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Design of An Automatic Machine for Scissor Testing

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Abstract

The first objective of this work is to provide the basis for the future design and realization of an automatic machine to test the wear and the cutting capability of scissors. The idea is to provide the requirements and functional analysis of the machine, meaning what the automated system must do, without exceeding from the boundaries imposed by mechanics, electronic controls, ease of use and costs. The main objective is to fully satisfy the expectations of the customer developing a product which is first of all effective and reliable and then competitive in terms of manufacturing cost. Different solutions will be analyzed in detail and pros and cons of each alternative will be discussed. A final configuration of the machine will be chosen from the ones proposed and all the functional groups involved in its realization will be described and analyzed even in terms of cost.
The second part of the thesis is focused on the validation of the measurement system of the cutting torque already developed for the machine; a series of experiments will be carried out to detect the relevant parameters that influence the cutting torque and the cutting procedure itself.

Il primo obiettivo di questo lavoro è fornire le basi per la futura progettazione e realizzazione di una macchina automatica per testare la durata e la capacità di taglio di forbici. L'idea è quella di sviluppare un'analisi dei requisiti e funzionale della macchina, ovvero ciò che il sistema automatico dovrà compiere, senza superare i limiti imposti dalla meccanica, dai controlli elettronici, dalla facilità d'uso e dai costi. L'obiettivo principale è soddisfare pienamente le aspettative del cliente nello sviluppo di un prodotto che sia prima di tutto efficace, affidabile e quindi competitivo in termini di costi di realizzazione. Diverse soluzioni saranno analizzate in dettaglio e verranno discussi i pro e i contro di ciascuna alternativa. Una configurazione finale della macchina sarà scelta tra quelle proposte e tutti i gruppi funzionali coinvolti nella sua realizzazione saranno descritti e analizzati anche in termini di costi.
La seconda parte della tesi è focalizzata sulla validazione del sistema di misura della coppia di taglio già sviluppato per la macchina; una serie di esperimenti sarà condotta per verificare se esistono alcuni parametri rilevanti che possono influenzare in modo significativo la coppia di taglio e la procedura di taglio stessa.

Keywords: functional analysis, cutting machine

1 Introduction

1.1 Cutlery standards and applications

The basic idea of the project (and the desire of scissors manufacturers in general) is to have the possibility of comparing and analyzing different kind of scissors, extract the data which can characterize in a peculiar way every single product and finally define which one can be considered the best one. This kind of comparison passes necessarily through the definition of mathematical parameters which can describe accurately the sharpness of the blades composing the scissors. During the years many studies have been developed to measure the performance of blades in general, because of their widespread use in different sectors, ranging from household applications to daily working operations. It is important to underline that one accurate analysis of the behavior, resistance and wear of the blades could be of interest for mainly two reasons. The first one is to prevent professional pathologies linked to a repetitive and constant task: for example, we can easily imagine that a dull blade requires a higher amount of force (more precisely torque) to be impressed during the cutting operation with the subsequent possibility of developing muscular pathologies for arms, hands or fingers. The second one is related merely to an economic point of view. In fact, the loss of sharpness implies an increase of the time required to complete a cutting operation and the necessity to re-sharpen frequently the blade, badly affecting the productivity. The problems that have been briefly described above are typical of a big variety of cutting tools, anyway literature provides few documents focused on the problem of studying specifically the properties of scissors. Developing a machine to test and compare different kinds of scissors could be useful to provide information about this specific item and to solve problems that are common to other cutting devices such as blades and knives. The machine could provide useful and objectives information to improve the productive cycle of scissors and to monitor the retention of the quality standards during the whole lifecycle of the product.
The document of relevant interest for the sharpening of cutting tools, such as scissors, blades and knives is the ISO 8442 “Material and articles in contact with foodstuff-Cutlery and table hollower”. The relevant part of the document is the section 5 “Specification for sharpness and edge retention test of cutlery”, which provides useful information to estimate parameters that are essential to test cutting items in general and so even scissors. This Standard specifies the sharpness and edge retention of knives which are produced for professional and domestic use in the preparation of food of all kinds, specifically those knives intended for hand use. Two types of knife blade are suitable for the cutting test described by the ISO 8442: Type A edges where the cutting edges which can be re-sharpened and type B edges where cutting edges are not intended to be re-sharpened. It is important to underline that the ISO 8442 standard has been developed for knives, so the creation of a standard for scissors would be a natural consequence of the actual standard. The fundamental idea of the ISO 8442 is to reproduce the cutting action of a blade (which is composed of a forward and a backward movement on a block of synthetic material) and collect and analyze data derived from

the cutting operation. In the following the most important and useful points developed in the ISO 8442 [1] are briefly explained.

1.1.1 Useful definitions and performance indexes

To correctly evaluate the sharpness of a blade a specific test (that will be explained in detail later) is carried out, but before entering in the description of the test it is important to introduce some basic definitions that will be used from now on:

- "Cutlery" are all the utensils whose aim is the preparation and serving of foods having a blade with a cutting edge.

- The "centreline" is defined as the line which divides into two parts the section of the blade (Figure 1.1)

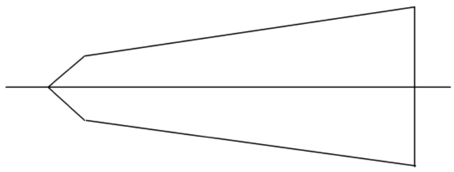


Figure 1.1 Blade section and centerline

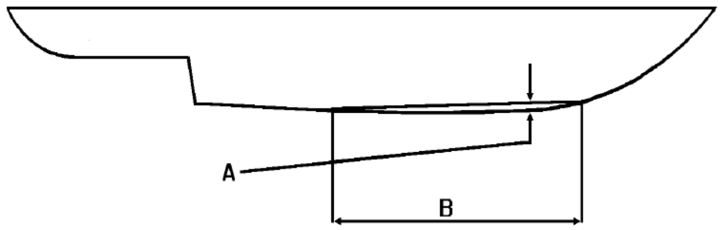
- The "initial cutting performance" (ICP) is defined as the expected cutting capacity of the blade which has just left the factory of production or the shop point. It is expressed in mm.

- The "cutting edge retention" (CER) is the capability of the blade to withstand wear during its lifetime. Even this parameter is expressed in mm.

- The "total card cut" (TCC) is the quantity of cut card during the whole duration of the test (expressed in mm).

- The "cutting cycle" is defined as one forward plus one backward movement of the blade on the target material.

It is obvious that the test must be performed with the cutting item exactly as it is provided by the manufacturer in order not to alter the sharpness of the blade. It is also required the cutting edge to be tested to be straight, but a deviation of 1 mm (in positive or negative direction but not both) is anyway admitted (Figure 1.2).



Key

A Max. deviation from straight (shown positive)

B Stroke length

Figure 1.2 Maximum allowable deflection from straight line

The test considers different modalities and parameters depending on the type (A or B) of the blade as it is clearly shown in Table 1.1.

Table 1.1 Cutting test parameters

Blade edge Type	Test load N	Stroke Length (mm)	Nominal cutting speed (mm/s)	Total no. Cutting cycles (F)
A	50	40	50	60
B	50	40	50	200

The performance indexes (ICP and CER) required are shown in Table 1.2

Table 1.2 Performance levels

Blade edge type	Minimum ICP mm	Minimum CER (TCC) mm
A	50	150
B	50	1 500

1.1.2 Test medium

The concept of the test is to cause wear on the cutting blade in the fastest way possible, so a special material must be used. A specially developed chemical pulp is produced in the form of sheets of card containing a fixed amount of abrasive materials i.e. quartz. This card shall be pure chemical soda pulp without no other chemical additive except for the addition of silica in the proportion of (5±0,5) % by weight. Properties of material and abrasives are expressed in Table 1.3 and Table 1.4.

Table 1.3 Composition of silica abrasives

Compound	Composition %
SiO_2	99
Fe	0,013
Al_2O_3	0,22
MgO	Nil
Alkalines	Nil

Table 1.4 Grain size distribution of silica

Grain size µm	Composition *(in weight)* %
> 50	0,2
> 30	4,7
> 20	15
> 16	2
> 12	11
> 10	10
> 8	7
> 6	9
> 4	12
> 2	29

The material is cut in strips of 10 mm width (with the fiber of the card grain flowing across the strip) and compiled into a pack maximum 50 mm deep when clamped under pressure (130±2,5) N in a holder.

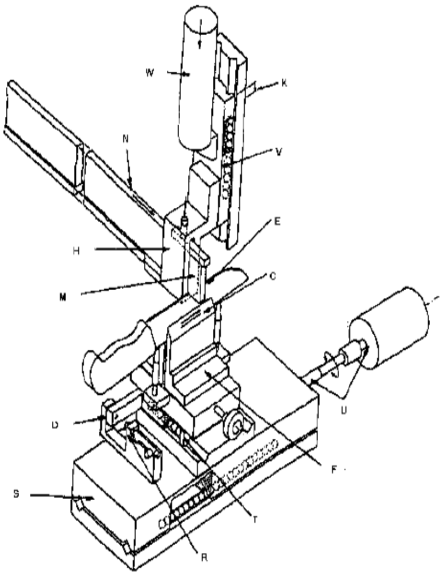
Table 1.5 Strips physical properties

Thickness mm	Weight g/m²	Strip (pack) width mm
0,31 ± 0,02	200 ± 10	10,0 ± 0,1

The material to be cut must be hold into controlled environment (55± 5 % of relative humidity and a temperature of 20 ± 2 °C) for 24 hours before starting the test, in addition the parts, once that they are cut, shall be allowed to fall away freely.

1.1.3 Test apparatus

In Figure 1.3 it is depicted a scheme of how a test apparatus should be designed. Only a basic idea of the apparatus is proposed, it is possible to refer to the ISO standard for a detailed description of the components.



Key

C	Cutting strokes	N	Medium feed forwards
D	1st cut datum	R	Retaining clamp
E	Test blade	S	Longitudinal slide
F	Component fixture	T	Transverse slide
H	Medium holder	U	Motor & ballscrew drive mechanism
K	Depth of cut measured by slide travel	V	Vertical slide
M	Medium	W	Additional test weight

Figure 1.3 Schematic test apparatus

1.1.4 Test procedure

In this paragraph, the steps necessary for a correct procedure of cutting in accordance with the standard are briefly explained:

- Select the part of the blade (remember that the portion of the blade must be straight in accordance with what explained before) which allows a total movement of 50 mm divided as 40 mm of net movement and additional 10 mm which consider the width of the test card.t
- Identify and sign the test interval on the blade.
- Mount the blade in the fixture with its blade pointing upward and set the length to be tested within 0,5 mm at either end.
- Load the test card into the apparatus and add weights to reach the 50 N necessary to perform the test. It is necessary for the card to be protruding of about 24 mm from the clamped end and the contact point of the blade must be 3 mm distant from the clamped end as illustrated in Figure 1.4.
- Move the blade in forward and backward direction using a cutting stroke of 40 mm. It is obvious that the test card must be in contact with the cutting edge for the whole duration of the cutting operation. When more card to be cut is required feed forwards the whole pack by approximately 3 mm.

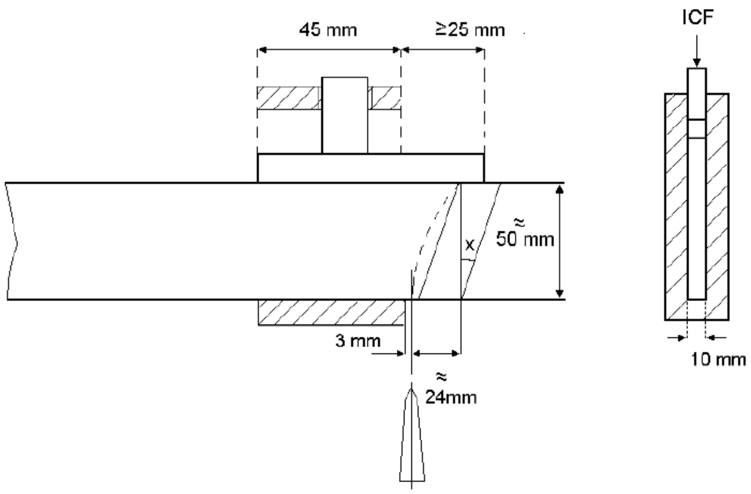


Figure 1.4 Arrangement of test medium clamp and blade presentation

All the results deriving from the cutting operation must be gathered in appropriate tables which provide for every row: number of the cycle (x), depth of cut of the cycle (y_x), cumulated depth of cut up to the actual cycle (z_x). In Table 1.6 is shown an example of how to collect data.

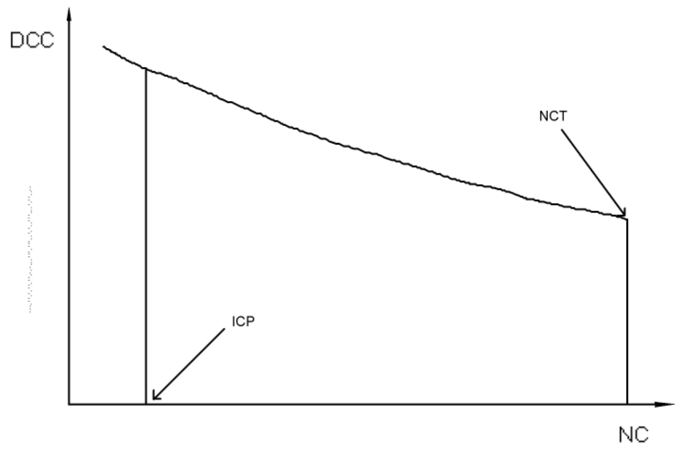
Table 1.6 Table for results recording

Cycle no. (x)	Depth of card cut (mm)	
	Per cycle $y_{(x)}$	Cumulative $z_{(x)}$
1	34,8	34,8
2	26,5	61,3
3	23,6	84,9
4	21,1	106,0
5	18,2	124,2
6	17,7	141,9
7	16,2	158,1
8	14,6	172,7
9	13,9	186,6
10	11,1	197,7
f	$y_{(f)}$	$z_{(f)}$

The characteristic parameters are calculated considering the following instructions:

- The “initial cutting performance” (ICP) is calculated summing the width of cut card (in mm) during the first 3 cycles ($ICP = z_3$).
- The “cutting edge retention” (CER) is determined by the total amount of cut card during the test ($CER = TCC = z_f$).

A graphical representation of the cycle is not mandatory but can help to clarify the results obtained as shown in Figure 1.5.



Key
DCC Depth of card cut per cycle (mm)
ICP Initial cutting performance – Cumulative depth of card cut after 3 cycles
NC Number of cycles
NCT Limiting number of cycles for test

Figure 1.5 Typical performance of a cut test

To ensure the apparatus performs with accuracy and consistency two forms of calibrations are required: at first, it is necessary to calibrate the parameters of force, distance and speed, once this has been completed the final adjustment of the machine is achieved by performing a cutting test with a standard blade. For further details on the modality of the various calibrations it is possible to make directly reference to the ISO 8442.

1.1.5 ISO 8442 applied to the case of scissors

The concept of "initial cutting performance" (ICP) cannot be transposed as it is on the case of cut with scissors, since depth of cut wouldn't be a useful parameter. A possible alternative, could be the integral of the force expressed on the length of cut and eventually normalized respect to the length of cut itself. In the same way, the "total card cut" is not a good indicator for the performances of the scissors. A useful parameter to express the quality of the scissors could be the number of cuts before tearing (CBT) which is going to substitute the CER parameter. It is obvious that in the case of scissors, a single cycle is defined as an opening plus a closing movement. Exactly as in the case of knives, the tested item is supposed to be new and the material to be cut be the same material described in the ISO 8442; it seems plausible to use the already mentioned material to test scissors with different purposes (office, cosmetic, fashion and design, household goods, etc.). It is reasonable to maintain unchanged all the constraints which were imposed on the ISO 8442 such as the length of material to be cut, the data report (paying specific attention to the different definition of the parameters of the cutting cycle), the setting and calibration of the machine.

1.2 State of the art

Even if norms and standards for testing scissors are not defined, some machines already exist, which are able to test scissors cutting capability; they range from very simple mechanisms to much more complex devices.

1.2.1 Newell and Scott machine

An example of simple cutting and testing mechanism is depicted in Figure 1.6 and it is identified as the Newell and Scott machine.

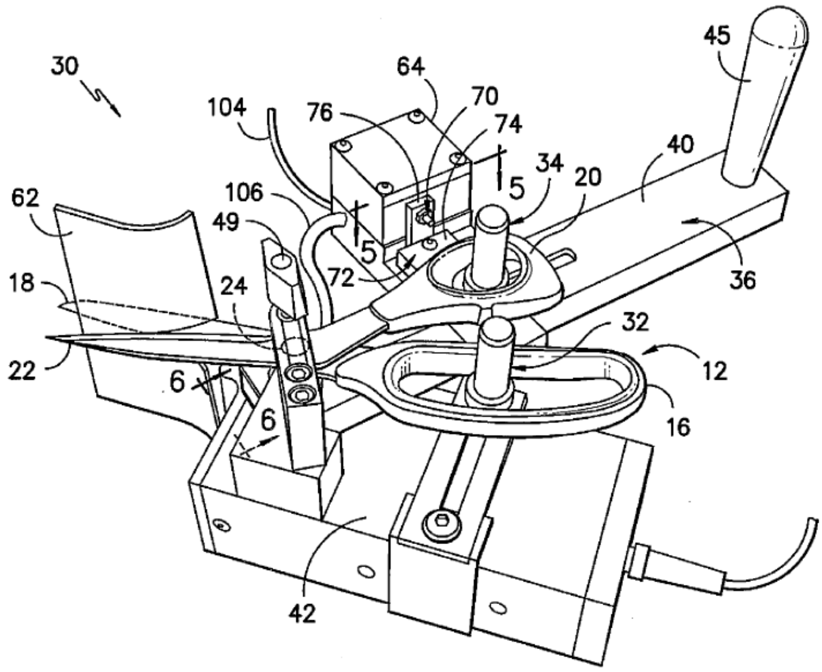


Figure 1.6 Newell and Scott testing machine

The machine was developed to measure the cutting capability of scissors and evaluate the decay of performances respect an optimal initial condition of the item. The cutting force is manually applied by the user through a handle (element 45). A potentiometer (element 42) measures the position of the blades, while the force is measured by a load cell linked to the mobile part and located inside the element 64. With the parameters above described is possible to make comparison and evaluate the wear of the scissors. The limit of such device is the manual actuation and the consequent lack of repeatability of the process (i.e. two operators could actuate the device at different speed and obtain different results). Other cons are given by the fixturing and regulation system, which is complicated and causes friction.

1.2.2 CATRA machine

The most complete and powerful machine available nowadays to test scissors is the "*Scissors cutting performance test machine for shears, wire cutters, scissors, secateurs, pruners and snip"* developed by CATRA (Cutlery & Allied Trades Research Association) and depicted in Figure 1.7.

