3	3	400
Circular Pattern 2	5	4	4	450

Figure 3.10: First trade off table performed for the preliminary design concepts selection

The three concepts developed for the preliminary design phase can be seen in Figure 3.11. During the development process of those three concepts their drawbacks and design flaws became more apparent and we revisited the ranking given earlier in the trade off table. Both the first two concepts did

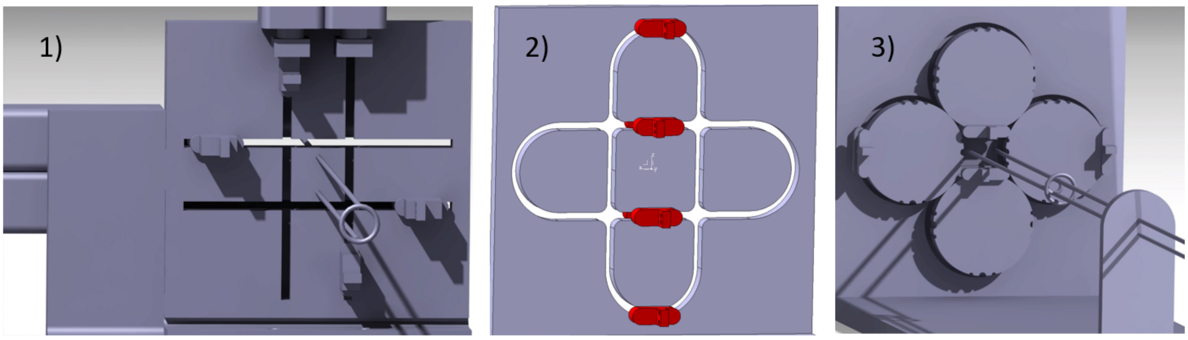


Figure 3.11: Three concepts developed for the preliminary design phase.

look easier to manufacture and assemble than the traditional path but there were many limitations and obstacles that we had to overcome. The vast majority of the problems is attributed to the nature of the concept itself as it requires cross braiding the micro wires. It is very important to not have the actuation crossing itself like in the case of the fist two concepts where linear actuators were implemented as this system generates additional complexity in the form or grab and drop mechanisms and a multi step process.

It is clear from the aforementioned analysis that the traditional path design ranks higher due to its simplicity, ease of use and assembly than the other two concepts, making it a superior choice for this problem. The new trade off table is presented in Figure 3.12

Concept\Criteria	Wire Quality	Complexity/ Ease of assembly/ Maintenance	Design/ manufacturing difficulty	Total
Weight Factor [%]	**50**	**20**	**30**	**100**
Circular (traditional) path	5	4	4	**450**
Simple Rectangular path	2	2	3	**230**
Circular Pattern 2	5	3	3	**400**

Figure 3.12: Re evaluated preliminary trade off.

Having concluded that the circular path design is the best choice for this application the concept was developed in more detail still under the preliminary design phase. More precisely, the design is functional but it is still not the final design of the machine. In order to finalize the preliminary design the selected design was evaluated further using a proof of concept and some design iterations. This process is described in detail later in this section.

After the final preliminary design is complete and evaluated the design of the machine is moving to the final stage of the design process, the detailed design where a complete functional machine is designed in CATIA®.

3.3.4. Rapid prototyping and proof of concept

After the decision of the final project at the end of the preliminary design phase and before moving towards the final and detailed design of the machine, there was one additional step in the design process. This step was the proof of concept where the selected concept was developed further to a working model, shown in Figure 3.13.

This step is added between the preliminary and detailed design phase in order to evaluate the final version and have a second level of verification in the selection process. The main goal of this process is to have a working proof of concept, a general evaluation of the selected concept, evaluation of the mechanisms developed and identify some potential week points on the design that can be improved during the final design process.

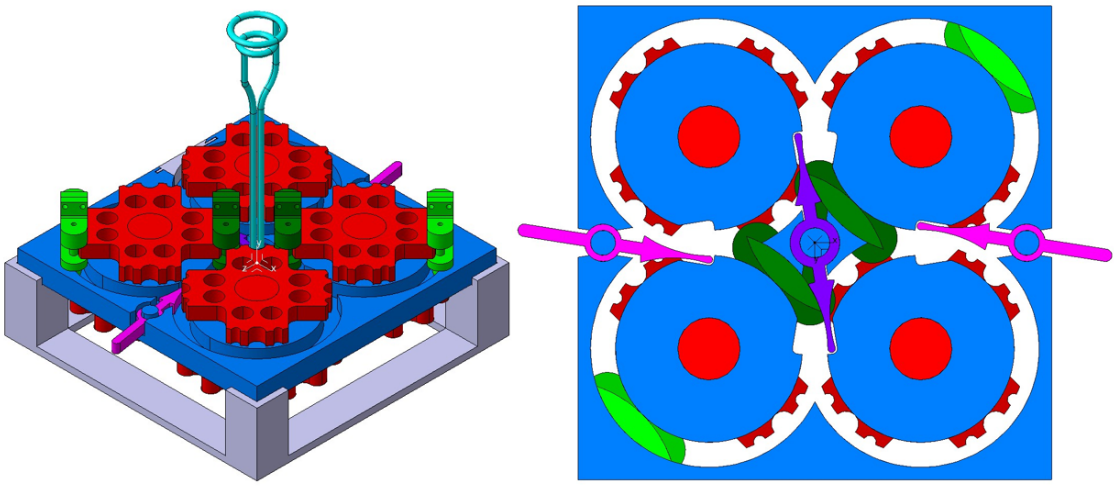


Figure 3.13: Isometric and top view cut section of the final preliminary design concept developed for proof of concept,

3.3.5. Design evaluation

All the parts of the proof of concept machine were designed in CATIA® and printed using an in house Ultimaker 3 and PLA filament. Some modifications on the design had to be done during the printing and assembly process to ensure fit and ability for the parts to move.

The final machine can be seen in Figure 3.14. Different colors of filament were used for different functions of the machine to be easier to evaluate their performance.

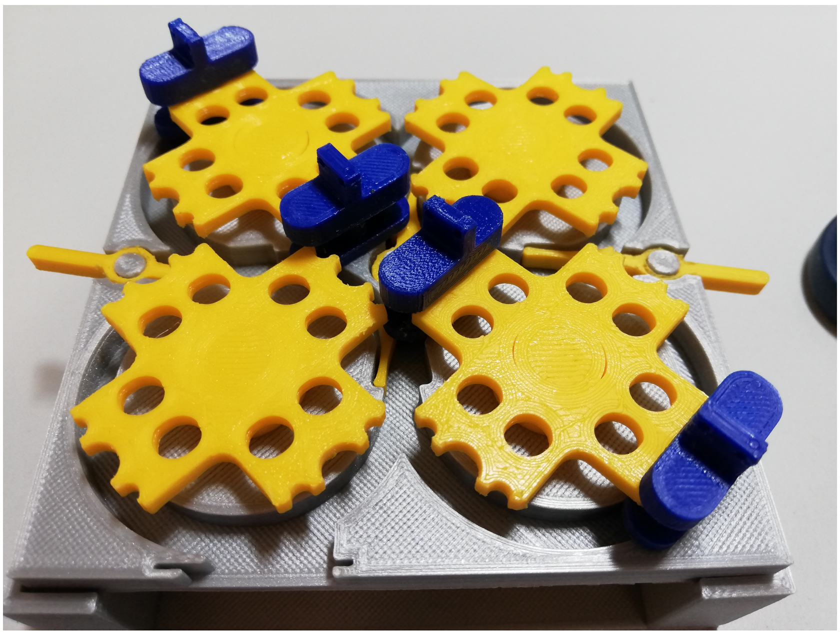


Figure 3.14: 3D printed assembly of the proof of concept.

After the assembly of the machine a series of wire braiding tests were performed. During those tests three different wires were braided in order to evaluate the performance of the machine. We started with a thick 2.5 mm string and moved down to 500 μm nylon string and finished with a 40 μm gold wire. Those braids were later investigated under an optical microscope to evaluate their pattern.

Figure 3.15 showcases the three different braids. It can be seen that the braids were successful even for the smaller wire as one can observe regular braiding form.

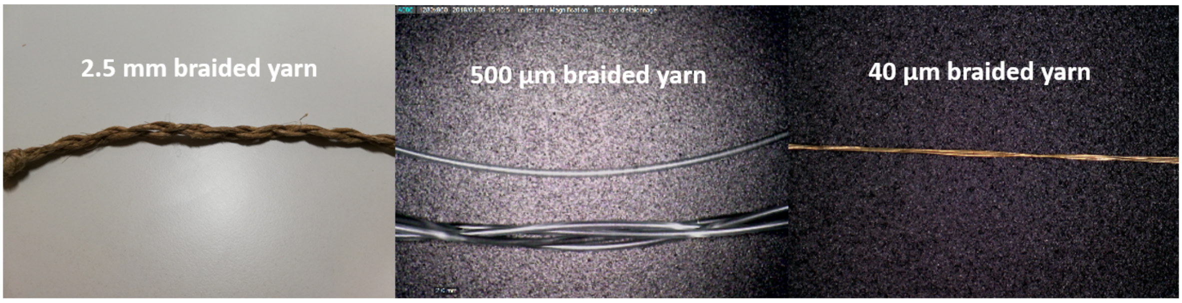


Figure 3.15: 3 wires braided to test the machine.

Issues detected

Nevertheless there were a set of issues detected during the proof of concept process:

- Guiding mechanism is needed to determine the braiding point of the wires.
- Sharp points along the path: result in carrier colliding and machine stalling.
- Carrier and Path dimensions/tolerance: slide fit required so there is not play of the carrier.
- Horn gears dimensions and interference (needs to be smaller so they do not clash where tangent the selected tolerances are olerances very important).
- Lack of vertical axis constraint for the carriers.
- Gate for carrier input needs to be usable.

The guiding mechanism is a cylinder that acts as a guide for the braiding point of the wire. The proof of concept machine was lucking such a mechanisms and after its manual operation we found ourselves constantly pushing the braiding point higher because the wires had the tendency to braid in random places producing an irregular wire. Further, as can be seen in Figure 3.13 there are some sharp points in the carriers (green) and along the path changes and path (purple and blue respectively). Those sharp points resulted in jamming the machine while operation so a solution is necessary for this problem. There were generally dimensions and tolerances problems for the carriers and the horn gears. Those problems were partly caused by the manufacturing method and scale of the design, but they were a good indication that this might be a problem in the real design as well. This highlights the importance of selecting the right dimensions for the resulting tolerances in the moving parts. Finally there were two additional problems, there was a luck of constraint for the carriers in the z axis and the insert door designed for the carriers was not functioning properly.

3.3.6. Design iteration

After using the proof of concept to evaluate the design and the design problems were identified, a design iteration was performed to correct them. For this design iteration, the sharp points along the path were removed and the carrier was redesigned with a round edge instead of a sharp one. Moreover, the fit of the carrier and path was taken into account and the horn gears dimensions were changed such there is no more interference. A z axis constrain was added for the gate was redesigned.

Concluding the proof of concept process, a secondary prototype was 3D printed and tested for sticking and movement of the carriers at the path changes parts of the machine. The new prototype can be seen in Figure 3.16. It is not a fully functioning machine as only the path changing and carrier components were modified and it is possible to test the modifications results with this partial printed machine. The testing resulted in smooth transition on the path change sections of the machine and good sliding function of the carriers in the rest of the normal path.

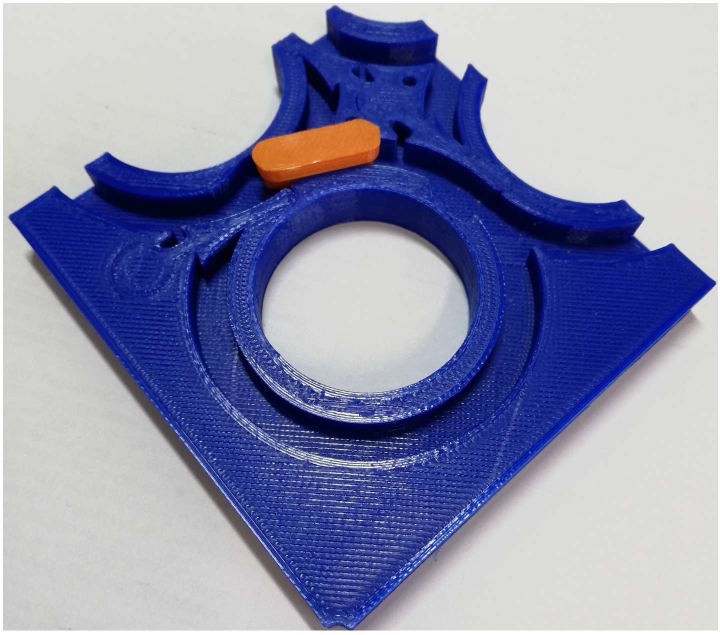


Figure 3.16: Design iteration for removing the sticking of the carriers to the paths.