Figure 1.7 CATRA testing machine

The objective of the machine is to study the development of the force required to cut a test material in standard conditions. The fixing system is composed of two adjustable pivots (one for each eyelet of the scissors) that must be calibrated (if the tested item is not a scissors a different fixing system must be employed). One of the two pivot is rigidly fixed to the structure, while the other one is connected to a motor through a piston rod mechanism. The fulcrum of the scissors must be aligned with the piston rod center of rotation. It is also present a pneumatic actuator on one side of the scissors to simulate the force generated by the human hand. A force sensor is located on the piston rod and it measures the load required (which is recorded on real time) to move the scissors along a pre-determined path. Different materials can be adopted to carry on the test, but the standard configuration implies the use of an abrasive paper such as the one described in ISO 8442. The material to be cut is carried by a system of rollers which is synchronized with the movement of the scissors. All the data are saved in a central memory and can be read in any moment. The operator of the machine has full control on all the parameters of the process thanks to a practical system of display and keyboard. The most important limits of the machine are about the fixing system and the cutting procedure. During the setting operation scissors must be mounted with their fulcrum aligned with the center of rotation of the piston rod; this kind of procedure is done using the slider number 1 in Figure 1.8.

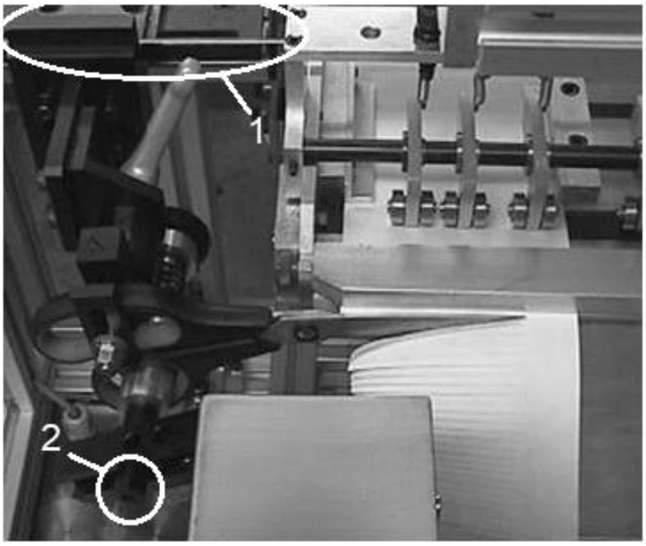


Figure 1.8 Fixing system for CATRA testing machine

The length of the piston rod is manually regulated to allow the pivot to enter inside the eyelet which is moved by the knob number 2 in Figure 1.8. When the test is started, the movement is transmitted to the scissors by mean of mechanical coupling: element 1 in Figure 1.9 provides friction between the eyelet and the plate which pushes the eyelet itself, the contact force is given by a spring system (element 2 in Figure 1.9) and finally the geometric contact is indicated as element 3 in Figure 1.9.

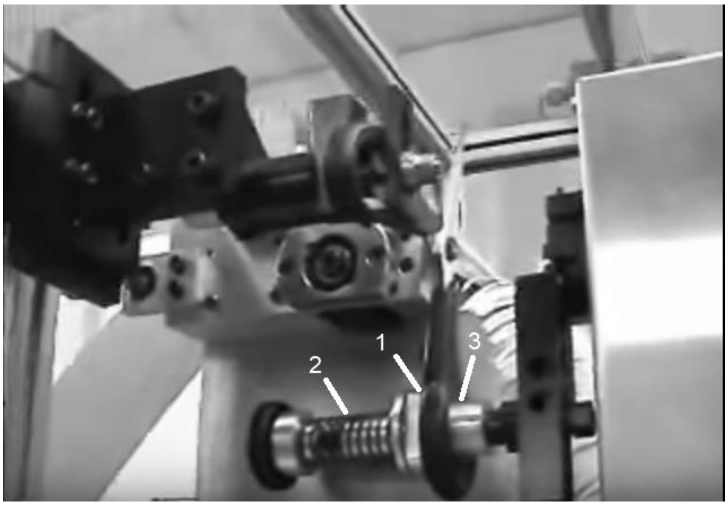


Figure 1.9 Transmission of the force

The disadvantages of the CATRA application are given by friction forces in the contact points, which generate an overestimation of the applied force. Even the mounting operation results to be critical, in fact a misalignment between the fulcrum of the scissors and the piston rod, or otherwise a not very well calibrated length of the piston rod, would cause an increase of the friction of the system leading to the effect above described.

1.2.3 PREMAX machine

The development of a new testing machine is based on the previous project developed by PREMAX and realized by “Officina meccanica e Automazione Giorgio Bevilacqua” depicted in Figure 1.10. The machine is constituted by electric and pneumatic actuators, controlled via PLC system. The scissors are opened and closed by a linear electric actuator and force and displacement of the blades are measured.

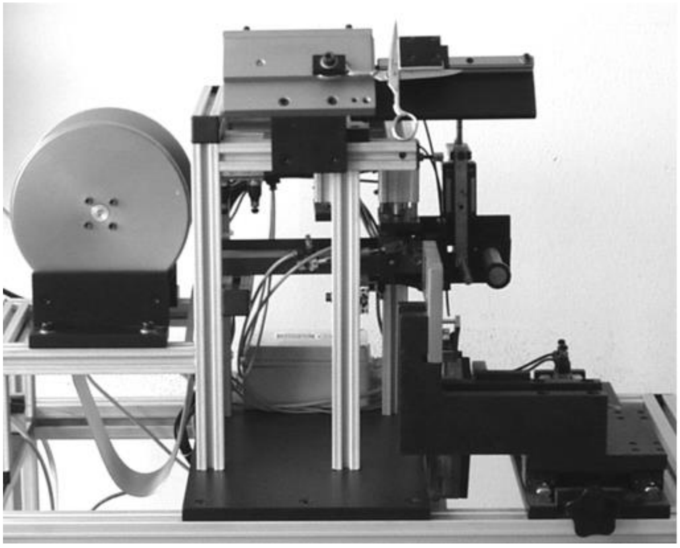


Figure 1.10 PREMAX testing machine

As it can be clearly seen in Figure 1.11, one of the eyelets of the scissors is connected to the actuator through a ball bearing, the other one is fixed to the frame of the machine.

Figure 1.11 Fixing system of scissors and actuator

The starting position of the scissors is identified using a mechanical jig (an element which has both the function of support and actuation) so that even scissors with different dimensions and geometries can be positioned in an analogous way (Figure 1.12).

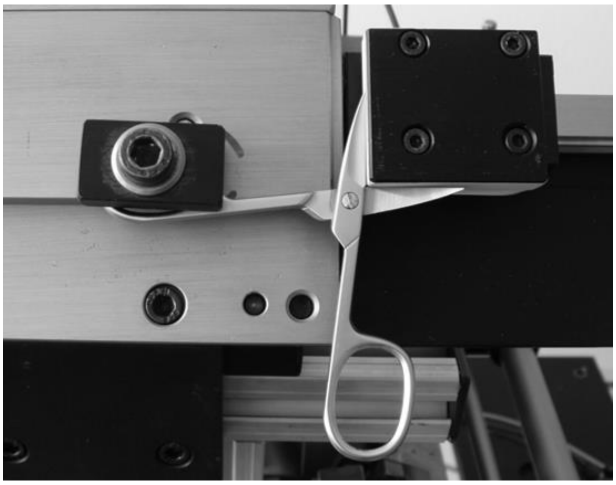


Figure 1.12 Mechanical jig for positioning

It is possible to remove the scissors from the cut material to verify the effectiveness of the cut itself, so it would be useful to measure forces and displacements also during this kind of operation.
The machine developed by PREMAX implements different operations:

- Slow closing: scissors are slowly closed by the linear actuator with constant speed (note that an initial acceleration is applied by the actuator then the speed is maintained constant until the blades are completely closed). This kind of movement is realized both in the presence of material to be cut or not. The force applied is measured in both cases.
- Fast closing: it is done when there is no material to be cut and it is used to evaluate wear and the loosing of the scissors bolt.
- Tear off: scissors are closed on the material which has already been cut and a tearing movement is performed with closed blades; this kind of the test is useful to evaluate if the cut has been regularly performed.

All these operations are useful to evaluate possible defects in the scissors; it is possible to divide them into three main categories

- Difficulty during the closure of the scissors: the bolt is tightened in an excessive way or we have severe interference among the blades of the scissors; this kind of problem generates an increase of the force necessary to close the scissors making them difficult to use.
- Soft closure of the scissors: is often symptom of a loose bolt. In this case quality of the cut drops down and only the portion of the scissors which is near the bolt can perform an effective cut.
- Blocked blades or irregular movement: irregularities or scratches on the surface of the blades generate sudden changes in the developed forces.

All these qualitative characteristics have a corresponding quantitative parameter, which can be measured and analyzed. It is important to notice that some limits on the actuation forces have been developed to avoid an excessive or a too weak cutting force. Moreover, a control on the first derivative of the force has been developed. All these parameters are evaluated a-posteriori using diagrams like the ones depicted in Figure 1.13.

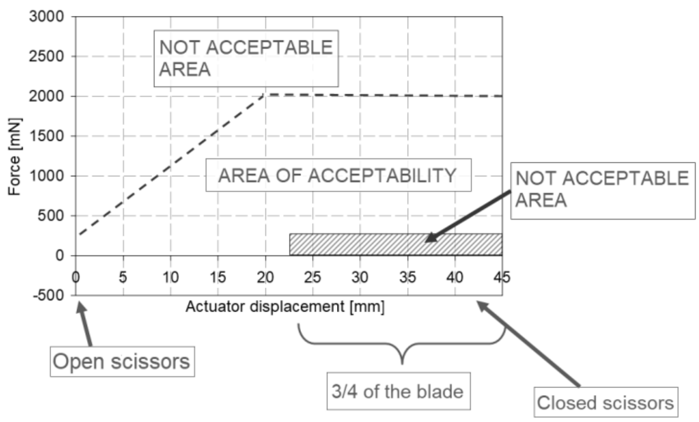


Figure 1.13 Limits of acceptability in the force-displacement diagram

The testing procedure can be described with the following steps

1. Switch off the motor and position the mechanical jig in the “positioning state” depending on the scissors to be tested. After this operation mark the position of the bolt so to notice eventual loosening of the bolt itself.
2. Place the scissors in the dedicated position and block one of the eyelet on the frame of the machine using a bolt. During positioning the fixed blade must be aligned with the jig without touching it (otherwise the edge of the blade could be damaged). Move the mechanical jig from the “positioning state” to the “test state”.
3. Set the actuator. Scissors are open, the rod must be aligned with the center of the two eyelets and in contact with the ball bearing in its center point. Note that the position of the actuator depends on the length of the blades to be tested.
4. Close manually the scissors and record the closing position.
5. The value found at the previous point needs to be inserted manually in the control program (in both the programs for fast and slow closure).
6. One opening movement is performed, then three movements of slow closure. The results of this kind of test are copied and manually stored. One cutting operation is performed to verify the efficiency of the scissors.
7. Automatic cycle for repetitive cut (the number of operations is varying depending on the type of scissors). Note that the frequency of the process should be equal o lower than 1 Hz to avoid an overheating of the bolt.
8. Cycle of three slow closures saving manually the results.
9. Control (by eyes or by lens) the possible rotation of the bolt.

Other tests have been configured which consider a higher number of cycles or the use of abrasive paper (P600 type) instead of the standard material.
In the following figures it is possible to observe the results of some test which were performed using some manicure scissors. Figure 1.14 and Figure 1.15 represent the case in which the scissors failed the test: for scissors of type A there are problems of difficult and hard closure and blocking, on the other hand scissors of type B showed a problem of soft closure.

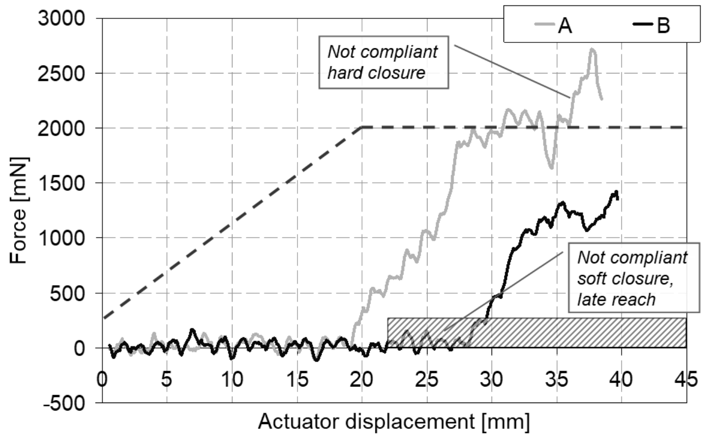


Figure 1.14 Example of results of a failed test: force

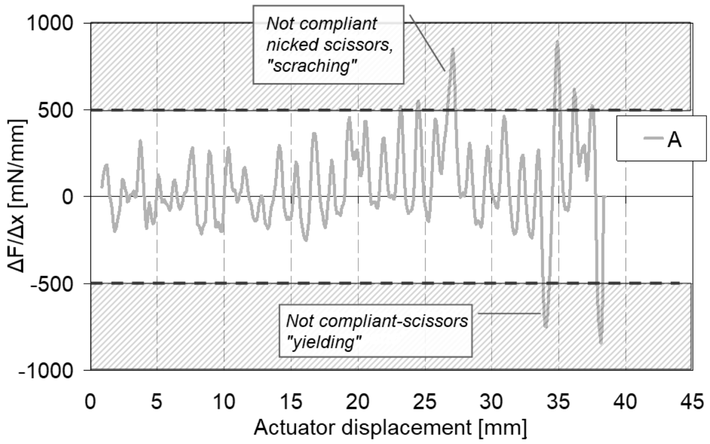


Figure 1.15 Example of results of a failed test: Δf/ Δx

In Figure 1.16 and Figure 1.17 is possible to observe the results for scissors that passed the test.

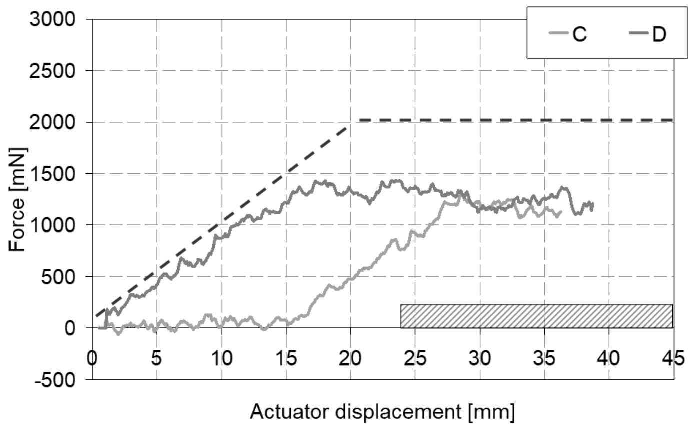


Figure 1.16 Example of results of a passed test: force

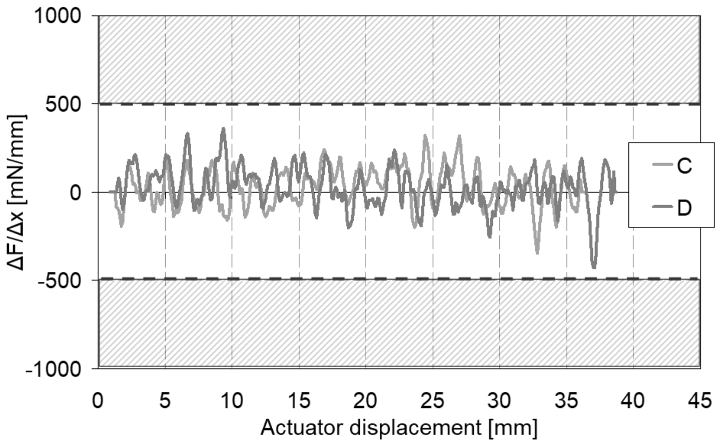


Figure 1.17 Example of results of a passed test: Δf/ Δx

1.2.4 Other machines

Is possible to find in literature many more machines developed to evaluate the sharpness of knives more than scissors. Even in the case of knives, machines exist ranging from very simple solutions to more complex ones; many have been developed based on the standard ISO 8442-5. In Figure 1.18 it is possible to see a machine able to quantifiy the load necessary to realize a cut. Carrying out the test at different speed it is possible to analyze the wear of the blade and so to realize the predictive re-sharpening of the blade.

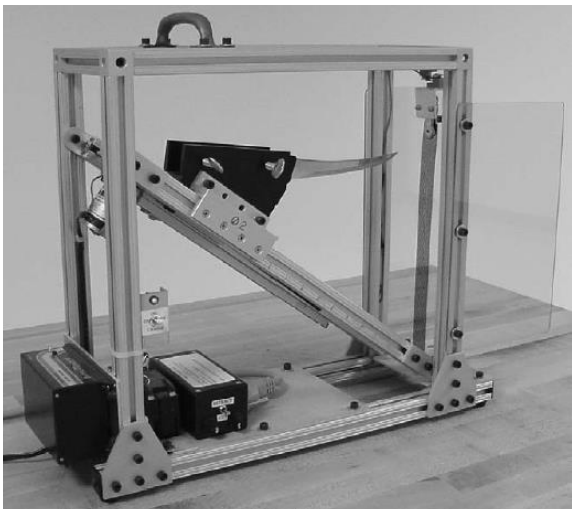


Figure 1.18 Machine for measuring the sharpness of knives

Other machines are available on the market that realize the test in accordance with the ISO 8442-5. CATRA developed a machine which respects the requisites of the ISO standard, but can also be modified to answer needs of research: the machine, in facts, allows the user to measure the applied load during the cutting operation along three directions.
Another machine exist which satisfies ISO 8442-5 and was developed by Haida international equipment CO., LTD.

1.3 Scheme of the thesis

The thesis is structured as follows: in the introductory chapter 1 have been described the reference ISO standard and the state of the art for the application under analysis.
In chapter 2 is fully described the design part of the thesis. In section 2.1 is briefly explained the theory of requirements analysis and it is applied to the case of the testing machine for scissors. In section 2.2 is presented the functional analysis of the machine; many solutions have been developed to better accomplish the desires and expectations of the customer (PREMAX) all of them will be presented, giving reasons to accept or discard what proposed. A solution will be selected as the best one, and all its components will be analyzed in terms of functionality and costs. In section 2.3 is briefly explained the problem of "tension control" (typical of all the winding-unwinding machinaries) since it must be considered in the design of the final version of the testing machine for scissors. In section 2.4 is carried out a preliminary cost analysis of all the devices that will be involved in the final version of the machine. In section 2.5 is presented the project of a prototype test bench that can be considered as the first step toward the final realization of the machine.
In chapter 3 is decribed the experimental campaign which has the target of inspecting the beaviour of the cutting torque as function of different working parameters. In section 3.1 is presented the instrumentation and the set-up for the experimental tests. In section 3.2 is provided an accurate description of the tests and their parameters. The results of the tests are presented in section 3.3.
In chapter 4 are drawn the conclusions of the thesis and are made suggestions for future developments of the machine for scissors testing.

2 Requirements and functional analysis

In this section the theory of requirements and functional analysis will be briefly explained making reference to [2] and [3] to provide basic knowledge of these two approaches and their related development tools.
The idea is to use the previously mentioned tool to develop a functional and requirement analysis for the scissors testing machine. Many functional solutions of the machine will be presented, but only one will be selected as the best one to accomplish all the features required by the customer PREMAX.

2.1 Requirements analysis

Requirements can be considered as the needs and objectives for a given system, they relate to how well a system will work in its future environment when fixed constraints are assigned. Constraints are conditions that exist because of the limitations imposed on the system by external interfaces, project support and technologies. Requirements are of primary importance since they will be transformed into specific guidelines for the successive phase of design of the system. Requirements are categorized in several ways, in the following a common categorization of requirements

- Customer Requirements: statements that define the expectations of the system in terms of mission objectives, environment, constraints, and measures of effectiveness and suitability.
- Functional Requirements: the necessary actions or tasks that must be accomplished by the system (what must be done).
- Performance Requirements: how the necessary actions or tasks need to be fulfilled (how well it must be done).
- Design Requirements: the “build to,” “code to,” and “buy to” requirements for products.
- Derived Requirements: requirements that are implied or transformed from higher-level requirement.
- Allocated Requirements: division of a high-level requirement into multiple lower-level requirements.

In conclusion, a good requirement must be expressed in terms of need, not solution; that is, it should address the “why” and “what” of the need, not how to do it.

2.1.1 Requirement analysis tasks and outputs

In general, Requirements Analysis should result in a clear understanding of:

- Functions: what the system has to do;
- Performance: how well the functions have to be performed;
- Interfaces: environment in which the system will perform.

The understandings that come from requirements analysis establish the basis for the following phases of functional and physical designs. Good requirements analysis is fundamental for a successful design. The requirements that result from requirements analysis are typically expressed from one of three perspectives (or views) listed below.

- Operational View: it addresses how the system will serve its users.
- Functional View: it focuses on what the system must do to produce the required operational behavior.
- Physical View: it focuses on how the system is constructed, but it's not the final design of the system.

2.1.2 Tools of requirements analysis: IEPP1220 standard

The following section provides a list of tasks that represents a plan to analyze requirements. Part of this notional process is based on the 15 requirements analysis tasks listed in the industrial standard IEEE P1220. The IEEE Systems Engineering Standard offers a process for performing Requirements Analysis that comprehensively identifies the important tasks that must be performed. These 15 task areas to be analyzed follow and are shown in Figure 2.2.

1. **Customer expectations**
2. **Project and enterprise constraints**
3. **External constraints**
4. **Operational scenarios**
5. **Measure of effectiveness (MOEs)**
6. **System boundaries**
7. **Interfaces**
8. **Utilization environments**
9. **LIfe cycle**
10. **Functional requirements**
11. **Performance requirements**
12. **Modes of operation**
13. **Technical performance measures**
14. **Physical characteristics**
15. **Human systems integration**

Figure 2.1 Tasks of requirement analysis

Task 1
The purpose of this task is to determine what the customer wants the system to do, and how well each function must be accomplished. This should include natural and induced environments in which the product(s) of the system must operate or be used, and constraints.
Task 2
Project and Enterprise Constraints identify and define constraints impacting the design solutions. Project specific constraints can include: approved specifications and baselines developed from prior applications of the Systems Engineering Process, costs, updated technical and project plans, team assignments and structure, control mechanisms, and required metrics for measuring progress.
Task 3
External constraints can include: public and international laws and regulations, technology base, compliance requirements (industry, international, and other general specifications, standards, and guidelines which require compliance for legal, interoperability, or other reasons), threat system capabilities, and capabilities of interfacing systems.
Task 4
For each operational scenario are described: interactions with the environment and other systems.

Task 5
Measures of Effectiveness and Suitability (MOE/MOS) identify and define systems effectiveness measures that reflect overall customer expectations and satisfaction.
Task 6
System Boundaries include: which system elements are under design control of the performing activity and which fall outside of their control, and the expected interactions among system elements.
Task 7
Interfaces define the functional and physical interfaces to external or higher-level and interacting systems, platforms, and/or products in quantitative terms. Functional and physical interfaces would include mechanical, electrical, thermal, data, control, procedural, and other interactions.
Task 8
Utilization Environments define the environments for each operational scenario. All environmental factors (vibration, electromagnetic problems, etc.) which may impact system performance must be identified and defined.
Task 9
Life Cycle Process Concepts analyze the outputs of tasks 1-8 to define key life cycle process requirements necessary to develop, produce, test, distribute, operate, support, train, and dispose of system products under development.
Task 10
Functional Requirements define what the system must accomplish or must be able to do.
Task 11
Performance Requirements define the performance requirements for each higher-level function performed by the system.
Task 12
Modes of Operation define the various modes of operation for the system products under development. Conditions (e.g., environmental, configuration, operational, etc.) that determine the modes of operation should be included in this definition.
Task 13
Technical Performance Measures (TPMs) identify the key indicators of system performance that will be tracked during the design process.
Task 14
Physical Characteristics identify and define required physical characteristics (e.g., color, texture, size, weight, buoyancy) for the system products under development.
Task 15
Human Factors identify and define human factor considerations (e.g., physical space limits, climatic limits, eye movement, reach, ergonomics) which will affect operation of the system products under development.

2.1.3 Requirements analysis for the cutting machine

In the following Table 2.1 the previously presented tasks are analyzed for the case of the cutting machine (tasks which are considered not relevant for the machine will not be mentioned).

Table 2.1 Requirement analysis for the cutting machine

TASK #	TASK NAME	DESCRIPTION
1	**Customer expectations**	Realize an automated cutting machine which is able of testing different types of scissors
3	**External constraints**	ISO 8442
4	**Operational scenarios**	Automated system (operator necessary only for start-up procedure)
7	**Interfaces**	Machine-operator interface via pc or display
8	**Utilization environments**	Laboratory environmental conditions. Temperature ranges are specified in ISO 8442
9	**Life cycle process concept**	Mechanisms and sensors are crucial for the lifecycle and performance of the machine
10	**Functional requirements**	Test scissors through cutting operations
12	**Modes of operation**	Two possible configurations: cut of cloth and cut of sheets
13	**Technical performance measures**	Depend on the design choice, control via software
14	**Physical characteristics**	No limitations on size and weight.
15	**Human factor**	Machined controlled via software and display. Minimum interaction machine-operator

2.2 Functional analysis

2.2.1 Functional analysis tasks

The process of functional analysis is a top-down process whose goals can be summarized as in the following:

- Define the system in functional terms and identify what actions the system must do at successively lower levels.
- Identify how well the functions must be performed.
- Group functions that logically fit with the components likely to be used and minimize functional interfaces.
- Determine the functional characteristics of existing or directed components in the system and incorporate them in the analysis and allocation.
- Performing trade studies to determine alternative functional approaches to meet requirements.
- Revisit the requirements analysis step as necessary to resolve functional troubles.

During the performance of the Functional Analysis and Allocation process, it is expected that a revision of the requirements analysis process will be necessary. It is important to remember that the final objective of functional analysis and allocation is not yet the design final solution. The output of the functional analysis and allocation is the functional architecture which can be described as a simple hierarchical decomposition of the functions with associated performance requirements. As the architecture definition is refined and made more specific the functional architecture becomes more detailed. There are many tools available to support the development of a Functional Architecture, such as: functional-flow block diagrams (FFBD), timeline analysis sheet (TLS), process and data flows (IDEF0 diagrams) requirements allocation sheet (RAS), Integrated Definition, and others.

2.2.2 Tools of functional analysis: functional flow block diagram (FFBD)

The purpose of the functional flow block diagram (FFBD) is to describe system requirements in functional terms. The FFBD is functionally oriented and not solution oriented. FFBD allows to the trace vertically functions and sub-functions composing the system (Figure 2.4).

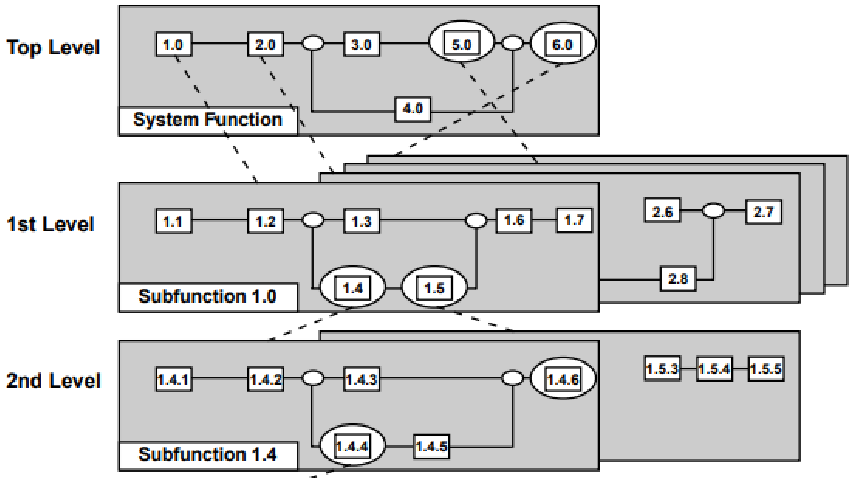


Figure 2.2 Structure of a FFBD

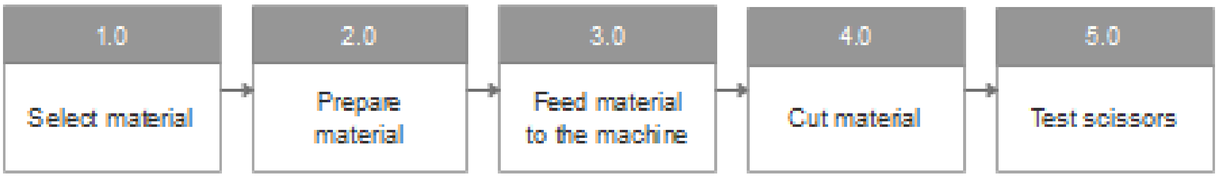
2.2.3 Tools of functional analysis: integration definition for function modelling (IDEF0)

IDEF0 stands for Integration Definition for Function Modeling (IDEF0). Where the FFBD is used to show the functional flow of a product, IDEF0 is used to show data flow, system control, and the functional flow of life cycle processes. The IDEF0 process starts with the identification of the prime function to be decomposed; this function is identified on a "Top Level Context Diagram," that defines the scope of the IDEF0 analysis; from this diagram lower-level diagrams are generated.

2.2.4 Functional analysis for the cutting machine: proposal 1

In the following the above discussed methods of the Functional Analysis for the case of the cutting (and testing) machine that must be designed and developed are graphically presented. In Figure 2.3 is depicted the FFBD while in Figure 2.4 the IDEF0.

FUNCTIONAL FLOW: TOP-LEVEL



FUNCTIONAL FLOW: SECOND-LEVEL

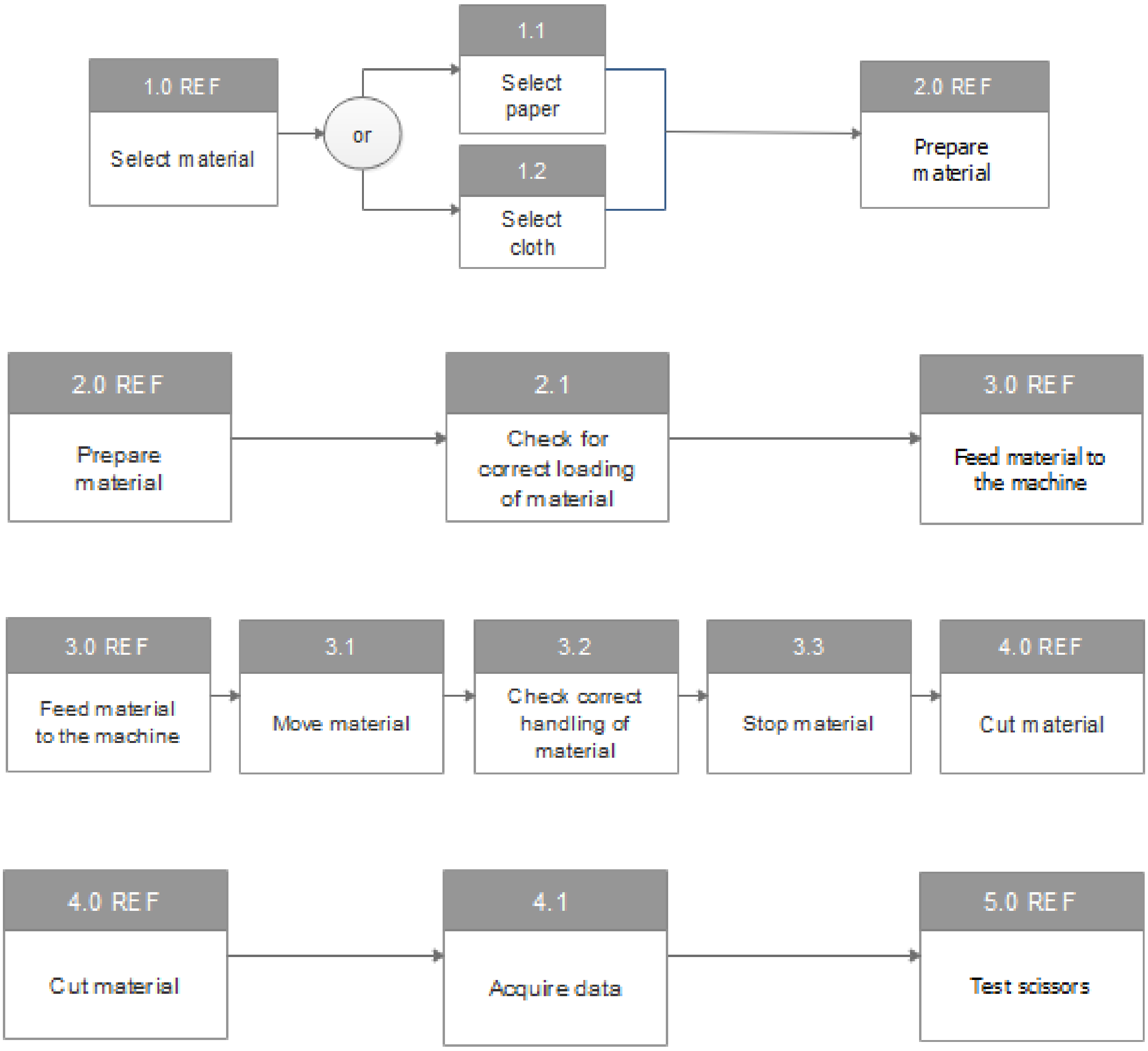


Figure 2.3 FFBD for the cutting machine

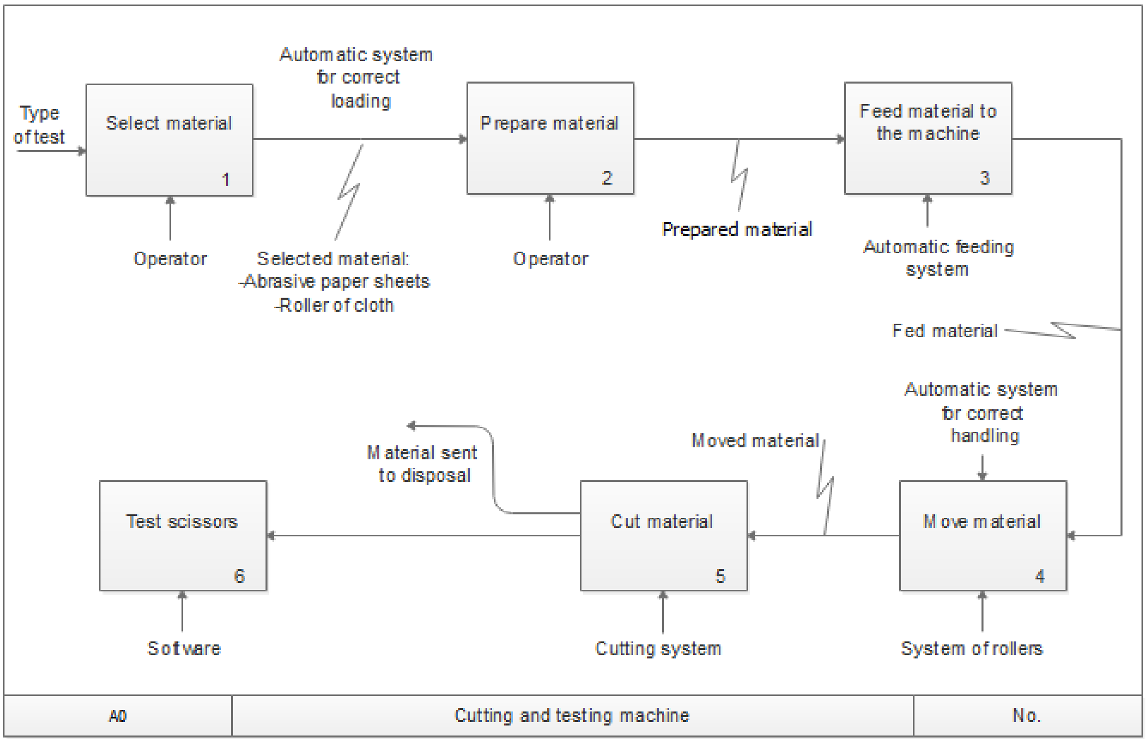


Figure 2.4 IDEF_0 for the cutting machine

In Figure 2.5 and Figure 2.6 two possible assembly of the functional groups of the machine, based on what obtained by means of the previous FFBD and IDEF0, are shown. It is important to notice that two different configurations are proposed depending on the target material to be cut: abrasive paper sheets or roller of material.

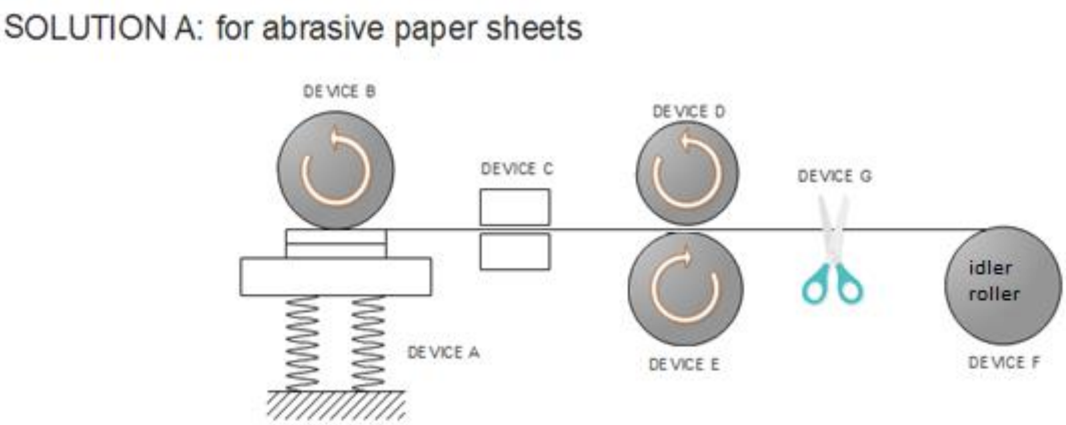


Figure 2.5 Functional groups: Solution A

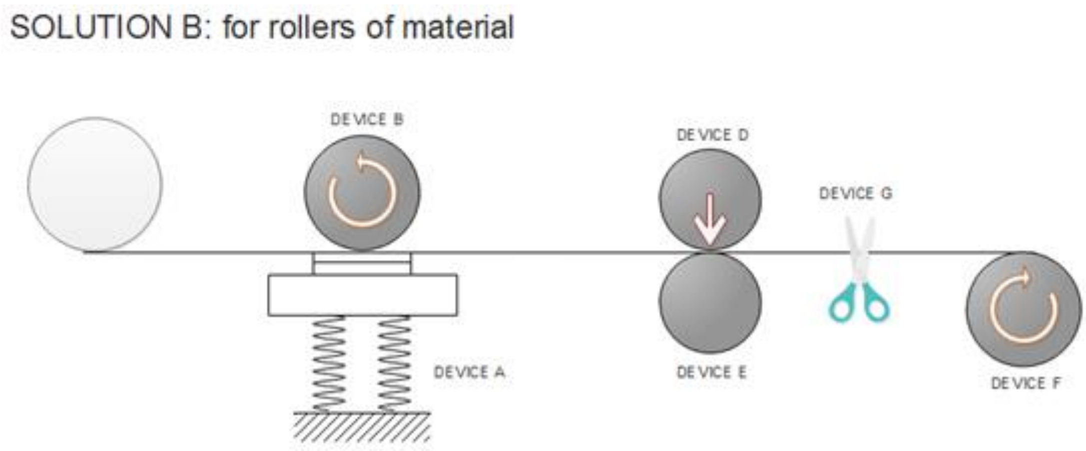


Figure 2.6 Functional groups: Solution B

SOLUTION A: for abrasive paper sheets:

- DEVICE A is a mechanism to pile up the abrasive paper sheets and to keep them in contact with the DEVICE B.
- DEVICE B: is a roller, with its rotations makes the abrasive sheet of paper moving rightward.
- DEVICE C: is a sensor to detect the possible passage of multiple sheets.
- DEVICE D: is a roller that makes the abrasive paper sheets continue their rightward movement.
- DEVICE E: is a roller activated only in case of passage of multiple packed sheets. It sends leftward the sheets that is in the bottom of the packed sheets.
- DEVICE F: a roller to keep the material in tension. In this configuration is an idler roller.
- DEVICE G: is the cutting mechanism.