3.3.7. Conclusion

To conclude, using a set of systems engineering tools such as functional decomposition, trade off tables, multi-step design, design evaluation and design iteration the concept for the final, detailed design of the microwire braiding machine was selected. Completing all these design steps provided a level of confidence in the final design as all the design decisions were justified, tested and proven during this process. With a final concept selected, the next step of the design process is the implementation of the design and moving from the preliminary design to the detailed design phase where the machine is designed with all the functional and production details.

3.4. Design Implementation

Following the conclusions of the design phase, a detailed, manufactureable design is created for the microwire braiding machine and the physical machine is built. For the manufacturing design all the knowledge obtained during the design phase was utilized to determine the best solution. Nevertheless, during the assembly and testing of the machine, there were a set of iterations and modifications necessary to optimize the machine and resolve detected issues in order to reach the final operating prototype.

For the manufacturing design all the issues detected earlier are addressed. Moreover due to ease of production and manufacturing an effort was made to implement as much as possible commercially available components in the design, such as extruded aluminum profiles. This resulted in a system that most of the components are commercially available and only the critical and specialized components are designed and made in house, reducing the overall cost and complexity of the project. Figure 3.17 illustrates a simplified engineering drawing for the complete assembly of the microwire braiding machine prototype.

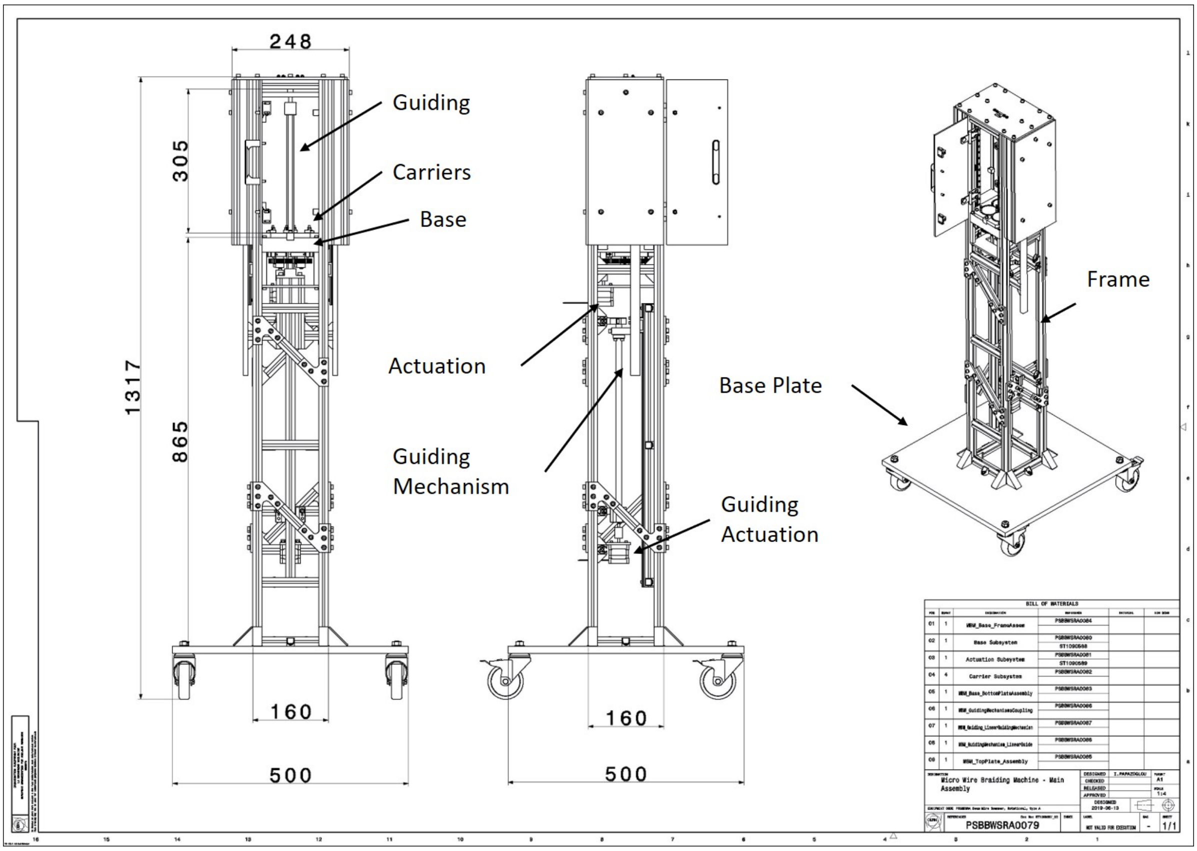


Figure 3.17: Simplified drawing for the main assembly of the braiding machine based on [19].

In order to manage the design of this rather complicated prototype, the machine was divided in the following set of sub-assemblies (or subsystems):

- Main body
  - Base frame
  - Carriers
  - Actuation mechanism
- Guiding system
- Support frame
- Electronics

3.4.1. Main body

The main body is the most complicated assembly of the machine and it is there where the braiding is achieved. Thus, it is the assembly that is fully custom designed and manufactured. Figure 3.18 demonstrates an exploded view of the main body assembly. It is manufactured out of an aluminum block and houses the tracks that the carriers follow for the braiding pattern. It is called the main body the rest sub-assemblies mount on and it is the most integral part for the braiding function. It has five feed through holes allowing the actuation system to mount using deep groove ball bearings, the path change assembly feeds through the body as well and the leaf springs and stepper motor mount underneath.

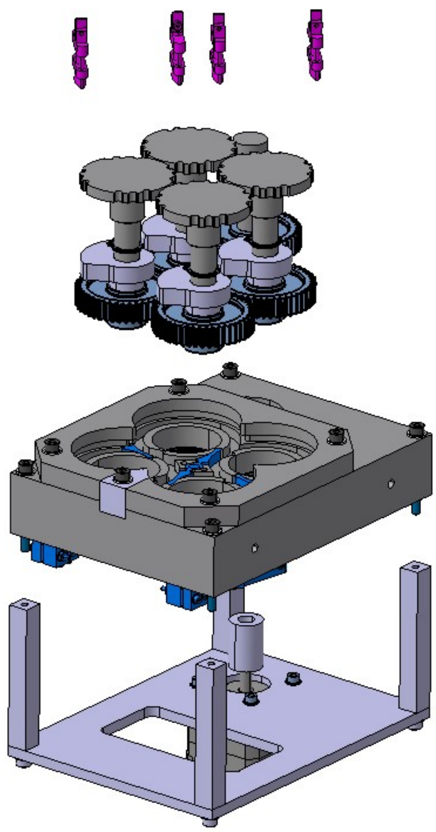
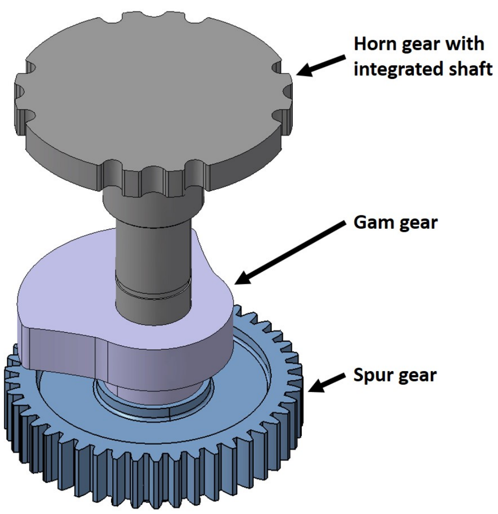


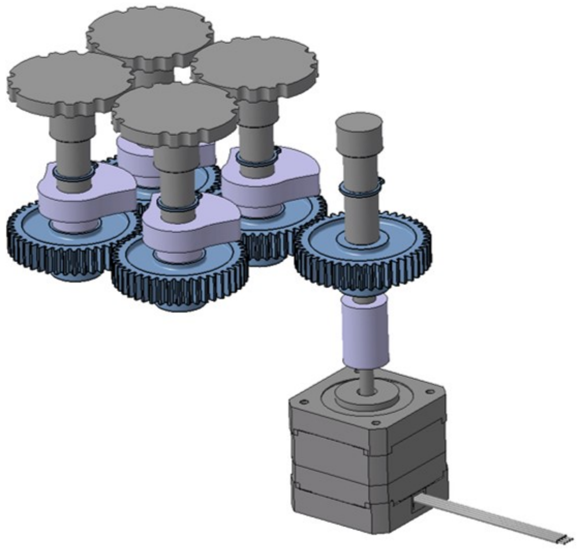
Figure 3.18: Isometric partially exploded view of the main body assembly.

The system is actuated via a stepper motor connected with a set of spur gears together with the cam and horn gears through a shaft as can be seen in Figure 3.19a. The spur gear is used to transfer the power from the stepper motor to the rest of the system. The cam gear implements the mechanical synchronization of the path changes subsystem in order to maintain the desired braiding pattern. Finally comes the horn gear, which is unified with the shaft, transfers the motion to the four independent carriers that slide around the main body path.

Figure 3.19b demonstrates the complete actuation assembly. The four identical modules are used for the actuation and synchronization of the system while the last one is only used for the power transmission via the stepper motor due to spacial constraints that don't allow the motor to connect directly to one of the four main shafts.



(a) Gears assembly with the horn gear, cam gear and spur gear.

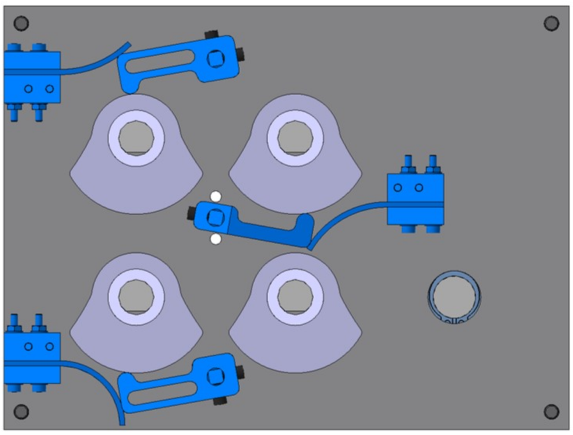


(b) Actuation system assembly.

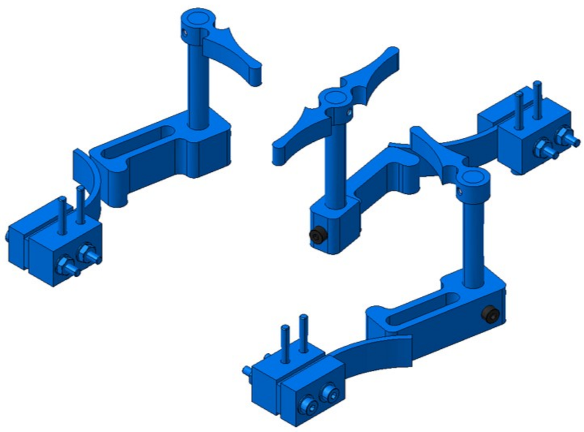
Figure 3.19: Actuation and gears assembly.

In order to manage the synchronization of the path change for the carriers a set of cam gears and followers is used. The followers are connected with a shaft, through the main body of the machine, to the path changing elements. Furthermore, leaf springs are used instead of conventional springs as it is easier to manufacture and tune for the special needs of the machine, are more space efficient and require less components for mounting. Figure 3.20a illustrates the synchronization of the system using the cam gears, followers and leaf springs system, while Figure 3.20b demonstrates the path change and followers assembly removed from its housing of the main body.

Using this mechanically synchronized assembly a level of complexity is removed compared to an electrically actuated path change system while the possibility of de-synchronization is eliminated. Making the system both simpler, more reliable and more compact.



(a) Cam gears with followers and leaf springs.

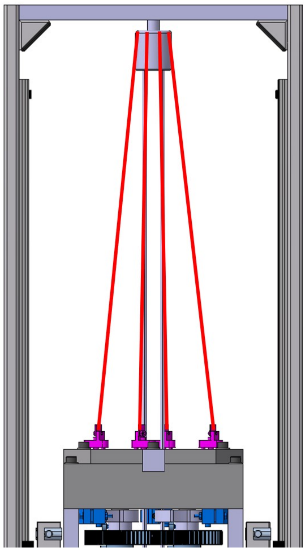


(b) Section view of the guiding system, showcasing the braiding functionality.

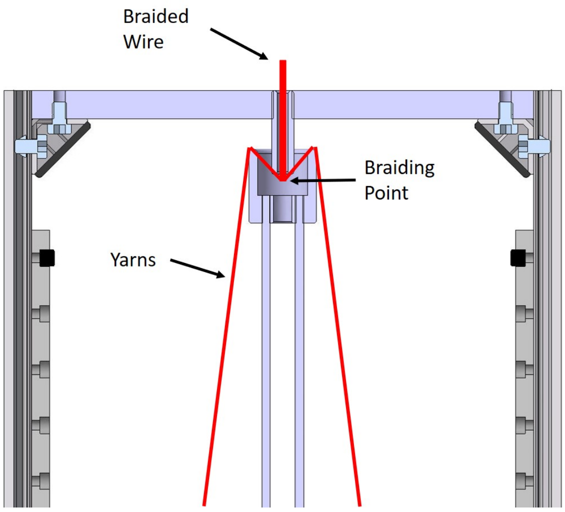
Figure 3.20: Path Change Mechanism.

3.4.2. Guiding

The guiding system is designed to force the braiding point of the wires. The system is derived from the state of the art machines with the difference that in those machine the guiding is stable, sitting in a fixed length above the carriers and the wire is moving and collected in a spool after braiding. As this is not possible for our wires; the wire stays at constant length and the guiding system moves down while the braiding occurs. Figure 3.21 illustrates the concept of the braid guiding system. The red lines represent the yarns and the guiding system consists of the upper and lower guiding. The braiding point is focused by those two parts to the intersection of the two cylinders as demonstrated in Figure 3.21b.



(a) Concept of guiding system in the main assembly.

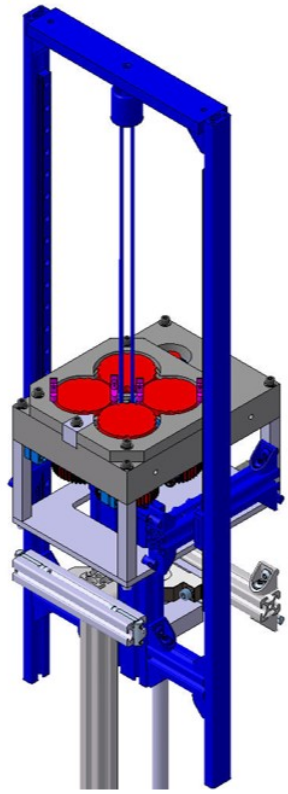


(b) Section view of the guiding system, showcasing the braiding functionality.

Figure 3.21: Concept of guiding system.

As this system needs to simultaneously move the upper and lower guiding modules a coupling mechanism, demonstrated in Figure 3.22a was designed in order to allow a single stepper motor to actuate both systems at the same speed. For the actuation of this system a similar stepper motor as for the actuation is used. The conversion from rotational motion to linear is achieved with the use of a ball-screw drive and a linear bearing and track is implemented for movement guiding and constraining the unnecessary degrees of freedom. All those parts can be investigated in Figure 3.22a

(a) Guiding system assembly with coupling, linear guide and actuation.



(b) Guiding system (highlighted in blue) assembled around the base plate.

Figure 3.22: Guiding design

Moreover the lower part of the guiding system needs to feed through the main body of the braiding machine through two 3 mm holes and the upper part around it in order to not interfere with the braiding function. This is showcased in the integration assembly in blue, in Figure 3.22b.

3.4.3. Frame

A frame is built around the main body of the machine as a support structure and to house and protect all the components. The whole frame is built out of commercial extruded aluminum profiles and it has four castor mounted on it in order to ease the transportation of the machine. In order to have a stable design the frame is mounted on a 15 mm aluminum plate and there is a set of stiffeners along its length to enhance the rotational stiffness of the frame assembly as it can be described as a long and thin beam.

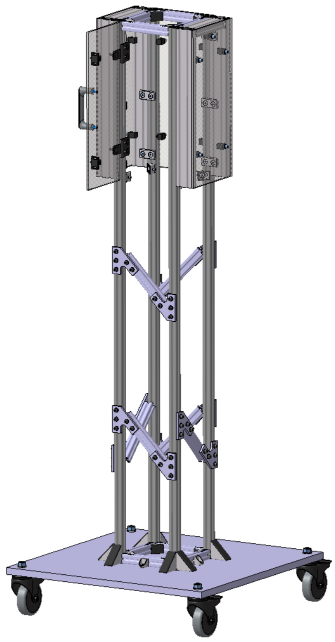


Figure 3.23: Frame design for the braiding machine.

3.4.4. Electronics

The final part added on the machine are the electronic components. The electronics necessary for this machine are very limited and they are required for powering the machine and providing the logic behind the braiding function and some safety features. The electronics components required are:

- two stepper motors, one for powering the actuation and one for the guiding,
- a few end stops for calibration and position control,
- a programmable Arduino board,
- an interface board
- motor controllers,
- a power supply,
- few cables and connectors.

All the electronics used are commercially available as for this prototype there are not special requirements regarding electronics, power or speed of operation. The position of the electronics is demonstrated in Figure 3.24.

In Figure 3.24, the detail highlighted in red shows the actuation components, the two stepper motors along with their power cables. In blue it is the electronics box that houses the power supply, the Arduino board, the interface board for the Arduino, the motor and the motor controllers. The green parts represent the end stops used for initial calibration of the machine and safety of the components and personnel operating the machine. Finally, with yellow the power cable is depicted that can be connected to wall power.

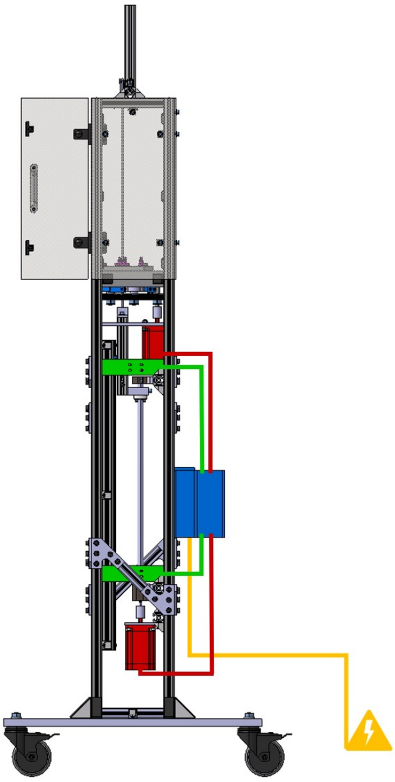
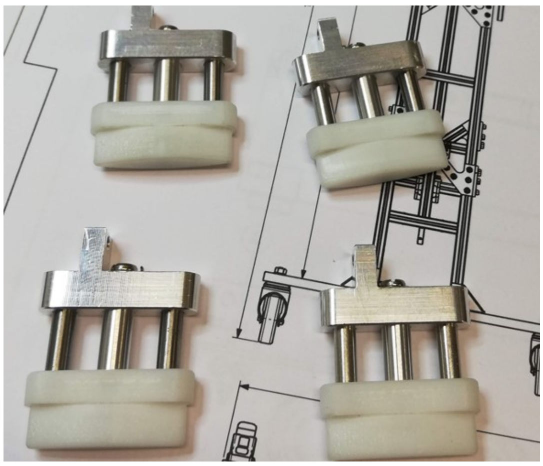


Figure 3.24: Electronic components showcased in the main assembly of the braiding machine.

3.5. Initial manufacturing

After completing the final design of all the components and assemblies, engineering drawings were created for all the components and assemblies. All those drawings where delivered to CERN's central workshop for manufacturing and procurement. A part of the custom parts can be seen in the Figure 3.25a, showcasing the actuation subsystem and 3.25b showing the four carriers assembled.

(a) Custom made parts for the braiding machine.



(b) Carriers assembled.

Figure 3.25: Manufactured parts.

As mentioned earlier, the design of this machine considers time and cost constraints and thus a large sum of the required parts are standard, commercially available parts. Figure 3.26 illustrates the greatest sub-assembly made almost entirely from standard parts and from easy to manufacture parts, the frame of the machine.

The frame is assembled out of commercially available 20 mm × 20 mm alumninume extruded profiles. Moreover, the only non commercial part, the base of the frame, is made out of a 10 mm thick aluminum plate. Even though this part is custom made for this machine, it requires minimum processing as it only designed as a base where thing mount on, thus a set of holes is enough.

Figure 3.26: Frame made mostly our of extruded aluminum profiles.

4

Testing and Analysis

During the testing phase the prototype microwire braiding machine is operated for the first time. Both the machine's functionality and the microwire braiding needs is verified. Thus the testing is done in two steps.

Initially the functions of the machine are explored. This testing process refers to free runs of the machine in order to verify its functionality. During this phase, the occurring issues are detected and resolved. The second phase is braiding a set of thick wires in order to identify the functionality of the systems. Both phases are thoroughly investigated and explained in the following.

4.1. Machine evaluation and iteration

In order to evaluate this prototype system three testing steps are implemented. First, static or assembly tests are performed. During this process the fit of all components is evaluated and any possible problems resulted in manufacturing or design mistakes are determined and corrected. After the static tests are concluded, a series of dynamic or powered tests are done. With these tests the machine is evaluated under simple operation, meaning just moving all the subsystems independently or even manually. Finally, the last series of tests, and the most critical, are the functional tests where the performance of the machine for braiding is evaluated.

4.1.1. Static tests

The fist step after receiving all the parts is to test them for fit and evaluate first the manufacturing of the parts and second the function of the machine itself. Thus a preliminary assembly was done as soon as all the parts were here in order to define if all the parts follow the specifications. The initial mechanical assembly can be seen in Figure 4.1.

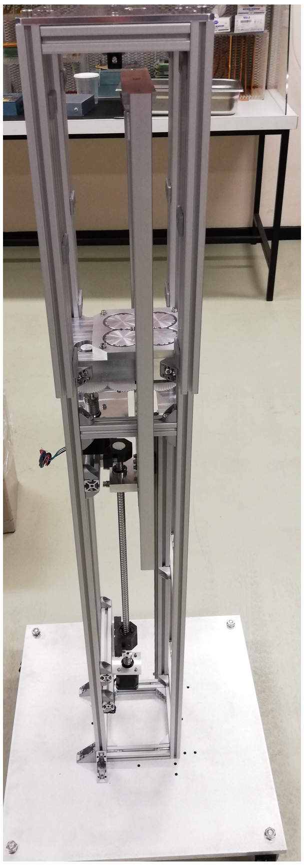


Figure 4.1: Initial assembly for the static tests.

4.1.2. Dynamic tests

After evaluating the mechanical fit of the components in Section 4.1.1, the dynamic evaluation is necessary where the machine is operated in order to define if there are any further issues. Thus a set of manual and powered tests were conducted to evaluate the performance of the machine under free operation. As expected by a prototype machine, during these tests a set of problems were identified.

More specifically, there were four major issues detected during this series of testing: the horn gears resulted in locking the carriers when the curvature of the path changed. Additionally, there was an issue with the stiffness and mounting of the leaf springs. Furthermore, an issue with the cam gears and the followers was detected as sticking during a section of the circle. Finally for the guiding assembly it appeared to be a problem with the stepper motor when it was changing direction of rotation and thus of movement from up to down of the system, rendering it stuck. For all those issues the root cause was identified and the appropriate action was taken to solve each issue.

The locking of the carriers was solved by increasing the depth of the support groves on the horn gear. After testing this issue was determined as solved and further investigation and testing showed that there were no residual issues due to this modification.

The issue with the leaf springs was resolved by mounting the springs in a different manner and mounting them on the rockers. Moreover the additional issue with the stiffness of the leaf springs was addressed by trimming the width of the steel plates and thus reducing the stiffness.

The cam gears and followers getting stuck and stopping the motion of the machine was attributed to the combination of weak stepper motor and steep curvature change of the cam gear. It was solved by redesigning the cam gears by changing the geometry of the cam gears and making the leaf springs less stiff. By implementing these modifications there is smooth rotation and path change along the whole period of rotation. The difference between the new and old design of the cam gears is showcased in Figure 4.2

Finally there were issues appearing in both the actuation systems, the main actuation system and the actuation of the guiding system. Even though the motors were selected with all the load and losses

Figure 4.2: Original cam gear on the right with redesigned on the left.

taken into account they were not strong enough to overcome the actual load of the machine. The main cause of the load was the cam gears for the actuation system and the seal of the ball screw drive of the guiding system which appeared to lock every time the direction of movement changed. As a result it was decided to replace both the motors with two of higher torque specs and thus they were changed from Nema 17 to Nema 23 stepper motors.

Concluding, with all the modifications after the dynamic tests and the installation of new stepper motors, the whole system worked smoothly and it was ready for the final testing phase the functional tests explained below.

4.1.3. Functional tests

The functional tests is the longest and most critical phase of the testing period. During the functional tests, the braiding performance of the machine is evaluated. For this series of testing the machine is completely assembled and is used under nominal situation. The conclusion of this phase is a functional machine with all its parts finalized and optimized for carbon wire braiding. This testing phase is split in 3 distinct periods, first there are stainless steel wires of 500 µm 250 µm and 50 µm also Nylon wires of 100 µm tested and finally carbon yarns of 100 µm.

During this testing phase there was one major issue detected and solved. This was the performance of the guiding system. Figure 4.3 demonstrates the problem on the guiding mechanism. The concept dictated that the wires to be braided (pictured red in Figure 4.3) were kept in relative tension and dictated at the selected guiding point, in the middle of the two cylinders of the guiding system. By using the relevant speed of braiding rotation and translation of the guiding system, the braiding frequency can be tuned.