SOLUTION B: for roller of material:

- DEVICE A is a mechanism to pile up the abrasive paper sheets and to keep them in contact with the DEVICE B. In this configuration it is fully extended and works only as a guide.
- DEVICE B: is a roller, with its rotations makes the material moving rightward.
- DEVICE C: In this configuration is switched off.
- DEVICE D: is a not rotating roller, its role is to apply only and exclusively a pressure to the material.
- DEVICE E: is a roller. It stands still in this configuration.
- DEVICE F: a roller to keep the material in tension. In this configuration is necessary and is rotating in the opposite direction of DEVICE B.
- DEVICE G: is the cutting mechanism.

As already explained in previous sections, during this phase of the project the final objective is not yet the solution of the problem, meaning that is not important to obtain the final design of the cutting and testing system. What is needed to know are the functional groups of the machine, that only in the next phases will be effectively developed. To clearly understand the meaning of what expressed above let’s consider the example of Figure 2.11 and Figure 2.12. Note that none of the devices has been properly described, in fact for the DEVICE A is said it is only a mechanism to pile up the abrasive paper sheets, nothing is said about the way of piling, the working mechanism, the actuation system, etc. In Figure 2.7 and 2.8 are depicted two plausible macro alternatives for the mechanism which strongly differs one form the other from the point of view of the actuation.

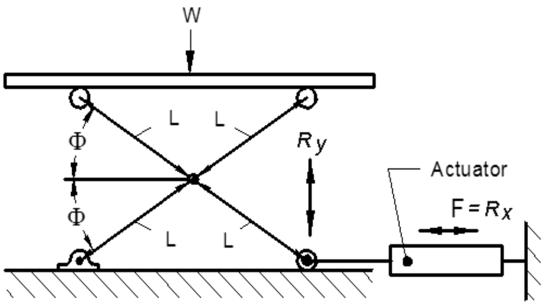


Figure 2.7 DEVICE A: actuated system

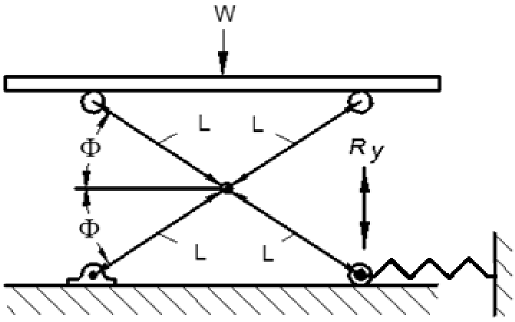


Figure 2.8 DEVICE A: mechanical system

For DEVICE B, DEVICE D, DEVICE E and DEVICE F is said they are simply rollers, of course they will be electrically actuated, but it is not expressed by mean of what, size and dimensions are not specified. For DEVICE C is said to be a sensing system, but of course a big variety of sensors should fulfill (ultrasonic, photoelectric, laser) the requirement; at this stage the type of sensors is not yet defined.

2.2.5 Functional analysis for the cutting machine: proposal 2

Proceeding in the development and revisiting of the functional groups of the cutting and testing machine, it was observed that most of the effort, from the design point of view, would have been made for developing a system which is able to feed paper sheets to the machine (device previously depicted in Figure 2.5 and 2.6). The design of a mechanism (from mechanical and electronic point of view) which can easily switch from solution A to solution B, could be so complicated to discredit the pros that the mechanism itself effectively would offer. With the configurations proposed in Figure 2.5 and Figure 2.6 the design of the machine would tend to the design of a classical ink or laser printer and its design will be inevitably complicated. The idea is to create a unique solution for the preparation of the material whether in form of sheets or rollers so to simplify the project; if FFBD (Figure 2.3) is taken into consideration, the idea is to act in the block 3.0 “Feed material to the machine” (Figure 2.9) and try to simplify this operation.

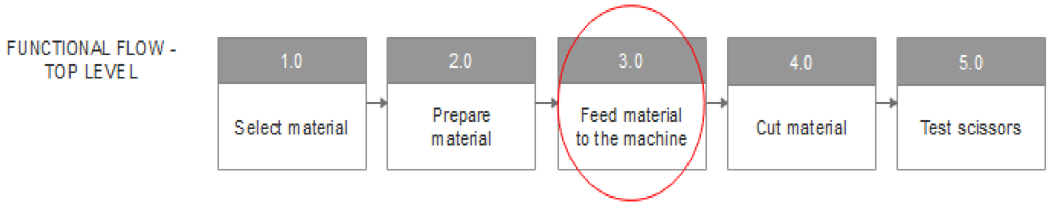


Figure 2.9 Simplify block 3.0 "Feed material to the machine"

The easiest way to make the machine able to act both on sheets of paper or roller of material in a unique solution, is not finding an alternative design for the machine, but acting directly on the material. Since is supposed that sheets of paper will not have such a high stiffness, it would be quite simple to fix multiple sheets and from them create rollers of abrasive paper. In such way the machine will be designed to act exclusively on rollers of material, whether of cloth, paper or other kind of material. If such "transformation" is made the configuration of Figure 2.5 and Figure 2.6 can be easily changed and most of the future mechanical design simplified.
Another simplification that can be made to make the whole system less cumbersome and that can greatly simplify the future mechanical design of the machine, refers to how to keep in tension the material before the cutting operation and so the related device which is dedicated to such operation (DEVICE C in Figure 2.5). Thanks to experimental tests performed on a roller of cloth, it was highlighted that applying the right amount of tension to the material which is undergoing the cutting operation is of fundamental importance. In fact, in general, cutting a material which is kept straight is easier than cutting the same material which is left limp and free to bend; the more the material is kept in traction, the more is easy for the cutting item (scissors in this case) to perform the cutting operation. For this reason, the operation of stretching the material is crucial and it can't be underestimated.
In the following, two possible solutions are presented whose aim is to solve and simplify the two problems previously exposed:

- SOLUTION C

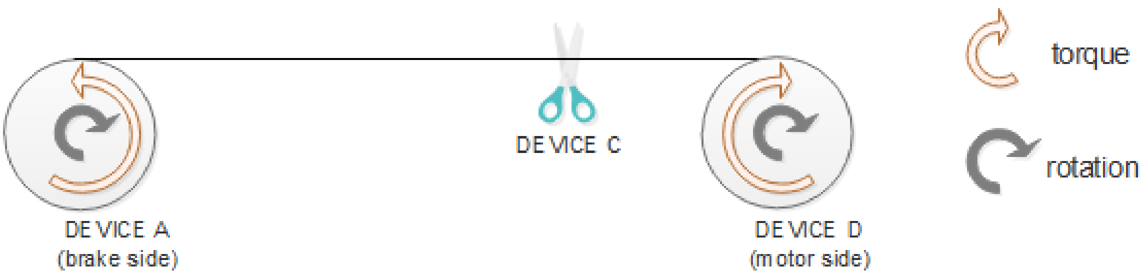


Figure 2.10 Functional groups: Solution C

DEVICE A: is the roller of material (which needs to be unrolled) with its respective motor group. A torque control is performed on the motor which act as a brake and allows the material to be kept straight. In this way a reasonable tension is applied to the material before the cutting operation.
DEVICE C: is the device that effectively performs the cut with its related actuation system.
DEVICE D: is the motor which effectively unrolls the material. Thanks to a position control implemented on the motor itself, the unrolling operation is performed with a given and controlled pace.

- SOLUTION D

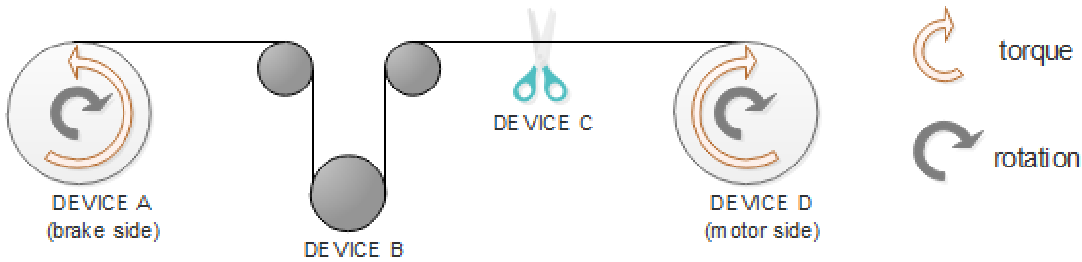


Figure 2.11 Functional groups: Solution D

DEVICE A: is the roller of material (which needs to be unrolled) with its respective motor group. In this case the motor is not torque-controlled, but a mechanical brake is applied to oppose the motor torque provided by DEVICE D.
DEVICE B: is a system of pulleys necessary to guarantee the correct tension to the material (usually is given the name of dancer to this device).
DEVICE C: is the device that effectively performs the cut with its related actuation system.
DEVICE D: is the motor which effectively unrolls the material. Thanks to a position control implemented on the motor itself, the unrolling operation is performed with a given and controlled pace.

As already mentioned, Solution C specifically needs: a torque control on the DEVICE A and a position control on DEVICE D to unroll the material at given pace, moreover the motor and the brake torque need to be synchronized. Solution D, on the other hand, do not requires a relevant effort on the development of a control system, since only the position control on DEVICE D is necessary; DEVICE A is simply controlled by mean of a mechanical brake. Even if Solution D is expected to be quite simple from the point of view of controlling the motor and the braking torque, a complicated design from a mechanical point of view is expected, in fact is mandatory the use of DEVICE B (with its respective control). The presence of DEVICE B, moreover, implies a bigger size of the whole group, making the machine losing in compactness and creating possible problems of space and dimensions for future applications. For this reasons Solution C is identified as the best alternative among all the possible solutions presented above (Figure 2.12).

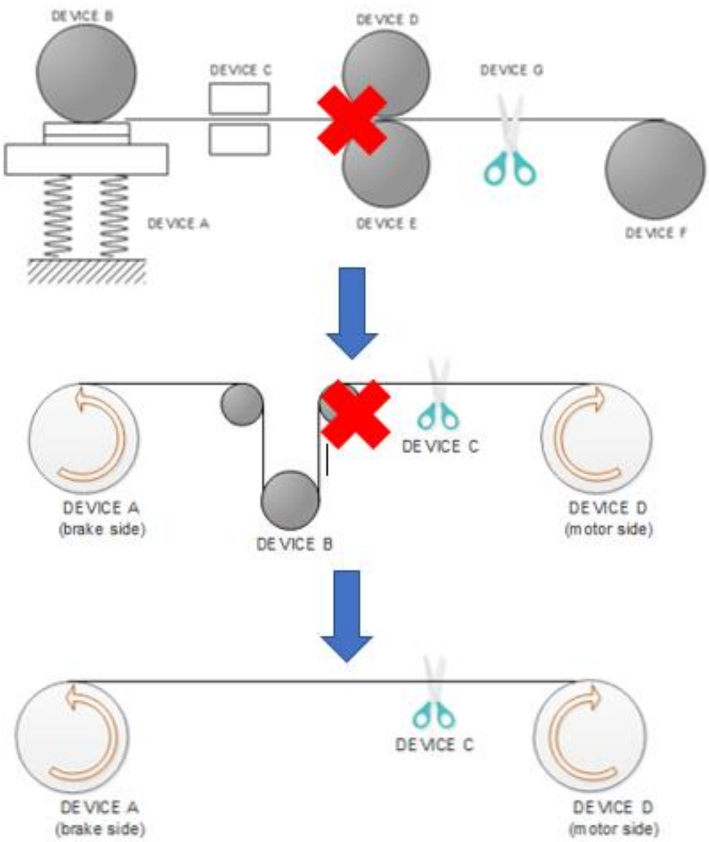


Figure 2.12 Choice of the best solution

2.2.6 Functional analysis for the cutting machine: definitive solution

In the previous section it was selected SOLUTION C as the best alternative among the possible solutions. In the next section are described 3 possible realizations (passing from a simple one to more sophisticated ones) of the logic used in SOLUTION C, that will be evaluated to define the definitive configuration of the machine.

To end up with the realization of the chosen and definitive configuration (Figure 2.12) is necessary to pass through the less complex solutions which can be implemented at low cost and that are not expensive in terms of time, design and assembly. A first approximation of SOLUTION C can be easily implemented and represented with the mechanical scheme depicted in Figure 2.13. The idea of this first approximation is to maintain the motor group (controlled in position) to unroll the material, while replacing the motor controlled in torque with an elementary system of free-falling masses. The traction of the material in this case is not given by a braking mechanical torque, but simply by gravity.

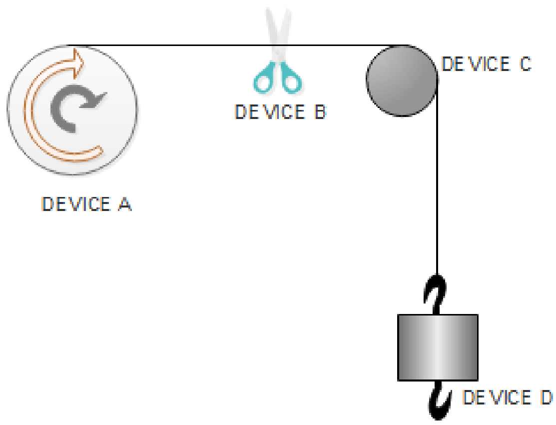


Figure 2.13 Realization 1 of the definitive SOLUTION C

The system is composed of:
DEVICE A: is the roller of material (cloth or abrasive paper indistinctly) which needs be unrolled and the respective motor group. In this case the motor is controlled in position. The control establishes the pace at which the material advances.
DEVICE B: is the device that effectively performs the cut with its related actuation system.
DEVICE C: is a fixed pulley whose role is to transmit and change the direction of the tension generated by the weight of the DEVICE D.
DEVICE D: is a mass which generates the necessary tension to keep the material straight.
The free body-diagram of the system is elementary and depicted in Figure 2.14.

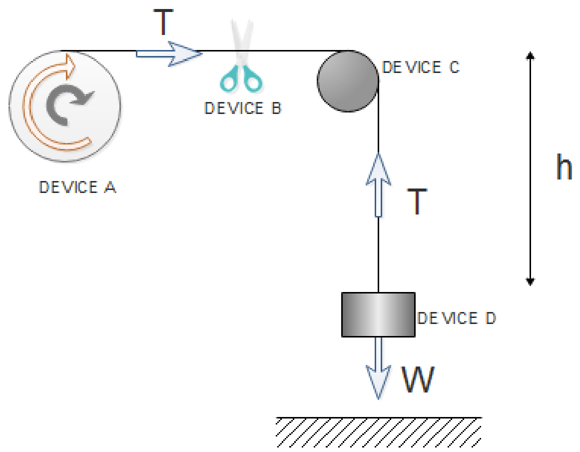


Figure 2.14 Free body diagram

It is important to take into consideration the distance "h" depicted in Figure 2.14, because since the motor continues in its procedure of unrolling the material, sooner or later, the mass will be in contact with the floor and the tension applied to the material will be lost. If we perform all the cuts one close to the other, the available height (h) can be fully exploited and more cuts can take place during the test (reliable tests need several cuts to be performed on the material). On the other hand, it is important to

remember that it is not convenient to perform cuts that are too much close one to the other, because the material on the neighborhood of the cut zone tends to bend and limp making the subsequent cut more difficult to be performed. A good trade-off between the different necessities could be of leaving about 2 cm between one cut and the next one; in this way a height (h) of 1 m, provides the amount of space necessary for about 50 cutting operations. In the case is needed to perform a huge amount of cutting operations is necessary to increase the distance h by moving the DEVICE A, DEVICE B, and DEVICE C, anyway this solution is rarely feasible, since the three groups are fixed to ground or other supports.
The solution presented in this section could be useful for making short tests and quick evaluations, but its use in the final configuration of the machine is not suggested, since the limit generated by the height of the free-falling masses could be of relevant interest, moreover much better results can be achieved with the configurations proposed in the following section.

Because of the problems presented in the previous section, the approximation of the definitive solution needs to be re-shaped so to create an alternative way to generate the correct tension on the material (without using free-falling masses) and making the solution more like to what proposed with SOLUTION C. In the following are represented two possible realizations which follow the logic of SOLUTION C in Figure 2.10 (use of a motor and a braking torque) and overcome the limits given by the realization previously described.
One possible realization is depicted in Figure 2.15 and described.

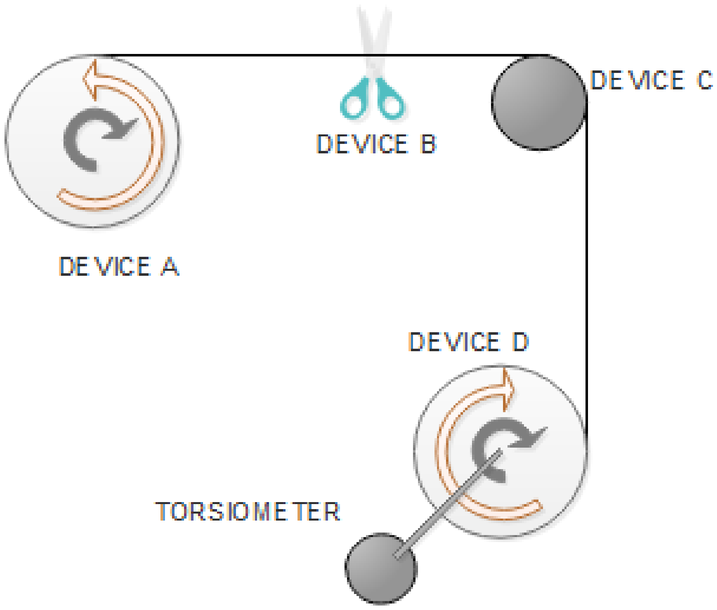


Figure 2.15 Realization 2 of the definitive SOLUTION C

DEVICE A: is the roller of material (cloth or abrasive paper indistinctly) which needs be unrolled and the respective motor group. In this case the motor is torque-controlled. The control provides the necessary braking torque which opposes the motor torque given by DEVICE D.
DEVICE B: is the device that effectively performs the cut with its related actuation system.