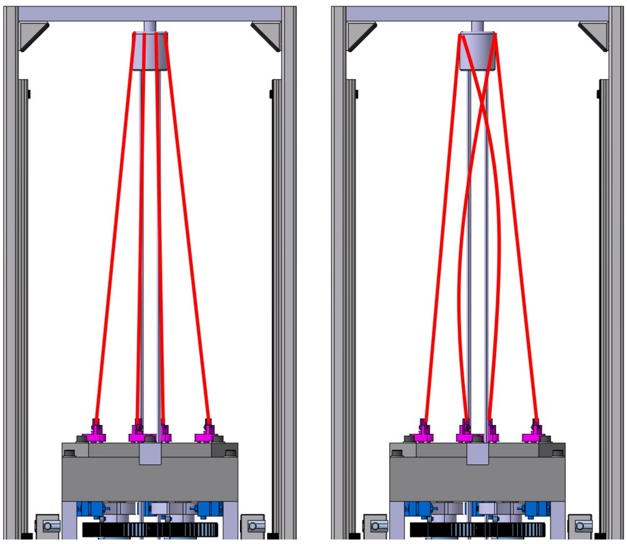


Figure 4.3: Schematic of the guiding system concept (left) and real application problem (right).

The right image in Figure 4.3 illustrates the actual operation behaviour under this concept. The wires always get entangled around the two steel beams of the lower guiding system, forcing itself to braid around the guiding system instead of the desired braiding point. This results to irregular braiding, uncontrollable braiding frequency and the machine is forced to stop due to high load and constant interventions are needed to keep it running and finish the wire braiding avoiding damaging the wires or the machine.

After multiple tests it was concluded that there are three main reasons of this phenomenon. Firstly, the wires used for e vast majority of these tests, were stainless steel, which is more rigid than the carbon and has a high friction coefficient with aluminum that the top guiding part is made of. Moreover, the shape of the guiding mechanism was not optimized for wires to slide around. Finally the wires on the inner part were not tensioned, allowing them to move freely and not follow the path of the carrier and thus getting entangled around the beams.

In order to address those issues two further concepts were developed, manufactured using 3D printing and evaluated by testing them on the wire braiding machine. The new concepts can be seen in Figure 4.4. The first concept, pictured on the left handed side of Figure 4.4 addresses only the issue of the not tensioned wires. This issue was considered to be the most important as as soon as the wires were with no tension tended to entangle. This concept addresses this issue by adding a spacer in the center or the braiding path that artificially increases the required length of the wires. After a set of testing it was concluded that this solution was not producing satisfying results as the wires kept getting entangled on the top of the guiding mechanism.

Further, the right image of Figure 4.4 demonstrates an additional concept attempting to address the second important issue of the mechanism, the underoptimized shape for wire sliding around it. Consequently, the upper guiding insert was changed to a better shaped one in order to allow better sliding of the wires and the bottom tensioner was also modified for better sliding. Those two new parts were 3D printed as well and tested in the wire braiding machine. After a set of testing it was concluded that neither this concept is a valid solution to these issues. Even thought it is a promising concept and part of it's failure can be attributed to the material and manufacturing method (plastic material and 3D printed making the round surfaces as polygons) neither of those two concepts can be considered as viable solution without at least further investigation.

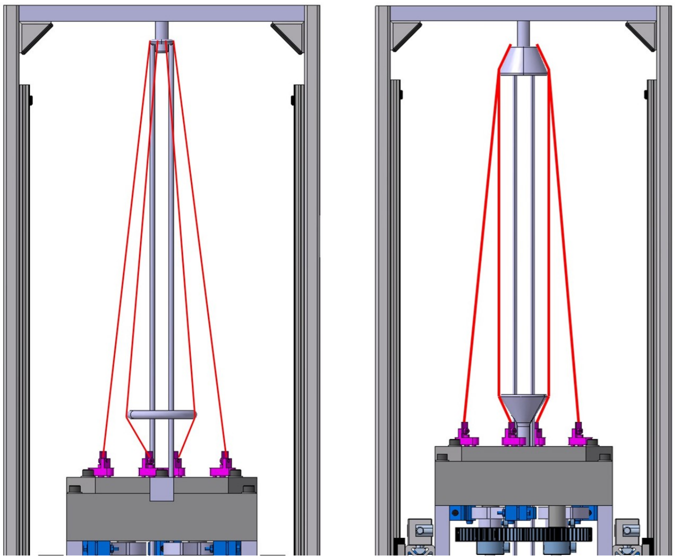


Figure 4.4: Concepts addressing the guiding system issues.

As the initial concept for the guiding system failed to meet the expectations and the attempts to salvage it were proven unsuccessful an alternative method is developed. The new method takes into account the excising design space available in the braiding machine as all the parts are already manufactured and assembled and the functional requirements that is to produce tightly braided wires without the need of constant interventions.

The improved design concept depicted in Figure 4.5 was designed. As can be seen from the Figure

4.5 this concept is differs from all the aforementioned guiding systems as it doesn't require constant contact with the wires. Moreover it will impact the continuously operation of the machine as it dictates to stop every half circle to ensure the guiding rod moves the wires onto the desired location. The braiding frequency control, although it might not perform as satisfactorily compared to the system explained in Section 3.4, can be achieved by calibrating the braiding length or the wire material and always attempting to braid as tightly as possible.

In order to tackle the challenges explained above, for every half rotation of the braiding motion the machine stops, the guiding system resets the braided wire to its tight braiding position and it retracts out of the way. After the guiding system is safely stored in its down position the period is repeated but this time the guiding system goes up at the same height minus half the length of the desired wavelength.

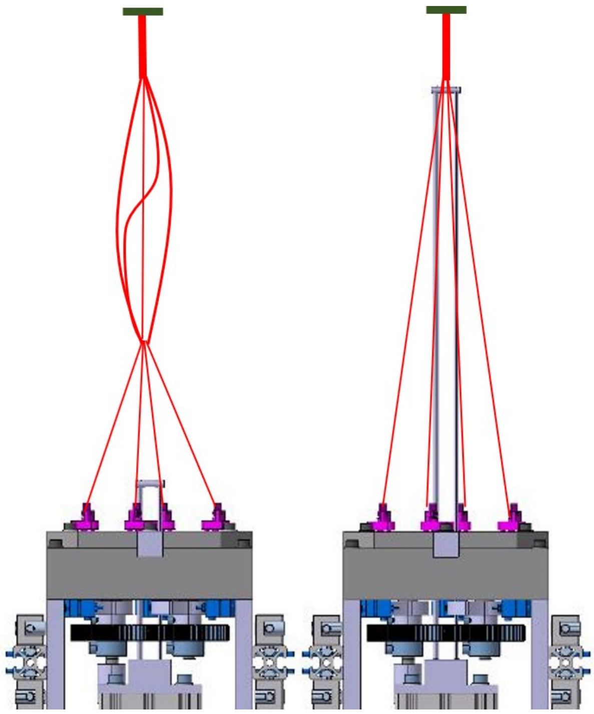


Figure 4.5: Final guiding concept.

Even though the guiding concept is conceptually different than the initial one, it is designed to take advantage of the excising mechanisms in place. More specifically, it uses the same beams as the initial system but rather than having the cylindrical guiding insert, a new horizontal beam is added. Furthermore, the rest of the systems in place for the upper guiding system are completely removed from the machine, making the overall system simpler. A further series of testing concluded that this concept produces acceptable results. All the aforementioned issues of the initial braiding system are resolved by essentially removing all the components that introduced them while keeping the braid guiding function.

Finally, during testing the machine under this configuration, an additional part was added to the braiding system. This was a small and soft spring at the static mount of the braided wire in the top of the machine. The addition of this spring allows all the yarns to be in tension during the whole braiding period. Figure 4.6 illustrates the new guiding system of the braiding machine. By adding this spring and after a final functional test, this testing phase was concluded with a modification on the guiding system of the machine.

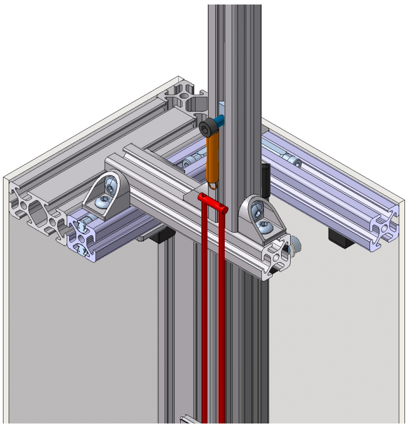
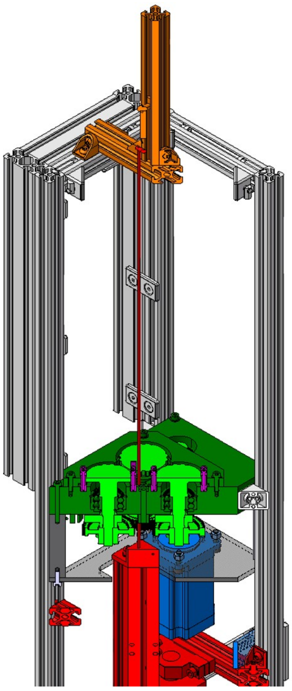


Figure 4.6: Addition of a spring on the static part of the braiding machine. Spring coloured orange and guiding mechanism red.

Concluding, it was proven that a series of functional tests is integral part of the design cycle as an important subsystem of the machine was identified as problematic and then adapted according to the functional requirements of the machine. Moreover by concluding this tests and the testing phase in general, the function, performance and limitations of the machine are better known and documented and additionally the braided wire characteristics dependent on the machine or on the braided wire characteristics are identified. Thus a more realistic expectation on how to tune the machine and what to expect as a result from the braided wires is obtained.

4.2. Final machine design

The overview of the final machine design, after all the aforementioned modifications implemented, is demonstrated by Figure 4.7. It can be seen that the machine is comprised by 7 subsystems. The top yarn mount, the support frame, the guiding mechanism, the actuation mechanism, the base frame that houses everything, the carriers and the electronics. Figure 4.7 illustrates all those subsystems and colour codes them.



Colour Code	Subsystem
	Top Yarn Mount
	Support Frame
	Guiding Mechanism
	Actuation Mechanism
	Base Frame
	Carriers
	Electronics

Figure 4.7: Final machine and subsystems highlighted.

The top yarn mount, pictured in orange, is the mounting point of the warns to be braided and where the tensioning spring, is added to ensure all yarns are under tension. The support frame is made mostly out of commercially available extruded aluminum profiles used in order to house and protect all the components of the braiding machine. In this frame there is a set of poly-carbonate windows mounted in order to protect the thin yarns from breaking or getting damaged or dirty (not pictured). The protection frame is pictured with gray colour. The guiding mechanism is the subsystem that was mostly revisited and discussed during the functional testing of the machine in Section 4.1.3. It is the subsystem pictured red and is the subsystem that guides the yarns to the desired braiding point. The actuation subsystem is responsible for the movement of the machine, pictured in light green. The base frame is the most complicated subsystem as it is made out of a single piece and is where most of the other subsystems are mounted and where the actual braiding function takes place. It is pictured in dark green. The carriers are the smallest subsystem and they are the parts where the yarns are mounted and actuated by the actuation system in order to be braided. Finally, the electronics, in blue color are all the electronic components providing the power and logic for this system to operate.

4.3. Wire testing methods

The wire testing refers to using the prototype machine in order to identify its performance for different wires braiding. Furthermore, by testing different wires better understanding is obtained for the braiding process, the material and machine parameters that are critical for the braiding characteristics. The wire testing was done according to the wire assessment criteria descried earlier:

- Braided length
- Uniformity of the braids
- Braiding packing
- Mechanical properties of the wire

4.3.1. Microscopy measurements

In order to measure and compare the different braids three optical measurements are used. The inner envelope diameter (D_{in}), where the wires converge in the plane of view, the outer diameter (D_{out}), where the wires are parallel to the plane of view and the wavelength (λ) that represents the regularity of braiding. Figure 4.8 illustrates the representation of these measures along the wire.

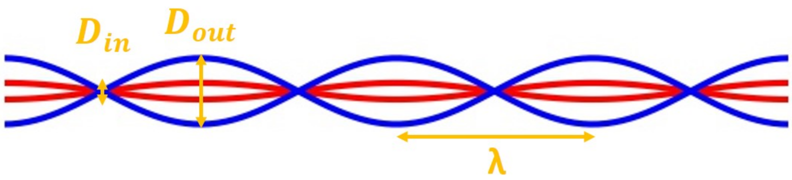


Figure 4.8: Schematic representation of the measured dimensions of the wires.

These three quantities are measured along the entire length of the wires and their average value is calculated from all the measurements. In order to evaluate the uniformity of the wire along their length, the standard deviation of the three metrics (D_{in}, D_{out} and λ) is used. With smaller standard deviation we can conclude that there is a high level of uniformity along the braided length of the wire and a large standard deviation means that the wires are not uniformly braided.

Finally, in order to compare the uniformity of different thickness and material wires, the standard deviation of the measurements is normalized with respect the average value in order to create a non dimensional parameter that can be expressed in percentage points as well. This normalized standard deviation represents how close to the average measured dimensions lies the majority of the wire. Figure 4.9 illustrates this using a standard deviation curve. The 2 σ lie within the blue shadowed area, where the 68.2 % of the measured diameters are located. In Figure 4.9 the 0 axis demonstrates the average measured dimension with -1 being the average minus the standard deviation (σ) and and +1 the average plus the standard deviation (σ).