DEVICE C: is a fixed pulley whose role is to transmit and change the direction of the tension generated by the DEVICE D.
DEVICE D: is a second roller with its respective motor group. In this case the motor is position-controlled. The control establishes the pace at which the material is unrolled.
TORSIOMETER: is a torsiometer which is coupled with the shaft of the DEVICE D.

When rotating, DEVICE D makes new material advance toward the cutting position (DEVICE B). During this movement the strip of material tends to bend if no resisting torque is applied by DEVICE A and this could alter the effectiveness of the cutting operation. When the torsiometer, which is coupled with the shaft of the DEVICE D, detects that the torque applied on the shaft drops down below a threshold level, a feedback control is activated on DEVICE A: the motor (DEVICE A) generates a braking torque, which stretch the material and keeps it straight; at this point the cutting operation can be correctly performed.

Another possible realization of the definitive solution is represented in Figure 2.16.

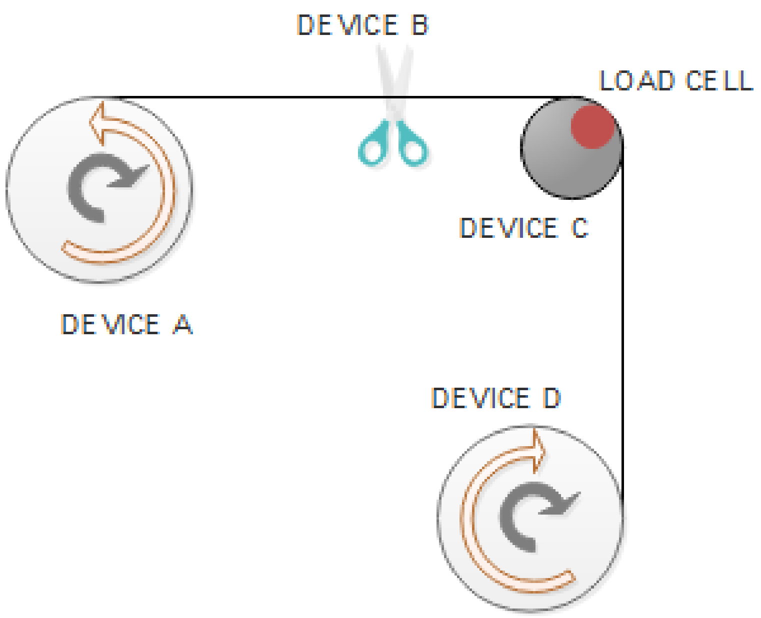


Figure 2.16 Realization 3 of the definitive SOLUTION C

DEVICE A: is the roller of material (cloth or abrasive paper indistinctly) which needs be unrolled and the respective motor group. In this case the motor is torque-controlled. The control provides the necessary braking torque which opposes the motor torque given by DEVICE D.
DEVICE B: is the device that effectively performs the cut with its related actuation system.
DEVICE C: is a fixed pulley whose role is to transmit and change the direction of the tension generated by the DEVICE D.
DEVICE D: is a second roller with its respective motor group. In this case the motor is position-controlled. The control establishes the pace at which the material is unrolled.

LOAD CELL: is a sensing element (e.g. a load cell) which measures the load applied on the pulley by the strip of material which is moving.
The working principle of this realization is analogous to the one of the previous realization, but in this case the control is activated by the signal generated by the load cell (DEVICE E). When rotating, DEVICE D makes new material advance toward the cutting position (DEVICE B). During this movement the strip of material tends to bend if no resisting torque is applied by DEVICE A and this could alter the effectiveness of the cutting operation. The load cell (DEVICE E) placed on the surface of the pulley can detect this situation since it is able to measure the load applied by the strip of material on the pulley itself. The value of the load detected by DEVICE E generates the signal to activate a feedback control on DEVICE A: the motor (DEVICE A) generates a braking torque, which stretch the material and keeps it straight; at this point the cutting operation can be correctly performed.

2.2.7 Additional features of the definitive solution

Referring to the definitive solution, it must be observed that the fixed blade of the scissors must be parallel and near the strip of material to be cut, moreover the mobile blade must be in contact with the material. To allow these conditions the scissors need to have the possibility of moving, at least, into horizontal and vertical directions (Figure 2.17).

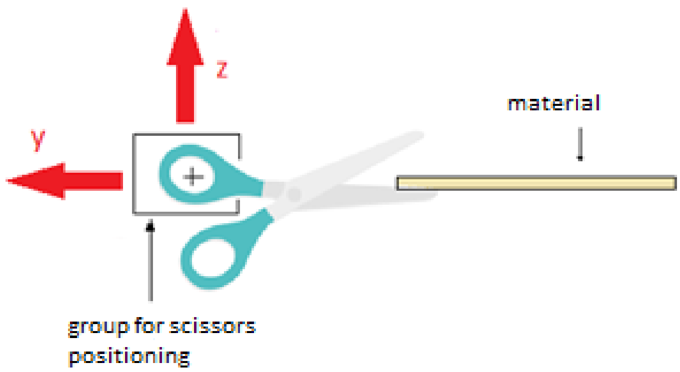


Figure 2.17 Scissors movement

To allow the movement of the scissors different alternatives can be used:

1) Plates with buttonholes and tightening bolts**.**
2) Bi-directional sledge.
3) Any mechanism that allows a bi-directional movement.

Once that scissors have been positioned, even the motor which is linked with them and allows their movement must be placed adapting to the physical dimensions of the scissors (Figure 2.18).

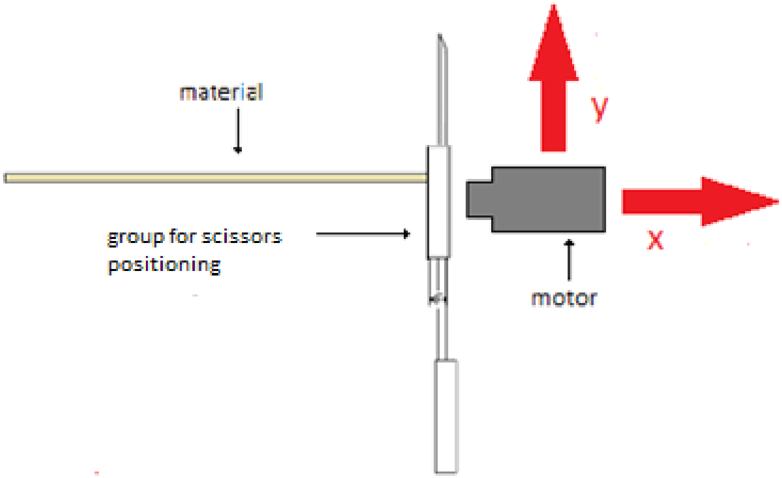


Figure 2.18 Motor movement

Even in this case the possible solutions are:

1) Plates with buttonholes and tightening bolts.
2) Bi-directional sledge.
3) Any mechanism that allows a bi-directional movement.

Another feature of the cutting system (which will be developed in later projects) is the possibility of performing a cut and a subsequent ripping action. The goal of this procedure is testing the effectiveness of the cut, in fact the ripping action will be impeded (or at least it will result difficult) if the cut is not performed correctly (meaning for example that scissors remains somehow blocked in the texture of the material).
The solution for the cut and rip mechanism is made available since the scissors and motor group (previously described) will be mounted on a monodirectional sledge (Figure 2.19).

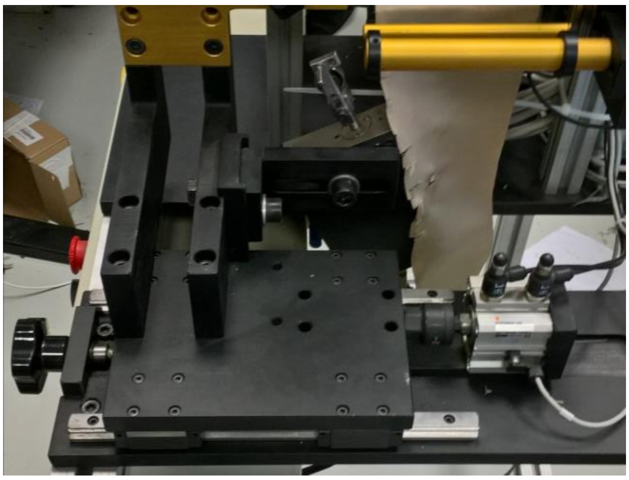


Figure 2.19 Monodirectional sledge for the cutting and ripping action

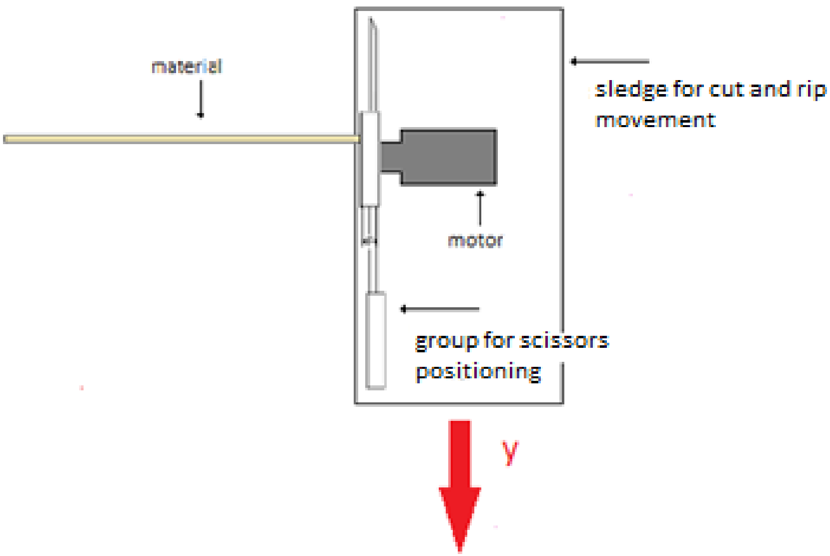


Figure 2.20 Cut and rip mechanism

The last feature that will be implemented on the definitive solution is a mechanism which allows to impress a pressure on the eyelet of the scissors during the cutting operation (this operation simulates the behavior of the palm of the hand which pushes on the scissors when a cut is performed). The pressure operation is simulated by a spring and rope mechanism (Figure 2.21)

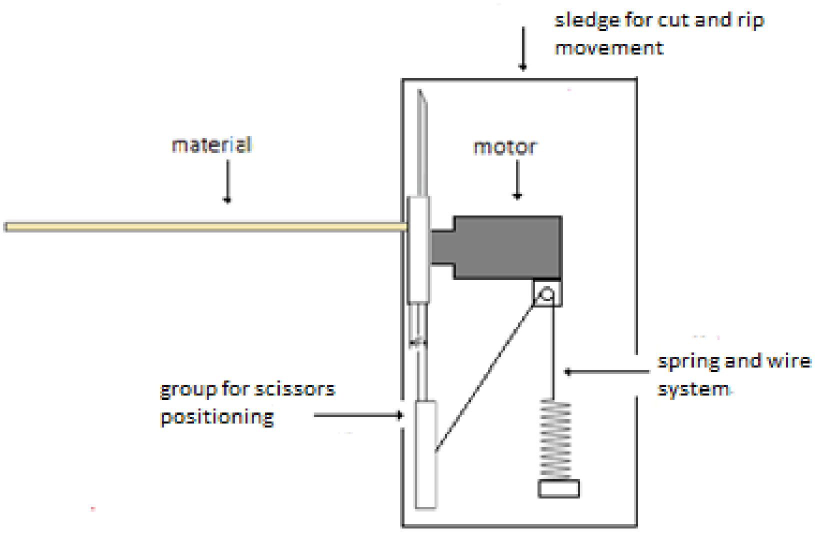


Figure 2.21 Pressure on the eyelet mechanism

2.2.8 Timing of the definitive solution

In the following Figure 2.22 is depicted an example of the scheme of the operations required to correctly set up the cutting machine and the sequence of the actions that will be performed.

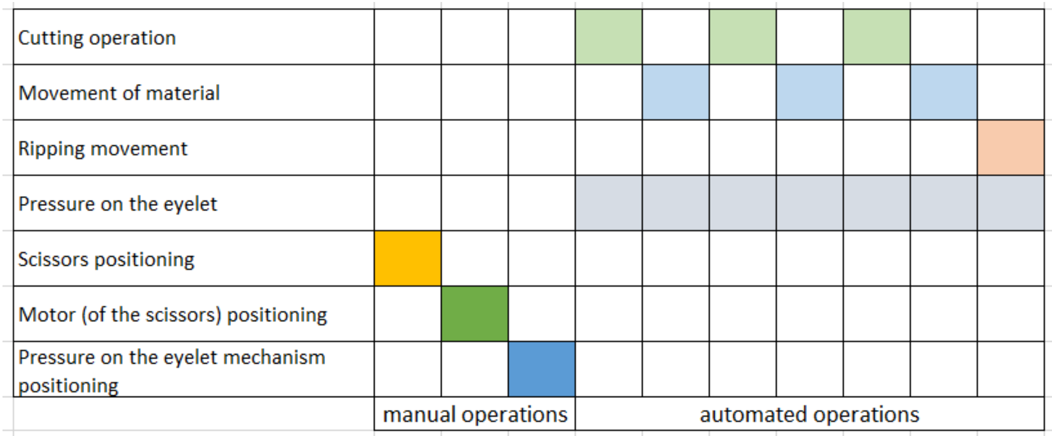


Figure 2.22 Timing of the cutting machine

2.3 The problem of tension control

2.3.1 Tension zones

For tension control is intended the possibility of continuously controlling the tension to which the material (or film) is subjected. The control of tension is of fundamental importance for the effectiveness of the machine since the right tension guarantees the correct movement of the material and its correct processing (in the case of the cutting machine the process is a cutting operation, but other processes could be considered for machines that works with the same logic of winding and unwinding). The idea of the control is based on the concept of controlling the resistant torque developed by the motor to apply the right amount of tension to the material. Making again reference to the definitive Solution C, is possible to split the system into three sections (Figure 2.23) which have the following characteristics [4]:

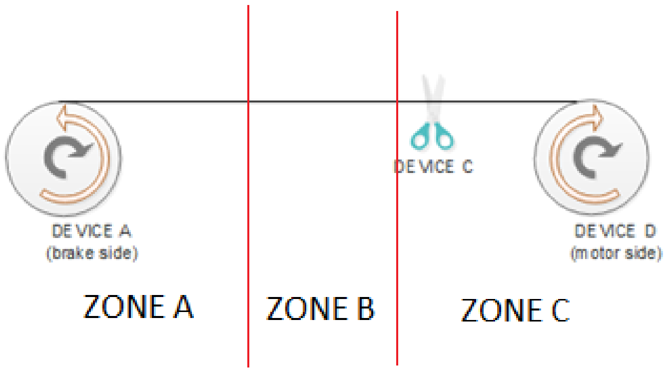


Figure 2.23 Tension zones in a winding/unwinding system

for ZONE A

- The angular velocity of the roller of material depends on the angular velocity of the motor.
- The inertia is variable since the radius of the roller is decreasing (the roller in this section is supposed to be unwound as time goes by).
- The tension must be kept constant.

for ZONE B

- The linear velocity of the material is supposed constant.
- Inertia of material is not relevant.
- The tension must be kept constant.

for ZONE C

- The angular velocity of the roller of material depends on the angular velocity of the motor.
- The inertia is variable since the radius of the roller is increasing (the roller in this section is supposed to be winded as time goes by).
- The tension must be kept constant.

2.3.2 Evaluation of the diameter

As already showed, the inertia in ZONE A and ZONE C is considered to be variable. The reason is that in one zone and unwinding roller (which radius is decreasing as time goes by) is located, while in the other one a winding roller (which radius is increasing as time goes by) is located. The measurement of the diameter of the roller of material wrapped on the shaft is of fundamental importance since many parameters of interest are function of such dimension: inertia moment and inertia torque of the load moved by the motor, velocity reference for the motor, etc. All these parameters will be necessary once that a standard position or torque control will be performed on the motor (is possible to implement other low-level control techniques for which such parameters are not strictly necessary). Different strategies can be adopted to measure the radii of the winding and unwinding sections in function of time; in the following are presented the logics of the most commons techniques of radius (diameters) measurement.

1) Measurement using distance sensors

Different typologies of sensors can be used in this configuration; possible solutions are offered by laser, optical or ultrasonic sensors. For example, if an ultrasonic sensor is used, an ultrasonic wave is send in direction of the winding/unwinding reel, the control system of the sensor calculates the time of reflection of the wave and evaluates the distance travelled. Once that the distance is known the measurement of the diameter can be obtained considering the geometry of the machine (Figure 2.24).

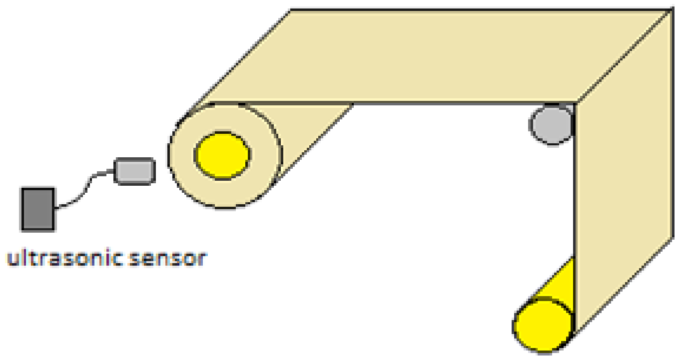


Figure 2.24 Diameter measurement using distance sensors

This kind of solution offers many advantages:

- Contactless measuring system.
- Compact system which can be placed in different positions of the machine.
- Simplicity of installing and calibration operations.
- No mechanical parts are involved, which means that if reels of larger/lower diameters are installed only a new calibration of the device is necessary.
- Can be controlled to check if an anomalous situation is detected on the size of the reel.

And some drawbacks:

- The presence of an obstacle between the sensor and the reel distorts the measurement.
- Calibration is necessary.
- The material wrapped on the reel needs necessary to be reflective; this problem should be not relevant because of the material involved in the cutting machine (mainly clothes or abrasive paper).

2) Measurement using mechanical systems

The basic idea is of mounting a movable mechanical element (a spring system could be the simplest one, but even a rotating arm could be used) in contact with the reel of material (Figure 2.25). When the radius of the reel varies (increases or decreases), the mechanical elements is moved, this movement can be read by a sensing element (ranging from simple potentiometers to more sophisticated sensors) and transformed into a radius measurement considering the geometry of the machine.

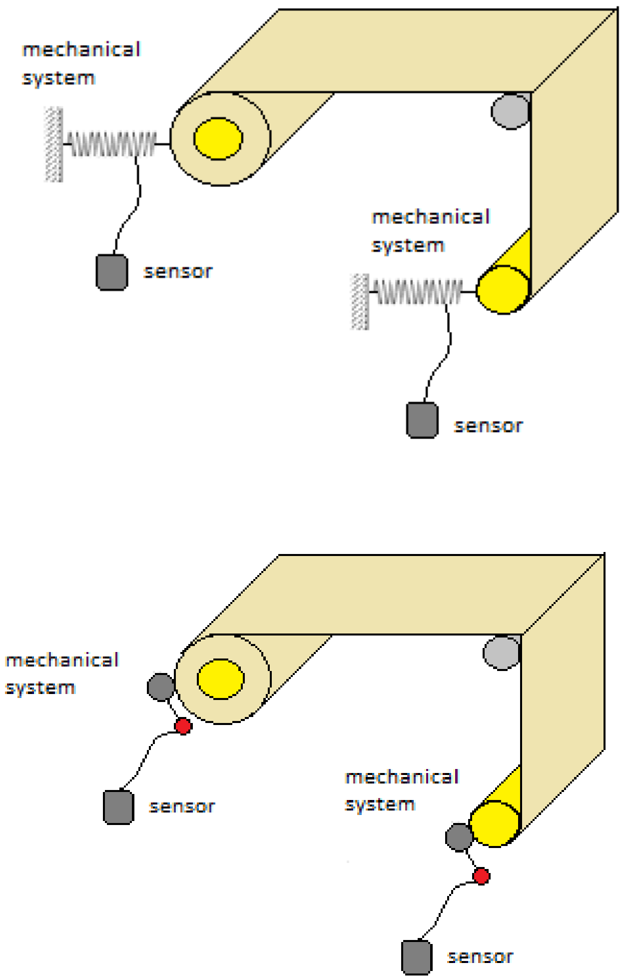


Figure 2.25 Diameter measurements using mechanical systems

The advantages offered by this kind of solutions are:

- Cost.
- Simplicity of the installation and of the device use.

Disadvantages are:

- The system needs contact between the mechanical part and the reel of material, this could generate wear on both and mostly requires an adequate actuation system.
- Mechanical parts increase the complexity of the overall system and can result cumbersome when the reels are mounted/dismounted.
- Maintenance of the mechanical parts is necessary.

3) Calculation using the thickness of the material

If the thickness of the material and the initial diameter of the roller are known is easy to imagine that for every complete round performed, for example, by the winding reel the diameter is increased of two times the thickness

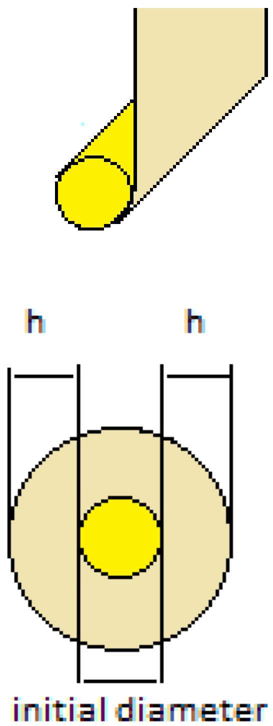


Figure 2.26 Diameter calculation using the thickness of the material

If we define the thickness of the material (h) and the speed of the motor (n) can be measured for example using an encoder, the diameter (D) as function of time can be expressed by the following integration:

$$D = \int 2hn \, dt$$

The previous integral can be transformed into a discrete integration:

$$D_i = D_{i-1} + \frac{2\,h\,n_i \Delta t}{T}$$

Where Δt is the constant time interval at which the speed n is sampled and T is the duration of the integration range.

The pros of this kind of solutions are:

- Simplicity of the calculation.
- Only an encoder is needed.

The cons are given by:

- The thickness of the material must be measured in an extremely accurate way.
- The initial diameter of the roller must be measured in an extremely accurate way.
- If the material is not perfectly wrapped on the roller a distorted

4) Calculation using linear and angular velocities

In this case the diameter of the reel is not directly measured, but its measurement is obtained measuring other physical quantities that properly linked lead to the evaluation of the diameter. For example, imagine of placing passive rollers after the unwinding section as in Figure 2.27.

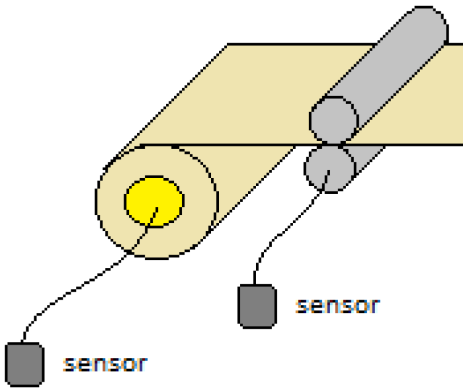


Figure 2.27 Diameter calculation using linear and angular velocities

Two relationships can be written for the system, one for the unwinding roller:

$$v = \omega_1 R_1$$

and another one for the passive roller

$$v = \omega_2 R_2$$

One encoder is used to detect the angular velocity of the unwinding roller ω_1, while another one detects the angular velocity of the passive roller ω_2 . The two previous relationships can be equated

$$\omega_1 = \omega_2 R_2$$

And the radius R_1 can be obtained.
More complex systems or sensors can be used to obtain the value of the radius as function of time.
The pros of this kind of solution are:

- Only encoders are used.
- Simple calculations.
- Contactless measuring system.

The cons are mainly given by:

- The procedure is precise when the machine is working at constant velocity, sudden accelerations or decelerations make the calculations not adequate.

5) Calculation using linear and angular displacements

This method is partially based on the previous one, since the values of linear and angular acceleration are integrated on a defined number of rounds of the winding/unwinding roller. Once that the values of linear (S) and angular (θ) displacement are obtained the following relationship is valid to calculate the diameter (D):

$$D = 2\frac{S}{\theta}$$

Doing this way, the diameter is updated after a fixed number of revolutions of the roller (N) and because of that also the thickness of the material (h) can be calculated:

$$h = \frac{D_i - D_{i-1}}{2N}$$

The significant pros of this kind of solution are:

- Usable even during accelerations and decelerations.
- Possibility to evaluate the thickness of material.

The cons are mainly given by:

- Complex calculations because integrations are needed and a counter to evaluate N.

2.3.3 Tension references

As previously said, the role of the tension is fundamental during the cutting operation, anyway do not exist standard procedures that define the correct amount of tension to be applied to the material to perform a cut of good quality. Intuitively is possible to say that the more the material is kept in traction before the cutting operation the more is

easy to perform the cut; a cut is defined “easy” to be performed when a low amount of torque is impressed to the scissors that perform the operation. An effective way to determine the optimal tension is to use previous experiences on materials that can be considered like the one that will undergo the cutting operation; if there’s a lack of such experience it will be necessary (and very effective) to proceed with experiments and tests.
Some technical tables draft by organizations working in the sector of winding/unwinding operations or found in literature [5] can be a good starting point to evaluate the optimal winding tension. Example of tables are reported on the following figure.

MATERIAL	TENSION
Acetate	0,035 N/cm/ μm
Rolled Alluminium	0,035 ÷ 0,11 N/cm/ μm
Paper	$\frac{(g/m^2)}{27 \div 40}$ N/cm
Cellophane	0,035 ÷ 0,07 N/cm/ μm
Nylon	0,015 ÷ 0,02 N/cm/ μm
Polyestere	0,035 ÷ 0,07 N/cm/ μm
Polyetilene	0,015 ÷ 0,02 N/cm/ μm
Polistirene	0,06 ÷ 0,08 N/cm/ μm
PVC	0,0035 ÷ 0,014 N/cm/ μm

Figure 2.28 Example of winding tensions for different material

The tension is expressed as a function of width [cm] and thickness [μm] of the material. The above values are referred to optimal tension for winding/unwinding operations and not for cutting operations, anyway it is supposed that for the cutting operations at least the optimal tension of winding/unwinding operation must be reached. Since it is not easy to find tables for different materials (for example the cutting machine is supposed to work with clothes or abrasive paper which are not listed in tables), a good starting point could be of considering that, always for winding/unwinding and not cutting, a tensile stress of about 1,5 % of the elastic modulus of the material can be applied without inducing permanent stresses on the material [6]. The previous consideration means that for a material of cross sectional A and elastic modulus E the maximum allowable tension should be of:

$$T_{max} = 1{,}5\% \cdot E \cdot A$$

A series of experiments could be performed on clothes and abrasive papers to obtain a series of stress-strain curves that, properly elaborated, could give the value of the elastic moduli. Once obtained the elastic modulus the previous equation could be used to obtain the value of the tension which must be kept during the winding/operation (and so even during the cut operation).

2.4 Preliminary cost analysis of the definitive solution

As explained in the previous section the definitive solution of the cutting and testing machine, can be developed using three different layouts: Realization 1, Realization 2 and Realization 3. If we consider that Realization 1 can be easily implemented with the material already available, the remaining two realizations share, more or less, the same functional groups:

- A control and acquisition board.
- One motor controlled in torque.
- One motor controlled in position.
- Torsiometer (Realization 2) or load cell (Realization 3) for the torque control.
- One sensor for the diameter measurement.
- Holding system for scissors.
- Scissors actuation and measuring system.
- Cutting and ripping system.
- A system for wrapping the material (pulley)

In the following a list is made of all the components necessary to develop the two realizations and a first cost analysis of both is developed.

2.4.1 Control board

Both Realization 1 and Realization 2 needs a control board to be implemented. The number of inputs/outputs is not depending on the chosen realization since both share the same components: an analog output is necessary to control the first motor in position, another analog output is necessary to control the second motor in torque, and an analog input is necessary to acquire the signal coming from the sensor (torsiometer for Realization 2 or load cell for Realization 1). The measuring and cutting group is supposed to work with the control board which is already used.
One possible control board is given by EPOS4 Compact 24/1.5 CAN by Maxon Motors. The choice of Maxon controller is made because the actual measuring and cutting system is already working with a Maxon device. The proposed control board is composed of one module EPOS4 Module 24/1.5 (code 536630) with its related connector board EPOS4 CB 24/1.5 CAN (code 536997). The cost of device is given by the cost of the module EPOS4 Module 24/1.5 (220.91 €) plus the cost of the connector board EPOS4 CB 24/1.5 CAN (117.18 €). The total cost is 338.09 €.

Figure 2.29 Epos 4 module plus connector board

In the following table the most important features of the control board (electrical rating, number of inputs and outputs, interfaces etc.) are summarized.

Table 2.2 EPOS4 Compact 24/1.5 CAN technical data

EPOS4 Module 24/1.5 (536630) EPOS4 Compact 24/1.5 CAN (546714)			
Electrical Rating	Nominal power supply voltage $+V_{CC}$	10…24 VDC	
	Nominal logic supply voltage $+V_C$	Module	10…24 VDC
		Compact	10…24 VDC, optional
	Absolute supply voltage $+V_{min}$ / $+V_{max}$	8 VDC / 28 VDC	
	Output voltage (max.)	0.9 x $+V_{CC}$	
	Output current I_{cont} / I_{max} (<30 s)	1.5 A / 4.5 A	
	Pulse Width Modulation frequency	100 kHz	
	Sampling rate PI current controller	25 kHz (40 µs)	
	Sampling rate PID speed controller	2.5 kHz (400 µs)	
	Sampling rate PID positioning controller	2.5 kHz (400 µs)	
	Max. efficiency	89% (➔Figure 2-4)	
	Max. speed DC motor	limited by max. permissible speed (motor) and max. output voltage (controller)	
	Max. speed EC motor (block)	100'000 rpm (1 pole pair)	
	Max. speed EC motor (sinusoidal)	50'000 rpm (1 pole pair)	
	Built-in motor choke	Module	–
		Compact	3 x 94 µH; 1.5 A
Inputs & Outputs	Digital Input 1 (general purpose) Digital Input 2 (general purpose) Digital Input 3 (general purpose) Digital Input 4 (general purpose)	Module	+2.1…+36 VDC
		Compact	DIP switch-selectable levels: • Logic: +2.0…+30 VDC • PLC: +9.0…+30 VDC
	Digital Output 1 (general purpose) Digital Output 2 (general purpose)	max. 36 VDC / I_L ≤500 mA (open collector with internal pull-up)	
	STO Input 1 STO Input 2	+4.5…+30 VDC (optically isolated)	
	STO Output	max. 30 VDC / I_L ≤15 mA (optically isolated with self-resetting short-circuit protection)	
	Analog Input 1 Analog Input 2	Resolution 12-bit, −10…+10 V, 10 kHz, differential	
	Analog Output 1 Analog Output 2	Resolution 12-bit, −4…+4 V, 25 kHz, referenced to GND	
	Digital Hall sensor signals H1, H2, H3	+2.0…+24 VDC (internal pull-up)	

Inputs & Outputs (continued)	Digital incremental encoder signals A, A\, B, B\, I, I\	EIA RS422, max. 6.25 MHz	
	Sensor signals (choice between multiple functions) • Digital incremental encoder • Analog incremental encoder* • SSI absolute encoder • High-speed digital input 1…4 and High-speed digital output 1	3-channel, EIA RS422, max. 6.25 MHz 3-channel, resolution 12-bit, ±1.8 V, differential configurable, EIA RS422, 5 MHz EIA RS422, max. 6.25 MHz EIA RS422, max. 6.25 MHz	
Voltage Outputs	Sensor supply voltage V_{Sensor}	+5 VDC / I_L ≤100 mA	
	Auxiliary output voltage V_{Aux}	+5 VDC / I_L ≤150 mA	
Motor Connections	DC motor	+ Motor, – Motor	
	EC motor	Motor winding 1, Motor winding 2, Motor winding 3	
Interfaces	RS232	Module	max. 115'200 bit/s; external transceiver necessary
		Compact	max. 115'200 bit/s
	USB 2.0 / USB 3.0	Full Speed	
	CAN	max. 1 Mbit/s	
Status Indicators	Operation	green LED	
	Error	red LED	
Physical	Weight	Module	approx. 17 g
		Compact CAN	approx. 58 g
	Dimensions (L x W x H)	Module	53.8 x 38.8 x 11.1 mm
		Compact CAN	55.0 x 40.0 x 31.1 mm
	Mounting	Module	pluggable female box headers 1.27 mm or mounting holes for M2.5 screws
		Compact	mounting holes for M2.5 screws 3)
Environ-mental Conditions	Temperature	Operation	Module: −30…+60 °C Compact: −30…+45 °C
		Extended range 1)	Module: +60…+73 °C Derating −0.115 A/°C (➔Figure 2-3) Compact: +45…+70 °C Derating −0.060 A/°C (➔Figure 2-3)
		Storage	−40…+85 °C
	Altitude 2)	Operation	0…6'000 m MSL
		Extended range 1)	6'000…10'000 m MSL Derating ➔Figure 2-3
	Humidity	5…90% (condensation not permitted)	

The control board is supposed to work with DC motors up to 36 W of power. The idea is to use the possibility of the encoder connection of the control board to perform the position control of one of the two motors, while using one of the two available analog output to torque-control the second motor, moreover one of the two analog input can be used to connect the sensor (torsiometer or load cell). In this way are still available one analog input port and one analog output port plus all the digital inputs and outputs (for eventual future necessity of applying switches or other devices).

2.4.2 Torque-controlled motor

A motor is already available by the old version of the cutting machine. The motor is realized by Micromotors, it belongs to the series E192 and the type is defined as $E192\,\frac{12}{24}\,67$. In figure 2.29 is represented the mechanical drawing of the motor and in Table 2.3 its datasheet.

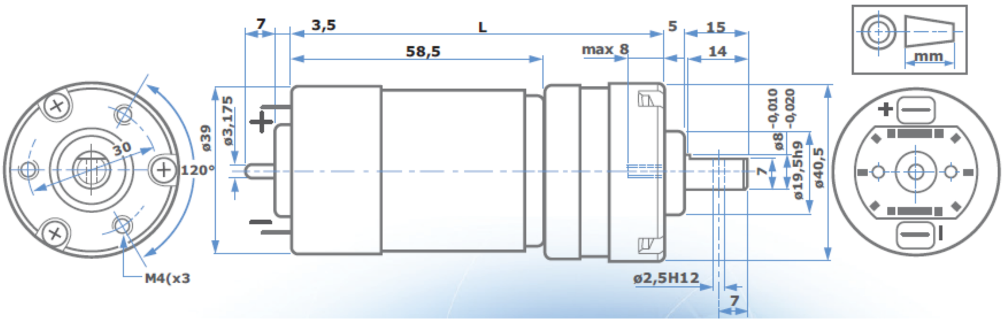


Figure 2.30 Mechanical drawing of E192 motor

Table 2.3 Datasheet of E192 motor

TYPE	NOMINAL VOLTAGE	L	RATIO TO:1	MAXIMUM TORQUE	SPEED NO LOAD	SPEED AT MAX TORQUE	CURRENT NO LOAD	CURRENT AT MAX TORQUE	INPUT POWER AT MAX TORQUE
	v	mm		Ncm	rpm		A		W
E192·$\frac{12}{24}$·3	12 24	86	3.66	15	1100 1100	700 770	<0.4 <0.2	1.70 0.96	20.4 23
E192·$\frac{12}{24}$·5	12 24	86	5	20	800 830	510 575	<0.4 <0.2	1.75 0.95	21 22.8
E192·$\frac{12}{24}$·13	12 24	93	13.44	45	300 300	200 225	<0.4 <0.2	1.65 0.85	19.8 20.4
E192·$\frac{12}{24}$·18	12 24	93	18.33	60	218 226	155 170	<0.4 <0.2	1.65 0.84	19.8 20.2
E192·$\frac{12}{24}$·25	12 24	93	25	90	160 166	105 118	<0.4 <0.2	1.75 0.88	21 21.1
E192·$\frac{12}{24}$·49	12 24	100	49.29	160	82 82	58 60	<0.4 <0.2	1.60 0.85	19.2 20.4
E192·$\frac{12}{24}$·67	12 24	100	67.22	220	59.5 61.5	40 45	<0.4 <0.2	1.80 0.88	21.6 21.1
E192·$\frac{12}{24}$·91	12 24	100	91.66	270	43.6 45	31 34	<0.4 <0.2	1.70 0.85	20.4 20.4
E192·$\frac{12}{24}$·125	12 24	100	125	300	32 33	24 26	<0.4 <0.2	1.32 0.64	15.9 15.4
E192·$\frac{12}{24}$·180	12 24	107	180.75	220	22 22	20 20	<0.4 <0.2	0.75 0.42	9 10.1
E192·$\frac{12}{24}$·246	12 24	107	246.48	300	15.2 16.8	14.5 15	<0.4 <0.2	0.87 0.43	10.5 10.3
E192·$\frac{12}{24}$·336	12 24	107	336.11	300	11.9 12.3	11 11.5	<0.4 <0.2	0.69 0.34	8.3 8.2
E192·$\frac{12}{24}$·458	12 24	107	458.3	300	9 9.5	8.5 9	<0.4 <0.2	0.54 0.28	6.5 6.7
E192·$\frac{12}{24}$·625	12 24	107	625	300	6.4 6.6	6 6.2	<0.4 <0.2	0.46 0.23	5.5 5.5

A dedicated support for the motor (Figure 2.30) has been already designed and 3D printed

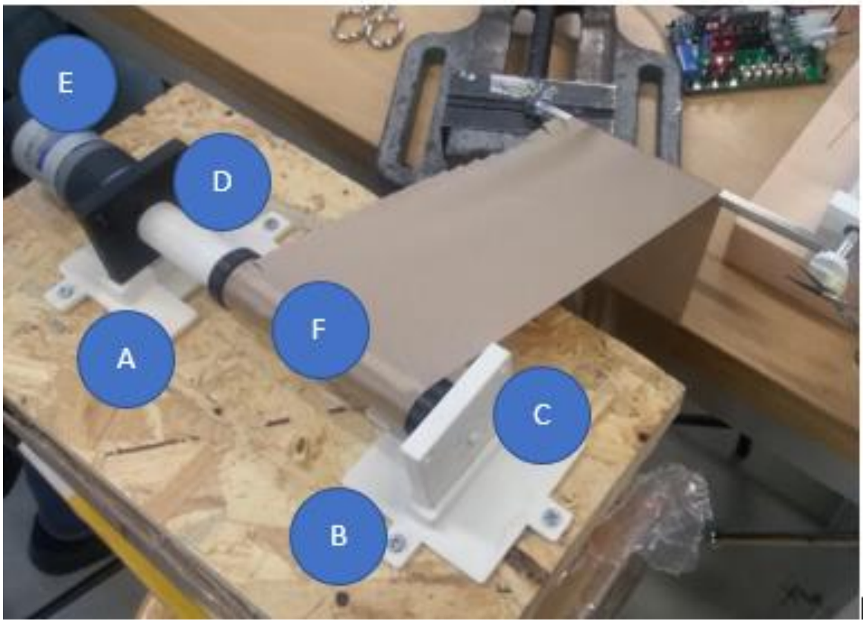


Figure 2.31 Support for the motor

The motor (E) is connected to one extremity of the shaft (F) thanks to ad-hoc designed manifold (D), while the other extremity of the shaft is in contact with the plate C thanks to a tailstock (not clearly visible in the figure). Everything is clamped to ground thanks to two systems of plates and bolts (A and B).
The material is kept in tension thanks to a system of free falling masses (DEVICE D Figure 2.18). A wide range of masses (from few grams up to few kilograms) is available at the Measurements laboratory.
The pulley (DEVICE C Figure 2.18) can be, for the moment, roughly implemented with systems of rigid sticks or with any valid idea. In the future is supposed to create a dedicated device.