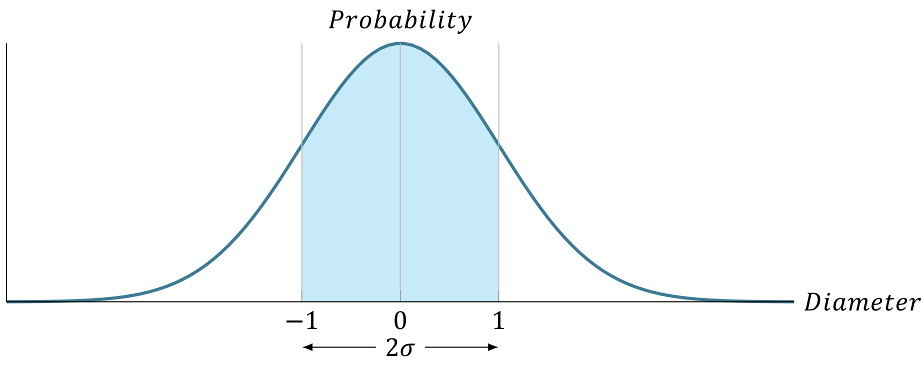


Figure 4.9: Demonstration of the wire braiding standard deviation

4.3.2. Wire packing

There are two measured quantities used to describe the packing of the wire, the outer diameter of the braiding D_{out} and the inner diameter of the braiding D_{in}. The outer diameter (D_{out}) describes the envelope which includes the braided wire and the inner diameter is a metric of how tight the braiding is, or how loose the wires are. These quantities are demonstrated on a schematic in Figure 4.8.

The wire packing factor can be extrapolated from the outer and inner diameter of the wire and the thickness and quantity of the individual braided strands in the wire. Thus, the packing factor is defined as the area of envelope of the wire divided by the total area of the cross section of the wires. It is simply calculated the equation 4.1:

$$F_p = \frac{n_{wires} \times \pi \times R_{wire}^2}{\pi \times R_{out}^2} = \frac{n_{wires} \times D_{wire}^2}{D_{out}^2} \tag{4.1}$$

where n_{wires} is the number of the individual wires in the braided wire.

Moreover, someone could argue that the wire envelope is not a circle but rather an ellipse, thus the packing factor will be the ratio of the total area of the wires by the area of the enclosed ellipse. The dimensional characteristics for the envelope can be derived from the measurements of the wire, where the inner diameter (D_{in}) is the small dimension of the ellipse and the outer diameter (D_{out}) the big dimension. Using this definition of the packing factor equation 4.2 is derived to calculate the packing factor of the braided wires:

$$F_p = \frac{n_{wires} \times \pi \times (\frac{D_{wire}}{2})^2}{\pi \times \frac{D_{out}}{2} \times \frac{D_{in}}{2}} = \frac{n_{wires} \times D_{wire}^2}{D_{out} \times D_{in}} \tag{4.2}$$

Figure 4.10 graphically represents the two concepts of the packing factor.

A third more theoretical definition of the packing factor can define as the envelope area, the area resulting by averaging the outer diameter D_{out} and inner diameter D_{in} and the wire area the sum of the cross section areas of the braided strands. Thus the packing factor resulting from this definition can be calculated using the equation 4.3 and 4.4. Unlike the two aforementioned methods depicted in Figure4.10 there is not a valid physical representation for this method of calculation of the packing factor as it is mainly a theoretical definition.

$$D_{equiv} = \frac{D_{in} + D_{out}}{2} \tag{4.3}$$

$$F_p = \frac{n_{wires} \times \pi \times (\frac{D_{wire}}{2})^2}{\pi \times (\frac{D_{equiv}}{2})^2} = \frac{n_{wires} \times D_{wire}^2}{D_{equiv}^2} \tag{4.4}$$

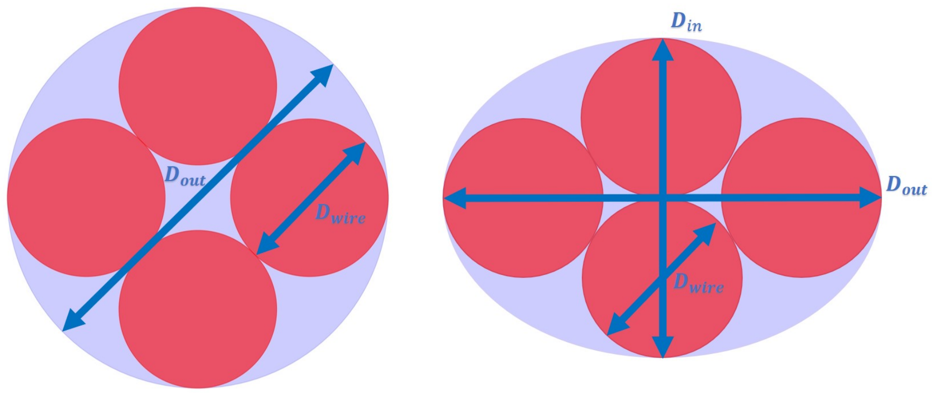


Figure 4.10: Graphical representation of the wires(in red) circular and elliptical wire envelope(in light blue).

Concluding, the second method, the elliptical representation of the wire envelope is used in the rest of this study. This definition of the outer envelope of the wire appeared to be the most accurate while investigating the wires using an optical microscope and examining the wires while rotating them along their axis.

4.3.3. Mechanical testing of wires

The final testing of wires is the classical strength and stress measurements using a tensile strength instrument. Those measurements are performed to identify the strength of the wires and identify if there are strength benefits on braiding the wires compared with unbraided lines.

4.4. Wire testing analysis

4.4.1. Stainless steel wires

The first stages of testing are performed using stainless steel wires. Three set of stainless steel wires are used, 500 µm, 250 µm and 50 µm. Stainless steel wires are selected as they are easy to obtain and there is big variety of dimensions available. Those dimensions are selected in order to have a wide range of dimensions for braiding in the for the initial tests. As a result, the limitations of the machine on wire dimensions are explored and a preliminary study is done to understand the wire diameter influence on the braided wire characteristics and braiding process.

The thicker wire of 500 µm is used for the initial testing phase: this wire is able to withstand high loads and is more versatile in handling and fixation compared to the thinner wires that followed. As the machine operation became more stable and knowledge and experience gained the thinner wires were used. The thinner wires are necessary to reach the goal of 7 µm carbon yarns and observe if there are any issues in the machine that would damage or break more sensitive wires.

Figure 4.11 illustrates braided wires from the three aforementioned dimensions. It can be seen, even with no thorough analysis, that the thicker (500 µm) wire was not braided uniformly. This highlights the limitations of this method in thicker wires as it was not designed for this use-case and thicker wires require higher force and stiffness for the braiding machine components. Also, the 250 µm and 50 µm wires were braided more uniformly with the thinner one showing the better regularity. For this reason, the two thinner dimensions of the stainless steel wires are presented, analyzed and discussed for the rest of this report and the thicker version is disregarded.

Furthermore, Figure 4.12 depicts two optical microscope pictures of braided 250 µm and 50 µm wires. From Figure 4.12, and in combination with other measurements performed, we can see that the average outer diameter of the 250 µm is 930 µm, the inner diameter 476 µm with the wavelength at 5 mm. Along with standard deviation of 54 µm for (D_{in}) and 105 µmfor (D_{out}) this wire demonstrates good regularity along its braided length. Additionally, this wire presents a packing factor of 56 % meaning that the wire covers in excess of half of the area that this wire claims.

The same measurements and calculation are performed for the 50 µm wires. The inner diameter (D_{in}) is 142 µm, the outer diameter(D_{out}) is at 241 µm and finally the wavelength (λ) is at 1.1 mm. Those measures give standard deviation of 33 µm for (D_{in}), 48 µm for (D_{out}) and 358 µm for (λ). This gives

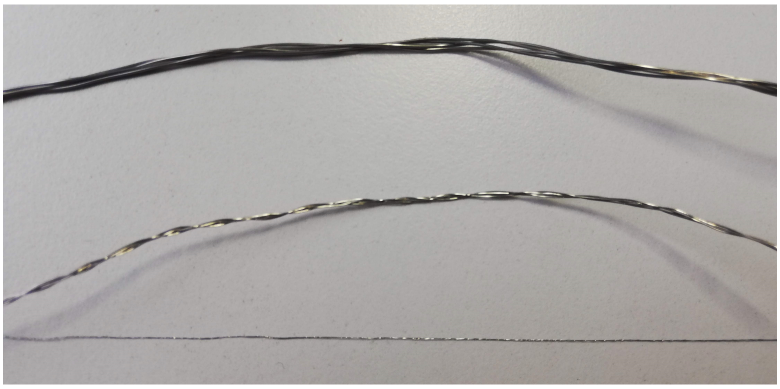


Figure 4.11: 500 µm, 250 µm and 50 µm stainless steel wires braided.

a much higher normalized standard deviation values compared to the thicker 250 µm wires, meaning that this wire presents smaller regularity with high deviation on the braiding frequency and dimensions along the length of the wire. The packing factor of these wires is 29% meaning that the wires cover only about a third of the volume this wire occupies.

Wire Diameter	**250** µm			**50** µm		
Data [unit] **\Dimension**	D_{in}	D_{out}	λ	D_{in}	D_{out}	λ
Average [µm]	476	930	5026	142	241	1142
Standard Deviation (σ) [µm]	54	105	N/A	33	48	358
Normalized σ [%]	11.3	8.9	N/A	22.9	19.8	31.3
Packing Factor [%]		56			29	

Table 4.1: Summary of measured data for stainless steel braided wires.

In general the stainless steel wires are rigid and difficult to braid because when there is a bent part along their length, they do not spring back but rather get stuck with the other wires sliding around them. This phenomenon causes the wires to knot or braid out of place. This phenomenon explains the large variation in (λ) along the length of the stainless steel wires and especially the thinner one. (50 µm) as it is by its nature easier to bend and requires less force to plastically deform.

This phenomenon makes the stainless steel wires undesirable for braiding using this machine. The constant length of the machine means that if a bent wire is mounted cannot be refreshed with new wire during the braiding process so the sticking and miss braiding is dependent on the mounting and initial wiring conditions that due to the thin sizes of the wires is very difficult to control.

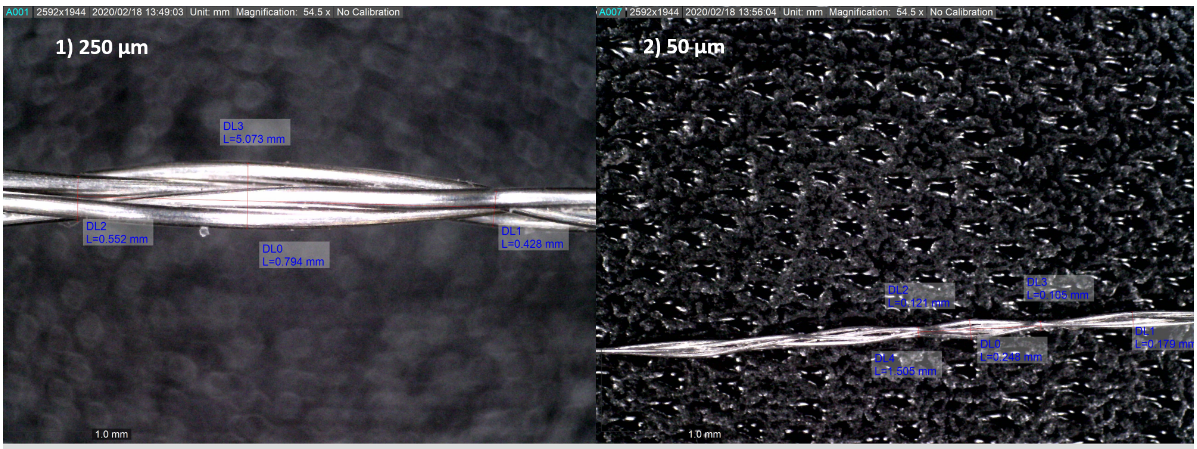


Figure 4.12: Stainless steel braided wires of 50 and 250 micro meters.

4.4.2. Nylon wires

Following the braiding of stainless steel wires, 100 µm Nylon wires were tested. The Nylon was selected as it is more flexible than the stainless steel and doesn't have the problem of wires sticking with each other due to bent parts. The nylon wires proved the easiest to handle and are more expendable than the stainless steel or carbon wires. Moreover, the braiding wire was used during a big part of the machine development and the functional tests discussed earlier in subsection 4.1.3

The result of the optimum machine configuration, resulted from the testing process can be seen in Table 4.2 and Figure 4.13. In combination with other measurements the average inner diameter (D_{in}) is calculated 191 µm, the average outer diameter(D_{out}) 472 µm and the average wavelength (λ) 1370 µm. Those measures give standard deviation of 23 µm for D_{in}, 5 µm for D_{out} and 155 µm for λ. These measurements are better in terms of wire regularity compared to the ones of the two stainless steel wires investigated earlier in this Section. The packing factor of those wires is 44%, lower than the 250 µm but still better packed than the smaller 50 µm wires.

Nylon 100 µm

Data [unit] **\Dimension**	D_{in}	D_{out}	λ
Average [µm]	191	472	1370
Standard Deviation [µm]	23	5	155
Normalized StDev [%]	11.9	1.2	11.3
Packing Factor [%]		44	

Table 4.2: Summary of data for 100 microns braided Nylon wire.