2.4.3 Position-controlled motor

The system can be described as a chain of motor, reduction stage and load as shown in the following Figure 2.31

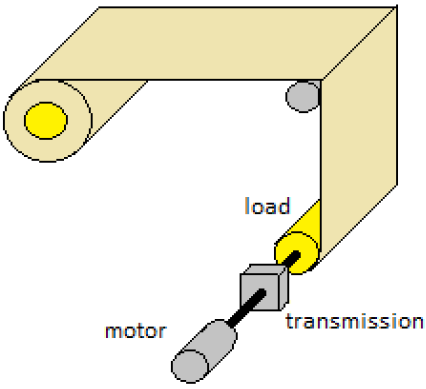


Figure 2.32 Motor, transmission stage and load system

The first step for selecting the motor is defining a plausible motion law. The motion law can be considered as a trapezoidal one (Figure 2.32): a first accelerating part (of duration t1), a second part at constant velocity (of duration t2=t1), a third part of deceleration (of duration t3=t1=t2) and a final part (of duration t4) of rest to allow the scissors system to perform the cut.

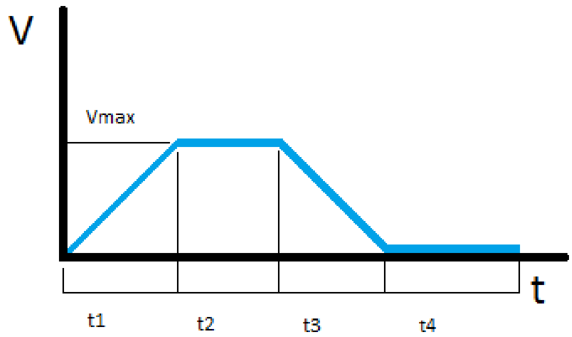


Figure 2.33 Speed profile

The maximum velocity v_{max} reached during the section at constant velocity is defined by the requirements (it is the linear velocity of the moving material); once that velocity is known the linear acceleration (a) can be defined (uniformly accelerated motion) as:

$$a = \frac{dv}{dt} = \frac{v_{max}}{t_1}$$

Once that the speed profile has been defined the mechanical system can be analyzed:

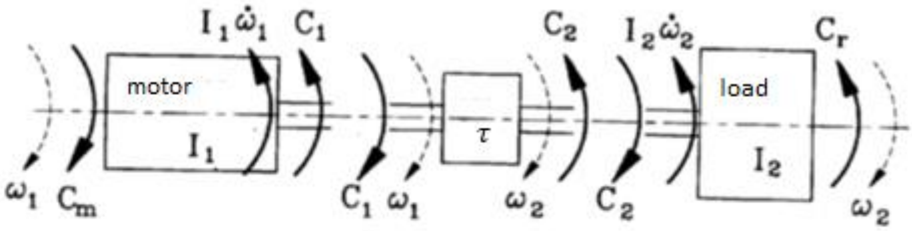


Figure 2.34 Motor, transmission stage and load equilibrium

Describing the mechanical behavior of each single stage (motor side, transmission and load side) is possible to write the system of equations:

$$\begin{cases} C_m - C_1 = I_1 \dot{\omega}_1 \\ \tau = \dfrac{\omega_1}{\omega_2} = \dfrac{C_2}{C_1} = \sqrt{\dfrac{I_2}{I_1}} \\ C_2 - C_r = I_2 \dot{\omega}_2 \end{cases}$$

Substituting the second and the third equation of the previous system into the first one, the following relationship is obtained

$$C_m = \frac{C_r}{\tau} + \left(I_1 + \frac{I_2}{\tau^2}\right)\dot{\omega}_2$$

The first term $\frac{C_r}{\tau}$ can be expressed as a function of the tension L (which generates a resistant torque) applied on the material

$$\frac{C_r}{\tau} = \frac{LR(t)}{\tau}$$

The radius $R(t) = \frac{D(t)}{2}$ of the roller of material is a function of time as it will be explained in the following. To calculate the second term of the motor torque equation is necessary to evaluate $\dot{\omega}_2$ and estimates the moments of inertia of the load. The angular acceleration $\dot{\omega}_2$ is linked to the linear acceleration by the relationship:

$$\dot{\omega}_2(t) = \frac{a}{R(t)} = \frac{v_{max}}{R(t)t_1}$$

It is important to notice that the radius of the load is a function of time: R(t). When the machine is started the material is completely wrapped on the top-left roller (Figure 2.31) and no material is present on the bottom-right roller, for this reason, R is simply the radius of the shaft. As the unrolling operation proceeds, more and more material will be moved from one roller to the other until all the material will be passed to the bottom-right roller (in this case R will be the radius of the full roller of material). For what explained, R(t) will have an increasing trend as time goes by, on the other side the angular acceleration, since is inversely proportional to R(t), will exhibit a decreasing trend (with the hypothesis of keeping a constant linear velocity). For what explained two limits value of the angular acceleration can be calculated:

$$\dot{\omega}_{2max} = \frac{v_{max}}{\frac{D_{min}}{2}t_1}$$

$$\dot{\omega}_{2min} = \frac{v_{max}}{\frac{D_{max}}{2}t_1}$$

For the calculation of the load moment of inertia the following calculations can be considered: the valued of I_2 is the sum of two components that can be calculated separately:

The first component is given by the material which is collected on the shaft (note that even this value of inertia will have a trend which is function of time for what previously explained); the roller of material completely wrapped on the shaft can be approximated as a hollowed cylinder with the following characteristics (a multiplicative coefficient of 1,5 was applied on the final value of inertia):

ROLLER OF MATERIAL		
density	60	kg/m^3
R_I	0,01	m
R_E	0,2	m
h	0,16	m
volume	0,020046	m^3
mass	1,202746	kg
inertia	0,036173	kgm^2

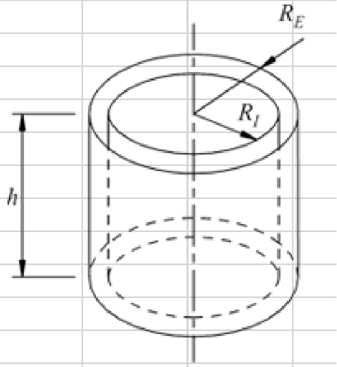


Figure 2.35 Inertial model of the roller of material

The second component is given by the shaft where the material is wrapped on and it is seen as the assembly of a full cylinder and two discs with the following characteristics (even in this case a multiplicative coefficient of 1,5 was applied on the final value of inertia):

DISC_1			DISC_2			SHAFT		
rho	2700	kg/m^3	rho	2700	kg/m^3	rho	2700	kg/m^3
r	0,1	m	r	0,1	m	R	0,01	m
h	0,01	m	h	0,01	m	L	0,16	m
volume	0,00031	m^3	volume	0,00031	m^3	volume	0,00005024	m^3
mass	0,8478	kg	mass	0,8478	kg	mass	0,135648	kg
inertia	0,00636	kgm^2	inertia	0,00636	kgm^2	inertia	1,0174E-05	kgm^2

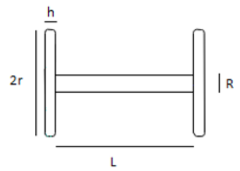


Figure 2.36 Inertial model of the shaft

The moment of inertia of the motor I_1 has to be estimated (since the motor has not yet been selected). Once that the motor is selected the guess must be verified. The motor is simplified as a full cylinder with the following characteristics (even in this case a multiplicative coefficient of 1,5 was applied on the final value of inertia)

MOTOR		
r	0,02	m
mass	0,5	kg
inertia	0,00015	kgm^2

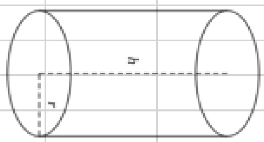


Figure 2.37 Inertial model of the motor

To perform the selection of the motor the following functioning situations have to be defined (no inertial terms will appear in the following equations since calculations are made considering the steady-state motion at constant linear velocity v_{max}):

- For the first case, the maximum allowable tension applied on the material and the largest diameter possible for the coil of material are considered (doing this way the most burdensome situation, in terms of torque required, is evaluated). The maximum motor power and maximum motor torque can be calculated:

$$P_{m\_max} = L_{max} V_{max}$$

$$C_{m\_max} = \left(L_{max} \frac{D_{max}}{2}\right) \frac{1}{\tau}$$

The angular velocity for the maximum diameter of the coil of material can be calculated as:

$$\omega_{min} = \frac{v_{max}}{D_{max}}$$

- In the second situation the torque required and the angular velocity of the motor in the situation of minimum diameter of the coil of material are calculated:

$$C_{m\_min} = \left(L_{max} \frac{D_{min}}{2}\right) \frac{1}{\tau}$$

$$\omega_{max} = \frac{v_{max}}{D_{min}}$$

To properly select the motor, is necessary that the following characteristics are satisfied:

1) $P_{nominal\_motor} > P_{m\_max}$
2) $C_{nominal\_motor} > C_{m\_max}$
3) $\omega_{nominal\_motor} \approx \omega_{min}$
4) $\omega_{max\_motor} > \omega_{max}$

Now it is necessary to verify the motor torque required in case of acceleration/deceleration (so inertial terms will be considered). The motor torque equation:

$$C_m = \frac{LR}{\tau} + \left(I_1 + \frac{I_2}{\tau^2}\right) \dot{\omega_2}$$

evaluated for both:

$$\dot{\omega}_{2max} = \frac{v_{max}}{\frac{D_{min}}{2} t_1}$$

$$\dot{\omega}_{2min} = \frac{v_{max}}{\frac{D_{max}}{2} t_1}$$

gives rise to:

$$C_{m1} = \frac{TD_{min}}{2\tau} + \left(I_1 + \frac{I_2}{\tau^2}\right)\dot{\omega}_{2max}$$

$$C_{m2} = \frac{TD_{max}}{2\tau} + \left(I_1 + \frac{I_2}{\tau^2}\right)\dot{\omega}_{2min}$$

The two motor torques needs to be lower than the nominal torque provided by the motor. The dynamic of the system doesn't need necessarily to be very fast, moreover the inertia of the moving parts are not high, so is possible that the contribution given by the inertial terms will not be relevant in the calculation of the motor torque.

In the following is provided a plausible calculation for the system under analysis.

Table 2.4 Calculations for the selection of the motor

motion characteristics			
max. linear velocity	v_{max}	[m/s]	0,02
time of acceleration	t1	[s]	0,20
linear acceleration	a	[m/s^2]	0,10
mechanical system characteristics			
max. diameter	D_{max}	[m]	0,20
min. diameter	D_{min}	[m]	0,01
max. tension	L	[N]	20,00
max. angula acceleration	$\dot{\omega}_{2max}$	[rad/s^2]	20,00
min. angular acceleration	$\dot{\omega}_{2min}$	[rad/s^2]	1,00
load inertia	I_2	[kgm^2]	0,05
motor inertia	I_1	[kgm^2]	0,00
transmission ratio	τ		18,00
required characteristics			
max. power	P_{m_max}	[W]	0,40
max. torque	C_{m_max}	[Nm]	0,11
max.torque	C_{m_max}	[Ncm]	11,11
min. angular velocity	$\omega_{m\ min}$	[rad/s]	0,10
min. torque	C_{m_min}	[Nm]	0,01
max. angular velocity	$\omega_{m\ max}$	[rad/s]	2,00
torque considering inertia	C_{m1}	[Nm]	0,01
torque considering inertia	C_{m2}	[Nm]	0,11

2.4.4 Load cell (Realization 3)

Considering the previous mechanical system (motor, reduction stage and load) the following scheme is used:

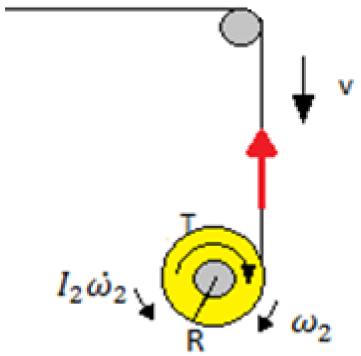


Figure 2.38 Forces and velocities at the load side

At the bottom-right roller is applied a torque depending on the motor which was previously chosen. The torque equilibrium can be expressed as:

$$C - LR = I_2\dot{\omega}_2$$

Which can be rewritten expressing the maximum tension generated:

$$L = \frac{T - I_2\dot{\omega}_2}{R}$$

It is important to remember that the angular acceleration $\dot{\omega}_2$, theradius R, and the inertia I_2 are all functions of time as explained in the previous section. If the idea is to estimate a maximum limit for the tension generated, the following considerations must be made:

- T: the value of T depends on the torque developed by the motor, since the maximum available torque is $C_{\max\_out} = Nm$ (for the previously selected motor) the value of tension referred to this value of torque will be the maximum that can be generated.
- R: the radius of the coil varies between two extreme values depending on the material winded.
- I_2: two cases can be presented, in fact the coil could have maximum or minimum diameter.
- $\dot{\omega}_2$: the angular acceleration could be maximum or minimum depending on the diameter considered.

For these reasons, two extreme values of L can be calculated:

$$L_1 = \frac{C_{\max\_out} - I_{2\_min}\dot{\omega}_{2max}}{\frac{D_{min}}{2}}$$

$$L_2 = \frac{C_{\max\_out} - I_{2\_max}\dot{\omega}_{2min}}{\frac{D_{max}}{2}}$$

Table 2.5 Load cell calculations

MOTOR CHARACTERISTICS			
			E192 12-24.67_24V
name	symbol	units	
ratio to:1	τ	[ ]	67,22
max. torque in output		[Ncm]	60,00
max. torque in output	$T_{\max\_out}$	[Nm]	0,60
max. torque in input	$T_{\max\_inp}$	[Nm]	0,01
speed in output at max.torque		[rpm]	45,00
speed in output at max.torque	ω_{Tmax_out}	[rad/s]	4,71
speed in input at max.torque	ω_{Tmax_inp}	[rad/s]	316,61
speed in output no load		[rpm]	61,50
speed in output no load	ω_{noload_out}	[rad/s]	6,44
speed in input no load	ω_{noload_inp}	[rad/s]	432,70
power input at max. torque	P_{Tmax_inp}	[W]	21,10

CALCULATIONS			
			1,00
minimum radius of the shaft	R_{min}	[m]	0,01
maximum radius of the shaft	R_{max}		0,20
space	S	[m]	0,02
time	t	[s]	1,00
average linear velocity	v_{ave}	[m/s]	0,02
max.linear velocity	v_{max}	[m/s]	0,04
linear acceleration	a	[m/s^2]	0,02
max.angular velocity	ω_{2max}	[rad/s]	0,20
angular acceleration	$\dot{\omega}_2$	[rad/s^2]	0,10
minimum load moment of inertia	I_{2_min}	[kgm^2]	0,01
inertia torque	C_I	[Nm]	0,00
torque in output from the motor	$T_{\_out}$	[Nm]	2,20
tension	L	[N]	59,87
tension	L	[kg]	6,11
tension	L	[lbf]	13,47

The maximum tension that can be exerted (with the motor of type $E192_{24}67$ by Micromotrs) on the material is about 60 N; for this reason, a load cell which can detect a value higher than this one can be considered excessive. For sake of simplicity, the value of the tension is reported in common measurement units N, kg, lbf.
Taking a load cell of the type "Cella di carico TE Connectivity FC2231-0000-0050-L", which ranges up to 100 [lbf] as shown in the following table

Table 2.6 Load cell Connectivity FC2231-0000-0050-L ranges

Range	lbf
0 to 10	•
0 to 25	•
0 to 50	•
0 to 100	•

The task of the load cell can be surely fulfilled. The cost of this kind of device is estimated of about 70 €. In the following figure the dimensions of the load cell are shown for future considerations about encumbrances.

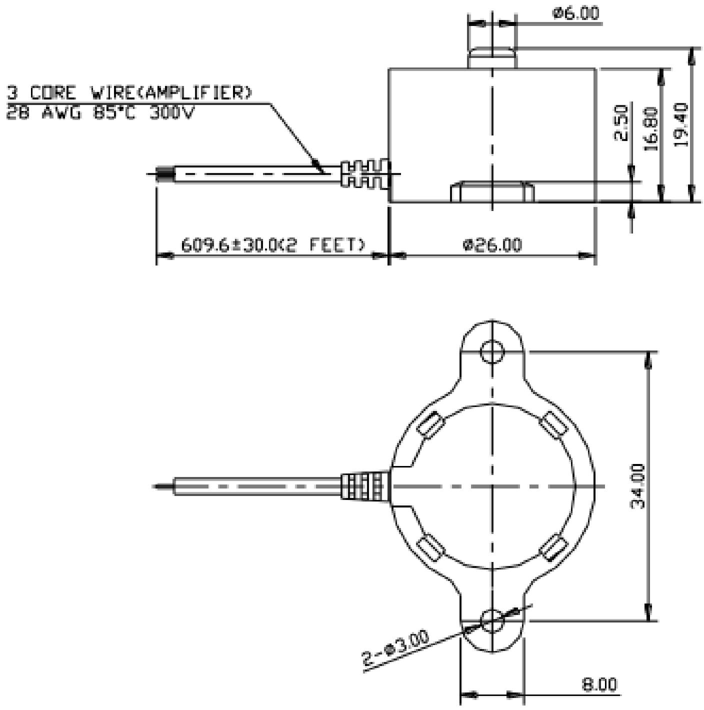


Figure 2.39 Connectivity FC2231-0000-0050-L mechanical drawing

2.4.5 Ultrasonic sensor for diameter evaluation

As explained in previous section one of the possibility to measure the diameter of the winding or unwinding roller is given by an ultrasonic sensor; this kind of solution can be considered as the most accurate one, but at the same time the most expensive. Since the idea is to give a maximum range for the design of the machine, the use of an ultrasonic sensor will be considered.