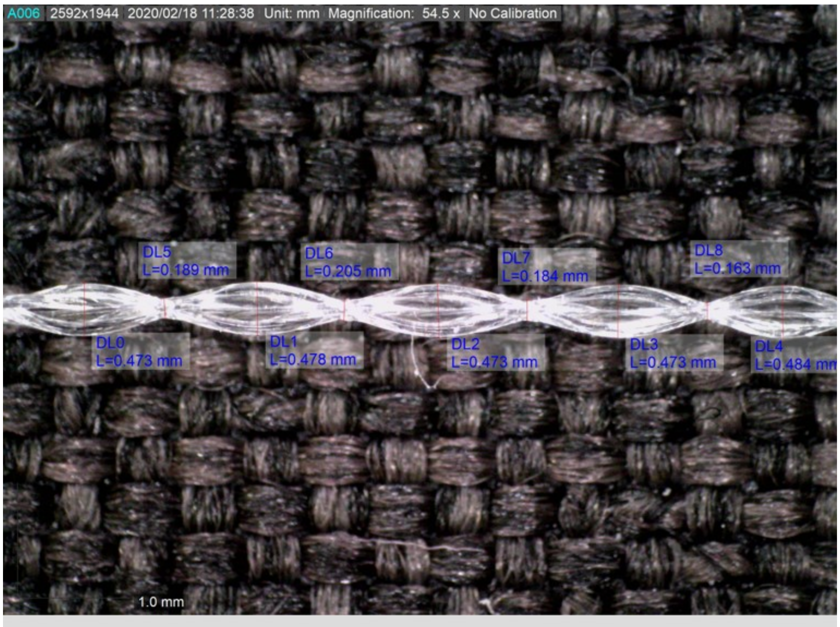


Figure 4.13: Nylon braided wires of 100 micro meters.

4.4.3. Nylon testing and machine development

The better performance of the Nylon wires is a result partially of the material itself: Nylon it is more flexible than stainless steel and it can slide better around itself, allowing more regular braiding to form. Moreover, the braiding described earlier was performed in later development stages of the machine and more specifically at the end of the machine development so it represents the best results obtained using the Nylon wires. Thus a part of the better performance of these wires - compared to the stainless steel wires - can be attributed to the improvements in machine performance. This is better visible by comparing nylon braids along the development process as demonstrated in Figure 4.14.

There were four main phases of the machine development, listed in Table 4.3:

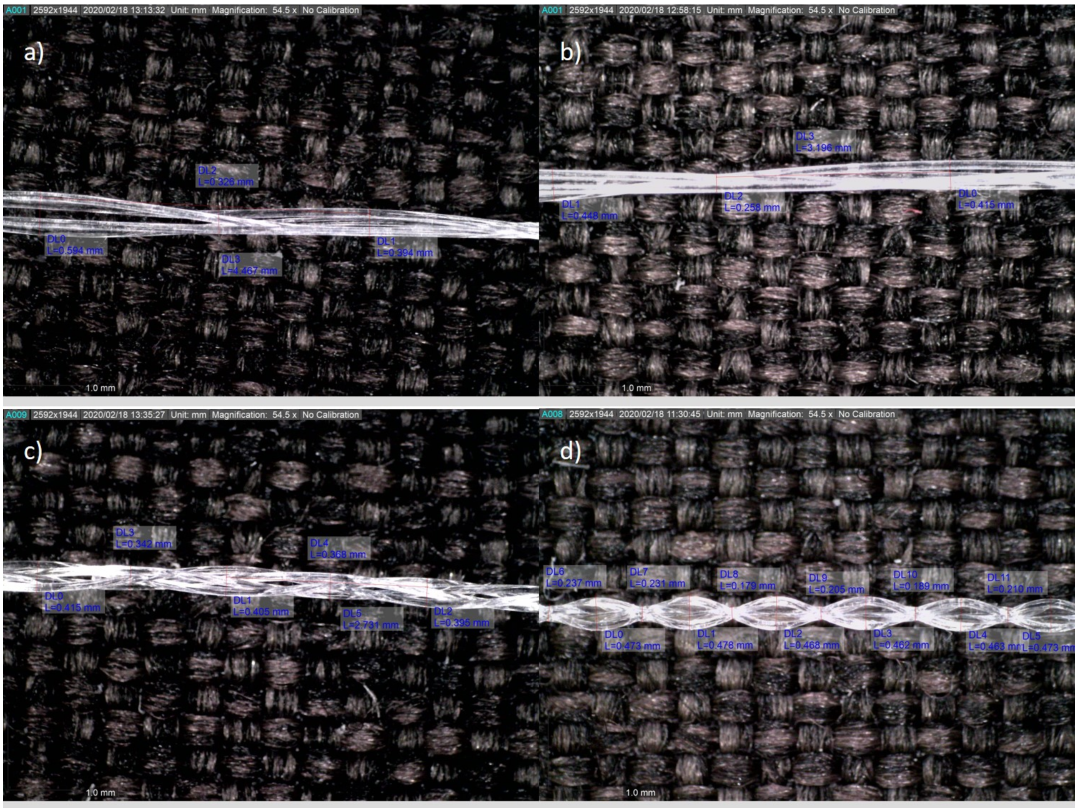


Figure 4.14: Nylon braided wires during development of the machine

Version	Case
1	No guiding with spring
2	Guiding with no spring
3	Guiding with spring
4	Tight guiding with spring

Table 4.3: The phases of machine development.

The aforementioned testing phases in Table 4.3 refer to the final adjustments of the machine where the function and even the existence of a guiding system was questioned and the addition of a spring, in order to keep all the wires in tension, was investigated. Thus, the four tests were conducted with the aim to evaluate the impact of a spring with no guiding mechanism. Further the guiding alone with no spring mounted, in order to investigate the importance of tensioning the wires and the guiding. Finally, two similar tests were performed with both the guiding system activated and the yarns always tensioned with the use of a spring. The difference between the last two tests was the function of the guiding system: in the simple testing, the guiding system was lightly guiding the braiding point but in the 'tight' guiding test, the guiding was dictating the braiding point such as the tightest possible braiding was produced.

The data obtained due to testing of the different development phases are demonstrated in the Figure 4.16 for the average braiding wavelength λ and Figure 4.15 for the average inner(D_{in}) and outer(D_{out}) braid diameter.

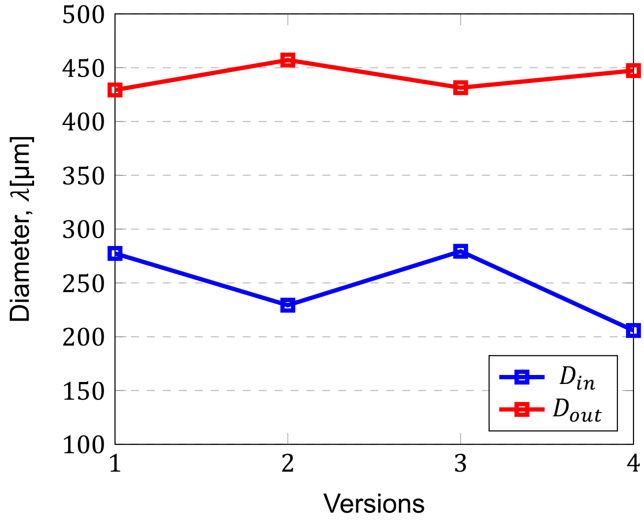


Figure 4.15: Inner and outer diameter of braids for the different versions.

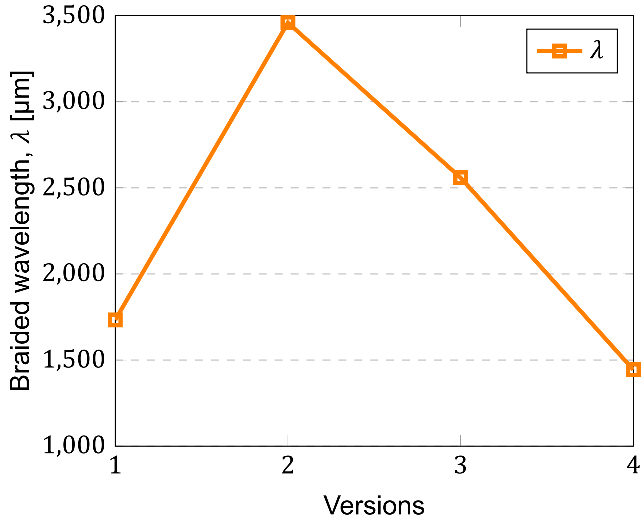


Figure 4.16: Average braiding wavelength for the different versions.

There are a few conclusions to be extracted by plotting the average values of diameter and braiding length in Figure 4.16 and Figure 4.15. It is clear by these plots, that during the tests with different machine configuration the average braiding wavelength had a big fluctuation but the diameters staid almost unchanged. This is an indication that the braiding length is a parameter dependent on the machine as we observe big changes depending on the configuration. On the other hand, the braiding diameter is a parameter mostly related to the wires themselves as we observe small changes in their average values.

A further analysis on the data was performed in order to evaluate the quality of the braiding. This is done by calculating the standard deviation of the set of measurements. In order to obtain comparable results, the standard deviation was normalized with respect of the mean value. This is necessary especially for the λ measurements as the mean fluctuates from 1500 µm to 3500 µm. Figure 4.17 and Figure 4.19 illustrate the changes in the standard deviation with respect of the median over the four different cases.

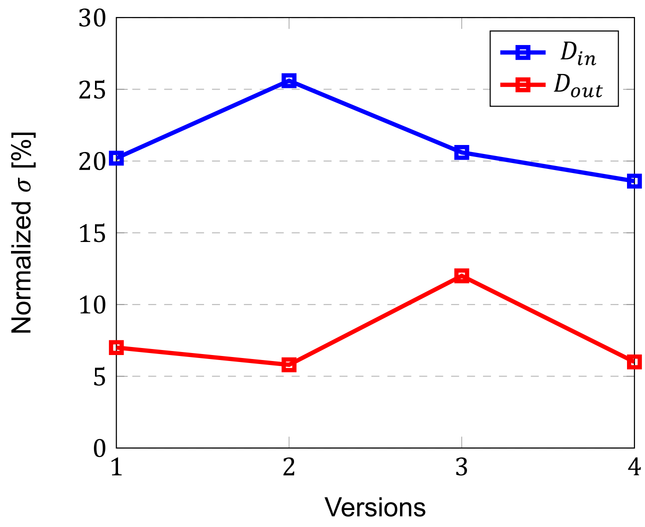


Figure 4.17: Normalized standard deviation of the three measured quantities.

It can be seen by Figure 4.17 that the distribution of the diameters is not impacted heavily from the machine's configuration. The inner diameter has a σ of about 20% of the mean for all the test performed and the outer diameter has a σ of about 5% for the tests performed. Regarding the inner diameter, it is expected to have larger variance as it has a smaller absolute value and thus even small changes can make a big impact. Moreover, the smaller dimension is more prone to changes in the orientation of he wire while taking the measurements meaning that a part of the big variance can be attributed to this. This measurement uncertainty is schematically demonstrated in Figure 4.18. Unfortunately, controlling the orientation of such small wires during measurement along their length is very hard and thus some of the measurements are impacted.

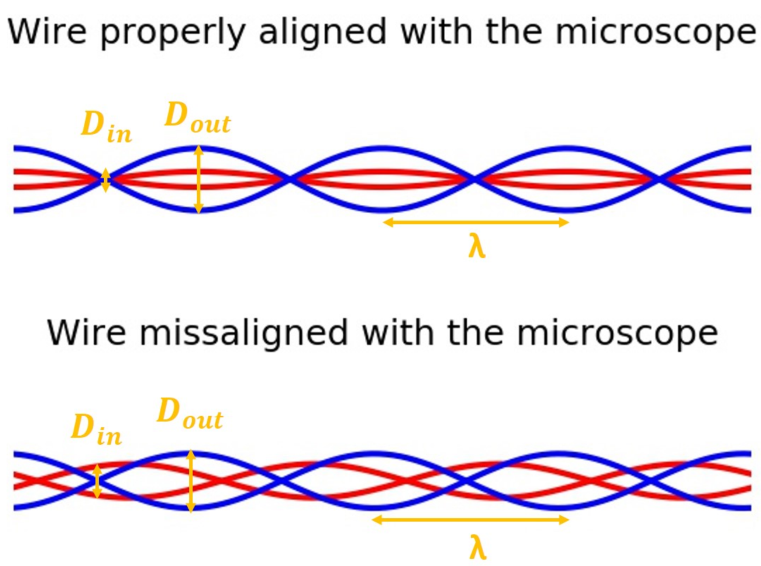


Figure 4.18: Measurements impacted due to the orientation of the wire during testing.

Moreover, Figure 4.19 demonstrates the changes of the standard deviation of the λ with respect of the median λ for each case. It can be seen that the variance is changing dramatically between the first and the last version of the machine from an initial variance of more than 40% of media to almost 10%. This further suggests that the braiding wavelength (λ) is dependent on the machine and its setup, in contrast on the wire diameter that is mostly related to the wire itself. It also means that the final machine configuration can produce more uniform wires than the other configurations investigated.

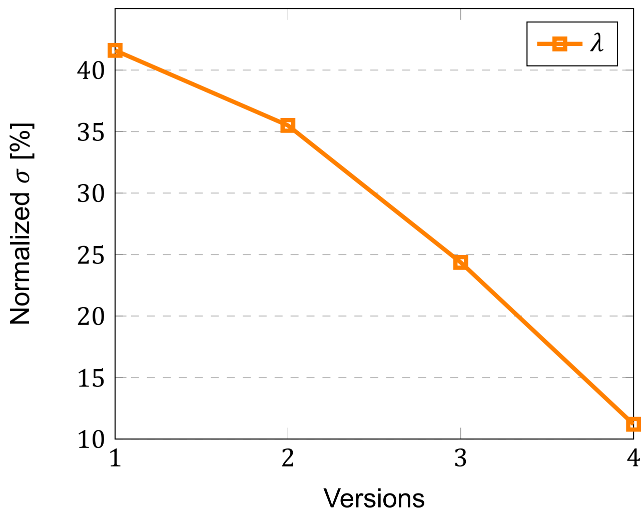


Figure 4.19: Normalized standard deviation of the three measured quantities.

Furthermore, by filtering the data used for the analysis and removing all the data points from miss aligned wires, as demonstrated in Figure 4.18, all the average values and standard deviations can be recalculated for the measured quantities, D_{in}, D_{out} and λ. The results of this procedure are presented in Table 4.4 and compared to the initial values.

By selecting the data that with correct wire orientation we see that the variance for the diameter is reduced dramatically, from 38 µm to 23 µm for D_{in}, equivalent to almost 40% reduction in variance and from 27 µm to 5 µm for D_{out}, or about 80% reduction in variance. This result is expected because as it was seen previously the diameters and especially the outer diameter is mainly a wire characteristic (material and diameter) and not influenced very much by the braiding method. That means, the D_{in} and D_{out} should be constant along the braided wire length, as the wire material or wire dimension doesn't change along the wire.

The wavelength (λ) for the selected data is virtually unchanged as it deviated only 5 % from the initial value and the its standard deviation only 4 % from the initial one. This again is expected as the braiding wavelength is a characteristic of the braiding process and changing the orientation of the wire should not make any change, the same applies with the pick or dip of the wires when measured, they are well visible even with wrong wire orientation.

Nylon 100 µm

Data\Dimension	D_{in}	$D_{in}^{selected}$	D_{out}	$D_{out}^{selected}$	λ	$\lambda^{selected}$
Average[µm]	206	191	447	472	1444	1370
Standard Deviation[µm]	38	23	27	5	162	155
Normalized StDev [%]	18.6	11.9	6	1.2	11.2	11.3

Table 4.4: Summary of the selected data for 100 microns braided Nylon wire.

Concluding this series of testing, the final version of the machine can produce wires with lower variance for the braided wavelength. This means that the wires present better regularity along their length and not considerable variations are detected. This analysis was the last part of non carbon wires testing. Following, carbon wires of 100 µm are braided as the first step towards 7 µm carbon wires braiding.

4.4.4. Carbon wires

Finally, some 100 µm carbon wires are tested. Figure 4.20 illustrates the braided carbon wire and it can be seen that the braiding pattern is regular and the wire envelope constant.

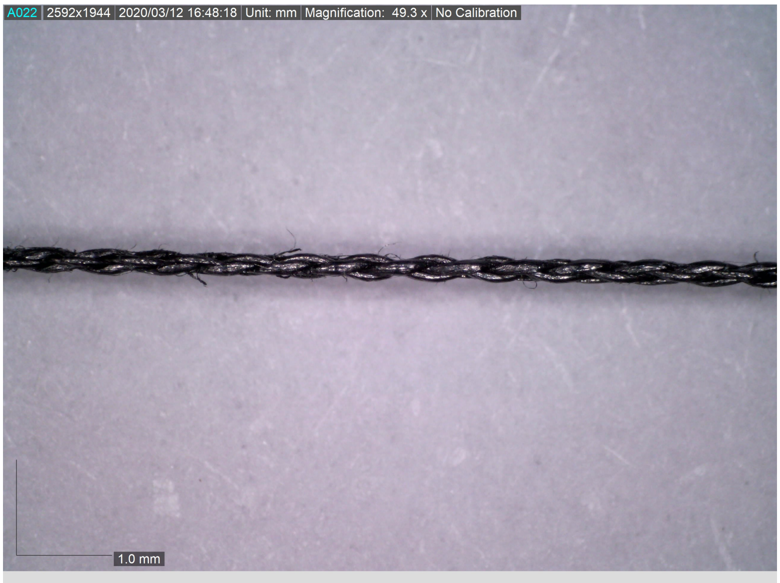


Figure 4.20: Carbon braided wires of 100 micro meters.

The average inner diameter (D_{in}) is 146 µm, the average outer diameter (D_{out}), 285 µm and the average wavelength (λ) 627 µm. Those measures give standard deviation of 12 µm for D_{in}, 17 µm for D_{out} and 64 µm for λ. This means that this wire presents a high regularity as there is not much deviation of its dimensions along its length.

Carbon 100 µm

Data [unit]\Dimension	D_{in}	D_{out}	λ
Average [µm]	146	285	627
Standard Deviation [µm]	12	17	64
Normalized StDev [%]	8.2	6.1	10.2
Packing Factor [%]		96	

Table 4.5: Summary of data for 100 microns braided Carbon wire.

Finally, the packing factor of the 100 µm carbon wire is extremely high, at 96%. The high packing factor can even be seen from Figure 4.20 as the wire appears as a very tight braiding pattern.

4.5. Wires testing results comparison

4.5.1. 100 µm Nylon and Carbon braiding dimensions

It is interesting to compare the testing results of the 100 µm Nylon wire with the 100 µm carbon wire. As those wires are of the same diameter we can directly compare how the three measured quantities vary. For this comparison, both the data used for the Nylon and the carbon wires are the selected data with the correct wire orientation, describer earlier in this Section 4.4. Table 4.6 demonstrates this comparison.

Nylon vs. Carbon

Data\Dimension	D_{in}^{Nylon}	D_{in}^{Carbon}	D_{out}^{Nylon}	D_{out}^{Carbon}	λ^{Nylon}	λ^{Carbon}
Average[µm]	191	146	472	285	1370	627
Standard Deviation[µm]	23	12	5	17	155	64
Normalized StDev [%]	11.9	8.2	1.2	6.1	11.3	10.2

Table 4.6: Summary of the selected data for 100 microns braided Nylon wire.

By directly comparing the two braided wires and knowing that the carbon wires are more flexible and compliant compared to the Nylon, we can identify better which parameters are mostly dependent on the material and which can be influenced by the machine design.

From the comparison in Table 4.6 it can be seen that the inner diameter (D_{in}) of the braiding is similar for both wires. This is reasonable as this is the part where the wires are stack one above the other, as illustrated schematically in Figure 4.8. Furthermore we can see that both the outer diameter (D_{out}) and braiding wavelength (λ) appear significantly smaller for the carbon wire. In summary, the Inner diameter (D_{in}) of the carbon wires is 24% smaller than the Nylon, the outer diameter (D_{out}) of the carbon is 40% smaller than of the Nylon and finally the braiding wavelength (λ) of the carbon is 54% smaller.

These observations mean that the carbon wires are packing closer than the Nylon wires and thus more tight braiding can be achieved. This is visible in the side by side comparison in Figure 4.21. It can be seen from this Figure that in the same wire length, the carbon wire has more braids and it is packed in smaller diameter.

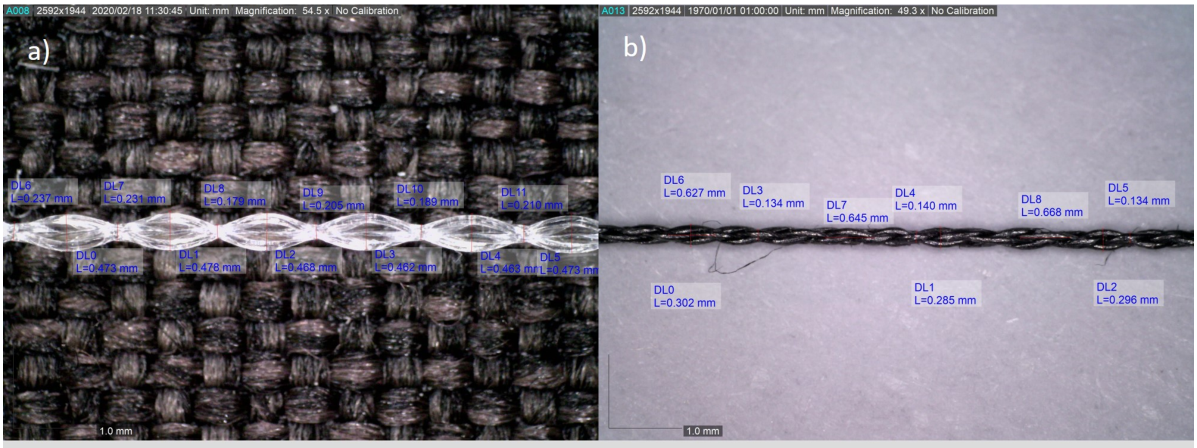


Figure 4.21: Visual comparison of a) 100 µm braided Nylon wires and b) 100 µm braided Carbon wires.

As there are no machine modifications between the Nylon and carbon wires braiding the braiding frequency is both a material parameter that is dependent both on the material (and dimensions of yarns) and the machine configuration. More specifically the minimum braiding wavelength is determined by the material itself and it can be larger depending on the machine settings. Moreover, the wire envelope (outer diameter D_{out}) and inner diameter (D_{in}) are mostly influenced by the material itself as we could see that there were very small changes when the machine and testing parameter were changing during the Nylon tests.

4.5.2. Packing factors of all data

One additional quantity that can be used to compare the braided wires is their packing factor. The packing factor is a non dimensional quantity and it can be used to compare the wire braiding and quality across the spectrum of the braided wires. There were three methods of calculating the wire packing described in Section 4.3.2. For calculating the wire packing for this braiding application only the method using the ellipse as wire envelope was used as this method describes in more comprehensive manner the wires braided with this machine. The packing factor comparison of all the test braided wires is summarized in Table 4.7.

Packing Factors

Wire\Quantity	D_{wire} [µm]	D_{out} [µm]	D_{in} [µm]	D_{avg} [µm]	F_p[%]
Stainless Steel	250	930	476	703	56
Stainless Steel	50	241	142	191	29
Nylon	100	472	191	332	44
Carbon	100	285	146	215	96

Table 4.7: Packing factors summary for all the braided wires.

For this comparison, it is more interesting to compare the stainless steel wires between each other and the Nylon and carbon 100 µm wires between them.

The thick (250 µm) stainless steel wire appears to be more tightly packed than the thinner (50 µm) ones. This can be partially attributed on all the issues that appeared during braiding of the thinner stainless steel wires. Those wires are harder to braid because they tend to bend and stuck between each other. This gives many open spaces in the braiding that reflects to high deviation in the inner diameter, outer diameter and braiding wavelength and a small packing factor. For this reason we see a good packing factor of 56 % for the 250 µm wires and only 29 % for the 50 µm wires.

Furthermore, comparing the 100 µm Nylon and carbon wires: the Nylon wire appears with 44 % packing factor where in contrast carbon appears much higher at 96 %. This result can be attributed mostly to the flexibility of the carbon wires. From the side-by-side comparison of the two wires in Figure 4.21 it is clear that the carbon wires appear to be more tightly packed. Also the carbon wires don't appear with the characteristic waveform of Nylon but they appear more like a tube of uniform wire.

4.5.3. Tensile testing

Furthermore, we had the opportunity to perform some material properties tests with the University of BATH Mechanical Engineering Department. The amount of testing was not necessary to produce statistically significant results but the preliminary results are promising and thus, are presented here.

The most interesting test performed was the comparison of a single 500 µm in diameter stainless steel wire and four braided 250 µm each in diameter stainless steel wires. Those two test pieces have the same effective diameter as they have the same area:

$$A = \pi \times r^2$$

$$A_{500} = \pi \times 250^2 = 196.350\mu m^2$$

$$A_{4x250} = 4 \times \pi \times 125^2 = 196.350\mu m^2$$

This means that, as the two wires are made from the same material should fail under the same stress. However, this has not happened during the testing. As it can be seen in Figure 4.22, the four 250 µm breaded wires appear to break at 154 N while the single 500 µm wire breaks at 141 N. This means that the braided wire appears to be 9% stronger than the single wire of the same effective diameter.

Furthermore, the performance of the single 250 µm and four upbraided 250 µm stainless steel wires is compared to the 4 braided. It can be seen in Figure 4.23 that the performance is very similar: the breaking force of the 4 unbraided wires is 154 N while the one for the braided ones 157 N, giving a difference of about 2%, meaning that there is no significant difference in strength of those wires. It needs to be noted that the four single upbraided wires are an extrapolation of the data for single 250 µm wire (also illustrated in Figure 4.23).

Moreover, combining those two studies, it can be seen that as the braided and unbraided 250 µm stainless steel wires appear to have similar performance between them, the difference shown with the single 500 µm stainless steel wires, of similar effective area, is a result of the testing multiple wires instead of single and possible material differences than the braiding of the wires themselves. In general similar testing campaign needs to be implemented for the same diameters but also for the Nylon and carbon wires to gain some additional data points and draw solid conclusions.

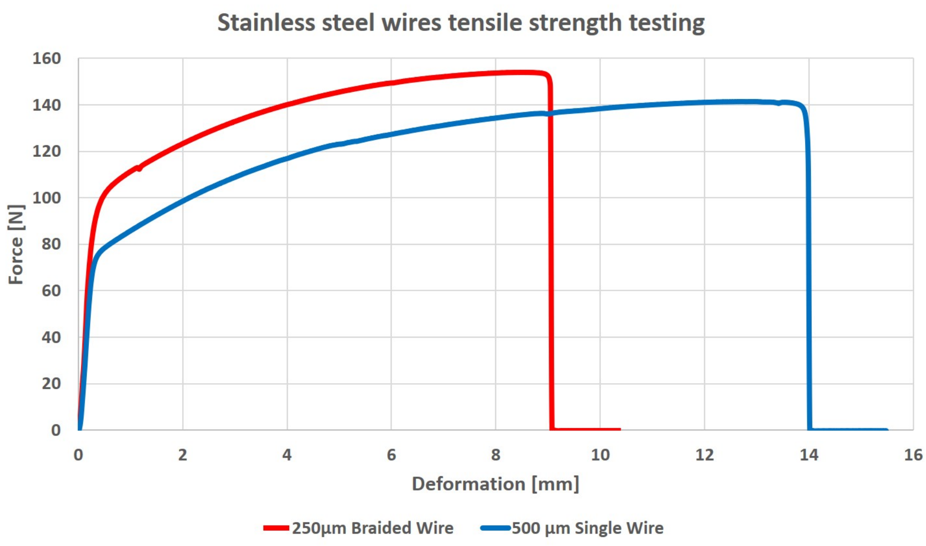


Figure 4.22: Strength testing of 500 µm and 250 µm stainless steel wire.

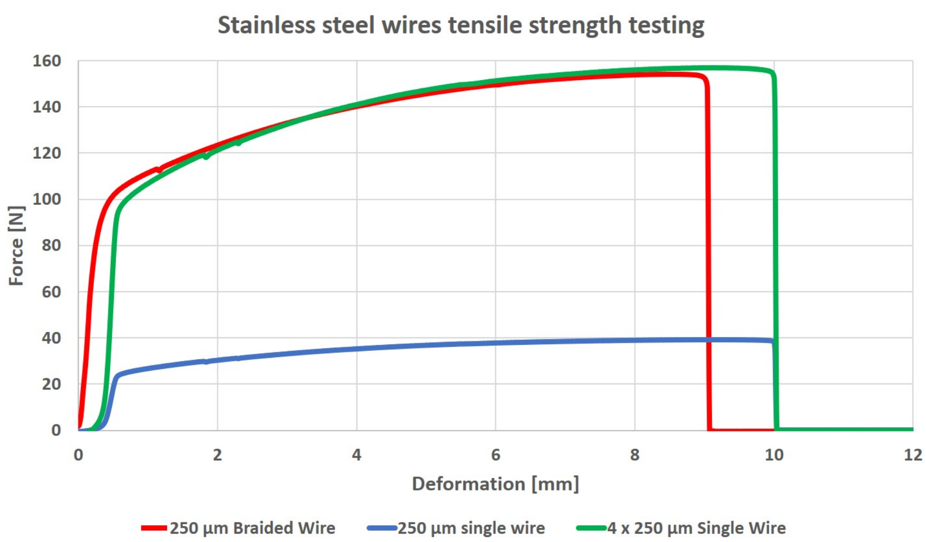


Figure 4.23: Strength comparison of braided 250 µm and single 250 µm stainless steel wire.

Concluding, preliminary data demonstrates that the performance of braided wire exceeds that of single wires of the same diameter. This performance increase has been studied in the literature as well [12, 18, 21**? ?**]. Nevertheless, the extrapolated data of single wires for the same diameter showed similar performance as the braided wires. Generally, the data we have at this time are insufficient to declare this study concluded and we plan to run some additional tests in house at CERN to verify these results and also include some Nylon and carbon wires.

5 Discussion

As this project includes a large amount of testing, there is a substantial amount of wire braiding experience gained that is not easily quantifiable or measured. This experience refers to the types of wire that can be used with the proposed braiding method, limitations of the braiding method and techniques to improve the braiding process and machine settings for optimum braiding.

5.1. Optimum braiding wavelength

By redesigning the guiding system for the braiding machine the improvement in machine's braiding performance was noticeable, but the potential ability to control the braiding wavelength by controlling the relative speed of the actuation and guiding subsystem was compromised by the nature of the new system.

Nevertheless, there is strong suggestion that for every wire there is a limit on the tightness of the braiding and that can be investigated by testing. After the tightest limit is found we could use the new braiding system to create a less tight braid. By doing so there can be some influence to the other characteristics of the wire such as the regularity and packing factor.

This means that even thought for every wire there, is a minimum braiding wavelength that might not be the optimum value for the wire quality, considering the packing factor as objective. The way to identify the new optimum braiding would be to run a series of wire braiding tests and measurements where a set of materials are used to identify their minimum braiding wavelength and then tested with longer wavelengths in order to identify their regularity and packing factors. If we see that the packing factor or regularity increases for looser braiding suggests that the optimum braiding is not the tightest one possible.

5.2. Wire packing and material influence

The theoretical packing factor discussed in Chapter 3 was about 69 % and by using the elliptical representation of the wire envelope to calculate the theoretical packing factor of four yarns was 73% and the packing factor of the carbon wires is calculated at 96%. These observations lead to two possible explanations.

First, the carbon wire is not a rigid yarn, meaning that it is able to deform and thus occupy the free space available. The latter combined with the tight braiding, fills the free void and results in a superior packing factor. One other explanation is that this definition of packing factor selected is not completely accurate for the whole length of the wire but distinct parts of it. If the packing factor is calculated using the outer diameter of the wires only, this definition is not representative but it is always on the safe side as it always includes the whole wire, the packing factor of the wire is at about 50 % that is below the theoretical maximum of 69 %. This phenomenon can give an explanation to the extraordinary packing performance calculated for the carbon wire. It does not mean that the carbon wire is loosely packed as it is close to the theoretical maximum but rather a reflection that this method of calculating the packing factor.

Additionally, we can combine the first aforementioned theory, that the carbon wires present higher packing factor because they are not rigid and can occupy the surrounding space with the ultimate goal of this project that is four bundles of 3 wires each. Following this theory, it is likely that the packing factor of this braided wire of 12 yarns can present higher packing factor of the calculated packing factor of four bundles, about 44 % and approximate or even outperform the packing factor of the four single yarns of 69 %. This is a promising theory for the next step of braiding the final wire scanner wires. Moreover, it was seen that every wire seems to have a minimum braiding wavelength as a material characteristic. This braiding wavelength can be identified in each case and each wire to during a testing phase before the proper wire braiding and can be used a calibration phase.

5.3. Tensile tests

The tensile test was briefly tested during this study. The tests were rather short and stopped abruptly. This means that there are no conclusive results available. Nevertheless the preliminary results were promising as shown in Section 4.5.3, a potential increase in braided wire performance compared to similar area single wires was observed.

This is a promising result and there is plausible explanations in literature [12, 18, 21, 23] but there are additional testing necessary in order to verify this phenomena. Moreover it will be interesting to run a series of experiments varying the braided wavelength for each material in order to see the impact on the tensile strength performance of the wires. By doing so, there is considerable chance that we might be able to identify a different optimum for the braiding wavelength in respect to the tensile strength of the braided wire that might be different than the minimum packing wavelength or the optimum packing factor wavelength.

Concluding, as the three aforementioned wire characteristics (tensile strength, regularity and packing factor) are better understood, and their relation to the braiding wavelength identified, it is possible to develop a better method for wire design according to each application and its desired wire characteristics with respect to the tensile strength, regularity and packing factor. This exercises requires extensive testing of many materials in order to collect an appropriate look-up table that can act as the model for wire braiding parameters decision making.

6

Conclusion and future work

This Chapter summarizes the design and implementation of the novel micro wire braiding solution for CERN's wire scanners. In order to achieve a new braiding solution, a set of research objectives were reached. The main sectors of the objectives are developing a standardized wire braiding procedure, developing a prototype machine that implements the braiding procedure and finally test the prototype machine and the braided wires and document the progress.

6.1. Braiding procedure development

A new standardized braiding procedure was developed. In order to develop this procedure, the state of the art was studied, and its limitations for microwire braiding were identified and explained. Furthermore, a study for the optimum wire configuration and dimension was conducted whose objective was the simplicity of the machine and the highest possible packing of the wires. A four wire concept was selected with the ability of having four strands of three 7 µm wires for a total of twelve yarns braided wire. The novel design results in a new procedure of braiding 4 yarns wires or 4 strand of multiple yarns wires. The procedure was further developed by creating design concepts for a microwire braiding machine.

6.2. Micro wire braiding machine development

During the machine development phase of the project, the proposed procedure was advanced to a braiding machine concept. More specifically, a three-phase design methodology was used. A set of concepts was created during the conceptual design phase; at the same time, a complete functional decomposition was performed to both this problem statement and to the state-of-the-art machines. Using the functional decomposition, the design criteria and the decision-making method of trade off tables, a subset of these concepts was pre-selected for the second phase, the preliminary design.

During the preliminary design in Section 3.3.3, the selected concepts were further developed with more details towards their functionality. Further, using the tradeoff tables, those concepts were evaluated to reach the final stage of the design, the detailed design phase. For the detailed design phase, in Section 3.3.4, the final concept was developed in more detail, including all the functional element and mechanisms. This design later evaluated using a proof of concept, in the form of a 3D printed machine in Section 3.3.5. From the proof of concept, it was concluded that the final concept works as desired and moved on some slight iterations from some detected issues, in Sections 3.3.7 and Section 3.3.6 respectively and the final manufacturing design was done in Section 3.4.

The machine was manufactured both in-house at CERN and external companies. Nevertheless, a large amount of commercially available components was implemented in the design, reducing the manufacturing time and cost of the machine to minimum while improving the reproducibility potential of the machine for potential future use. The manufacturing and procurement of all the components was followed by the assembly and testing. The first test for the machine was the static tests, meaning the assembly and fitting of the components.

After the simple assembly, a more tedious testing phase began. During this phase, first a dynamic test was done, where the function of the prototype was investigated in Section 4.1.2. The main issues detected was sticking on the cam gears, and it was resolved by redesigning the cam gears, the stiffness of the leaf springs, that was resolved by changing the position of the springs and trimming their width to reduce the stiffness and the torque of the motors that was resolved by introducing new, more powerful, motors to the design.

The final testing of the machine was with wire braiding. During the wire braiding phase, issues on the braiding system were identified. The braiding system that was designed in order to dictate the braiding point resulted in the wires getting stuck around it and the machine stalling. This problem was solved by a redesign of the guiding system, considering the available design space and it resulted in a simpler and better performing system.

6.3. Wire testing

The final step of this study is the wire testing of the new braiding method. For this reason, a set of wire material and diameters were used. Stainless steel of 500 µm, 250 µm and 50 µm were used along with nylon wire of 100 µm and carbon of 100 µm. By testing different wires, the machine functionality was investigated, and braiding experience was gained.

In order to compare the braided wires a set of wire parameters were measured and analyzed. Those parameters were the braiding diameters and the braiding wavelength. The average braiding diameter of the 100 µm carbon wires as measured at 472 µm with a standard deviation along its length of 1.2 % and the braiding wavelength at 627 µm with a standard deviation of 10.2 %. Meaning that the produced wires present a high regularity along their lengths.

Using the braiding diameters two observations were made. First, the outer diameter of the wires is material dependent rather than machine dependent. On the other hand, it was shown that while changing the wire material and keeping the machine unchanged the braided wire diameter appears changed. Moreover, by using the wire diameters the packing factor of the wires was calculated. The packing factor was found to be material dependent as well as there was a big change when the material was changed with all the other settings unchanged. For the 100 µm carbon wires, the packing factor was calculated at 96% giving a highly dense wire.

Furthermore, the braiding wavelength was measured as a metric or wire braiding regularity. The final wires produced achieved high level of regularity but also,it was seen that the braiding regularity and braiding wavelength to be highly dependent on the machine parameters together with the wire material. This means that for every future material used for braiding with this method there is an optimum braiding to be achieved through testing.

6.4. Future work

Concluding, all the data suggest that this new braiding method can be proven useful for the CERN's accelerator complex as it can potentially braid the next generation wire scanner's wires. In order to determine if the wires braided are suitable for machine use though a further set of testing is needed.

First of all, the testing of 7 µm carbon wires, suitable for the LHC wire scanners is required. The 7 µm carbon wires need to be tested expensively as well in regards of the reputability and regularity of the braiding.

Finally, there is an ongoing interest to perform tests with braided wires in lower accelerators machines of CERN such as the SPS.

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