A sensor of the type “Telemecanique Sensors XX918A3F1M12” can be used.

The price of the device can be estimated about 160 €

Main

Commercial Status	Commercialised
Range of product	OsiSense XX
Sensor type	Ultrasonic sensor
Series name	General purpose
Sensor name	XX9
Sensor design	Cylindrical M18
Detection system	Diffuse
[Sn] nominal sensing distance	0.5 m adjustable with remote teach push-button
Material	Plastic
Type of output signal	Analogue
Wiring technique	4-wire
Analogue output function	0...10 V
[Us] rated supply voltage	12...24 V DC with reverse polarity protection
Electrical connection	Male connector M12 4 pins
[Sd] sensing range	0.051...0.508 m
Beam angle	6 °
IP degree of protection	IP67 conforming to IEC 60529

Figure 2.40 Telemecanique Sensors XX918A3F1M12 main characteristics

2.4.6 Holding system for scissors

Different alternatives can be used to keep in position the scissors (ranging from bench vises to system of sliders and sledges). Since the price of a standard bench vise is of 30 €, this value will be used in the estimation of the costs.

2.4.7 Scissors actuation and measuring system

The movement of the motor which role is to open/close the scissors will be obtained using a combined system of sliders and sledges. The system of sledges will allow the motor to move along two different directions and align it with the fulcrum of the tested scissors. The cost for the whole-system (combination of sledges) is estimated at 50 €.

2.4.8 Cutting and ripping system

The system will allow to perform the ripping action after having performed a given amount of cutting actions. To compose the system will be necessary a monodirectional sledge (about 25 €) and an electric motor (about 100 €)

2.4.9 System for wrapping of the material

This system will be realized by means of common mechanical parts which won't be considered in the costs estimation

2.4.10 Resume

In the following table are resumed all the costs previously mentioned.

Table 2.7 Cost resume

COMPONENT	QUANTITY	PRICE [€/piece]	PRICE [€]
motor: winding	available	0	0
motor: unwinding	1	100	100
load cell	1	70	70
ultrasonic sensor	1	160	160
moving system (scissors motor)	1	50	50
holding system scissors (bench vise)	1	30	30
motor for cut&rip	1	100	100
monodirectional sledge for cut&rip	1	25	25
control and acquisition board	1	600	600
TOTAL			1135

2.5 Realization of a prototype test bench

Aim of this section is the realization and presentation of an autonomous test bench which is composed of all the materials and devices necessary to perform future tests on scissors. The solution that will be presented is not yet to be considered as the final prototype of the cutting and testing machine, but a transition stage between the final product required by PREMAX (whose functional analysis was developed in the previous sections) and the first solution developed for the preliminary tests.

The objective of the test bench is to collect on one single platform all the devices necessary for the test as depicted in the following Figure 2.47

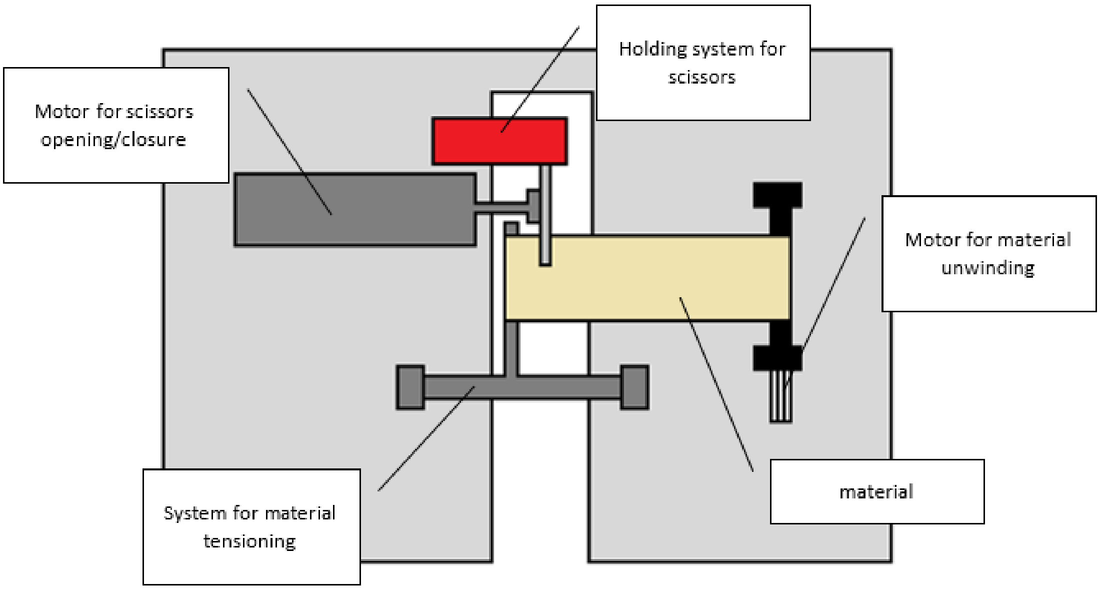


Figure 2.41 Functional groups of the test bench

The components involved on the test bench are:

- Motor for material unwinding and related support.
- System for supporting the strip of material and for tensioning it.
- Holding system for scissors.
- Motor which drives opening and closure of the scissors with related support.

2.5.1 Motor for material unwinding and support

The first realization of the unwinding motor was already presented in the previous sections. The support for the motor was 3D printed and fixed on a wooden plate.

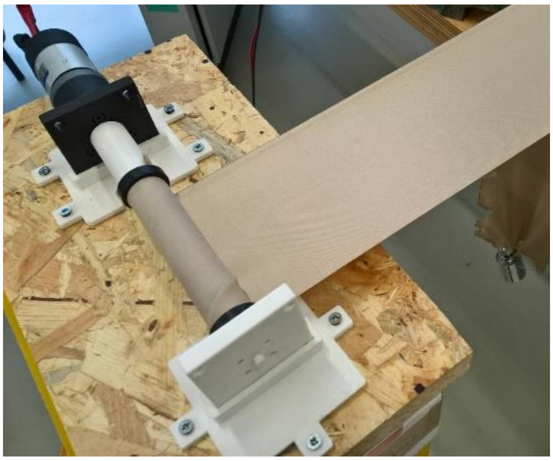


Figure 2.42 First realization of the unwinding motor

The CAD model of the solution is shown is Figure 2.49

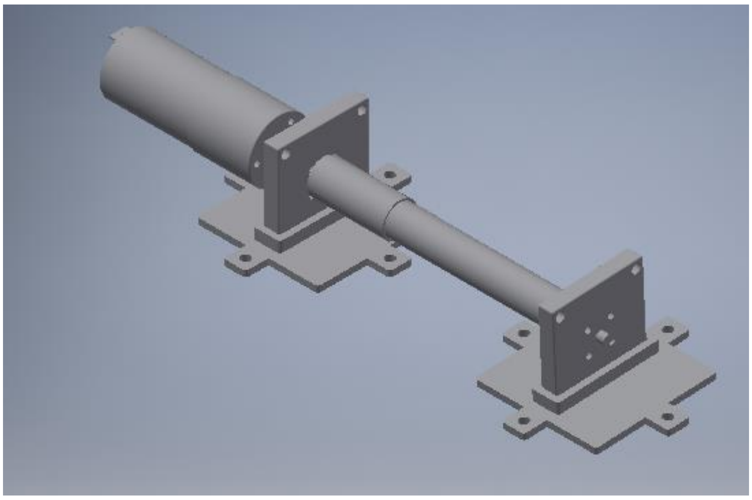


Figure 2.43 First realization of the unwinding motor: CAD

The solution presented can be simplified and additional features can be added. The new prototype for the unwinding motor and support is depicted in Figure 2.50

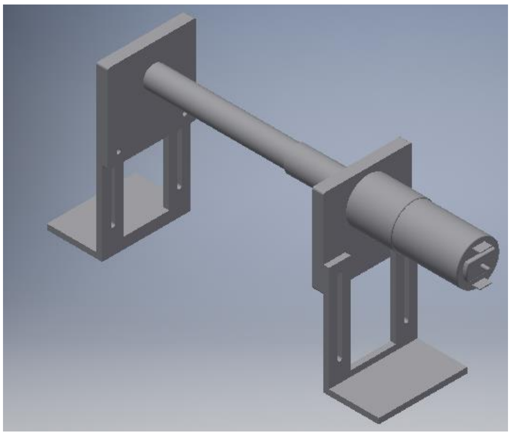


Figure 2.44 New realization of the unwinding motor: CAD

The system in Figure 2.50 can be considered as an improvement of the device depicted in Figure 2.48, in fact it is composed of two squared plates, aligned with two u-shaped supports, which can translate vertically, giving the possibility to the shaft of moving upward or downward depending on the necessities. Once that the proper height for the test is reached the squared plates are blocked with bolts passing through dedicated holes. A tip (Figure 2.51) is fixed into one of the two squared plates (on the left on Figure 2.50) and provides support for one extremity of the shaft.

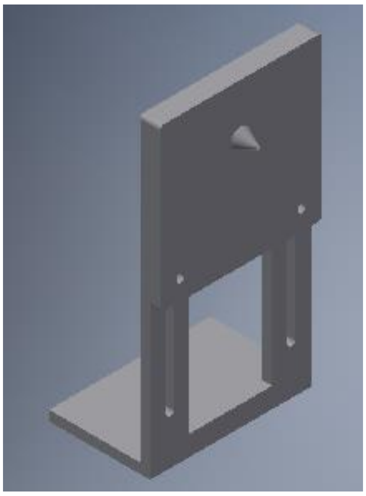


Figure 2.45 Tip for the connection of the shaft

The other extremity of the shaft will be inserted into a dedicated adapter which is linked to the shaft of the motor (Figure 2.52).

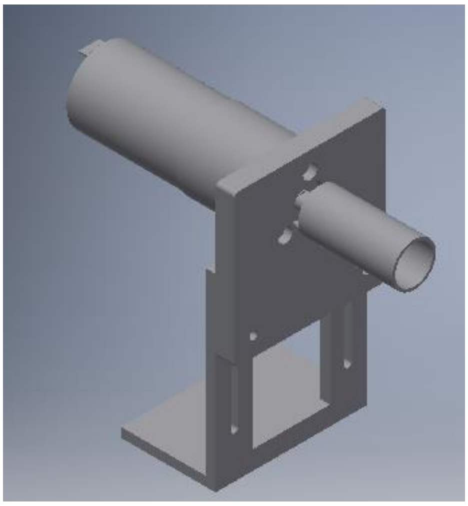


Figure 2.46 Adapter and motor

The described device will be mounted on a base plate by mean of clamps with the interposition of a Teflon sheet between the device and the base.
Is important to underline the pros of the described solution which are: functionality, easiness of use and mounting and most of all simplicity of the realization (the pieces can be obtained using l-shaped profiles 100x50x5, plates 80x80x10, and cylinders).

2.5.2 System for material tensioning and support

The role of this system is simply to provide an element for the material on which being wrapped on without losing tension (it acts as a pulley). When designing such component is important to keep in mind that since the material is continuously unwining, the diameter of the roller continuously decreases; for this reason the height of system for tensioning needs to be variable (one degree of freedom necessary) in order to adapt to the diameter of the unwinding roller. Doing this way the material is always kept in a straight direction and the cut is easily performed (to better understand the problem look at the following Figure 2.53, in the second case the system for material tensioning should be translated downward to allow the material to follow a straight path).

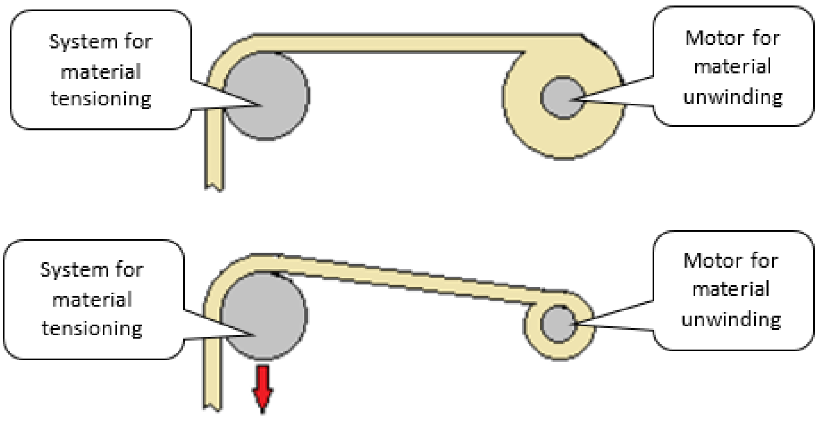


Figure 2.47 Movement of the system for material tensioning

The system for material tensioning is shown in the following Figure 2.54. The vertical displacement degree of freedom is provided, even in this case, thanks to a system of buttonholes and tightening bolts.

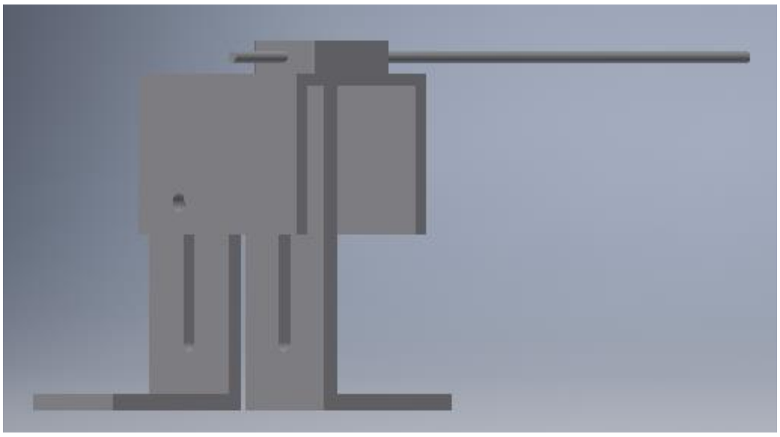


Figure 2.48 System for material tensioning: CAD

Even in this case, the described device will be mounted on a base plate by mean of clamps with the interposition of a Teflon sheet between the device and the base.
This solution is functional, easy to use and mount and simple to realize (the pieces can be obtained using u-shaped profiles 50x50x4, l-shaped profiles 100x50x5, plates 80x80x10, and cylinders).

2.5.3 Holding system for scissors

Scissors need to be in contact with the strip of material to be cut. For this reason the fixed blade of the scissors must be moved until the contact is guaranted, moreover the blade must be parallel to the material. To achieve such a condition is necessary to provide to the eylet of the scissors at least two degrees of freedom (X and Y as depicted in Figure 2.55)

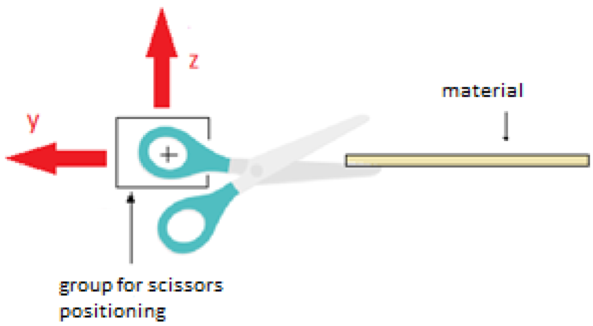


Figure 2.49 Movement of the holding system for scissors

To achieve the target and correctly place the scissors different alternatives can be used: use a bi-directional sldege (or use two mono-directional sledeges), design dedicated plates with buttonholes and tightening bolts, use a moving bench vise (and move the scissors inside the clamp), etc.. Due to its simplicity and its effectiveness the solution adopted is the use of a bench vise.

Figure 2.50 Bench wise

2.5.4 Motor for opening/closure of the scissors

The first realization of the motor (and support) for scissors opening and closure is depicted in Figure 2.57 and was composed of two parts: the effective support for the motor and the plate to fix the support.

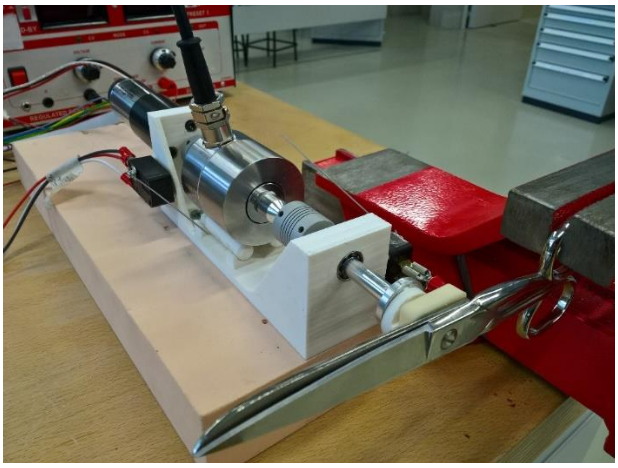


Figure 2.51 First realization of the motor for scissors opening/closure

The new prototype differs from the previous one for mainly one reason: the system is designed to have the possibility of horizontally moving (thanks to a combination of monodirectional sldeges).

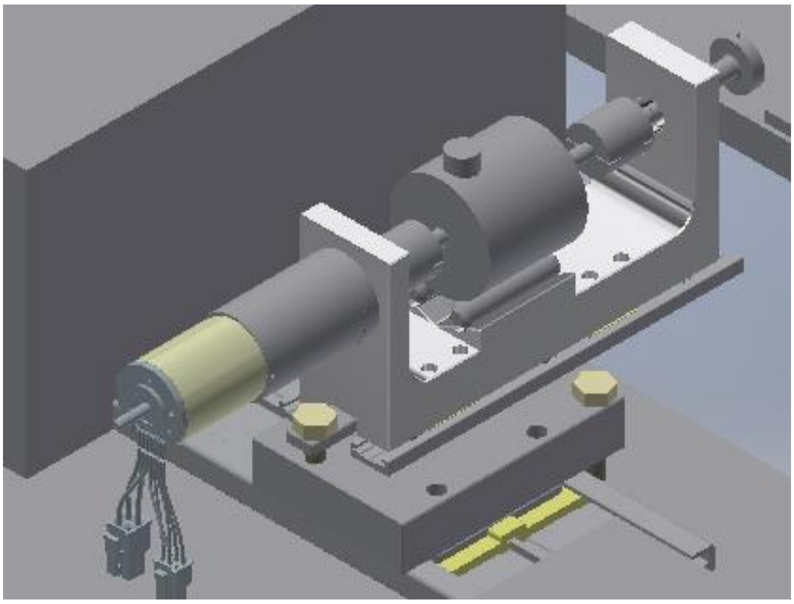


Figure 2.52 Motor for scissors opening/closure: CAD

Thanks to the use of the two monodirectional sledges two movements of the motor are allowed (Figure 2.59) and the motor can be easily aligned with the fulcrum of different types of scissors.

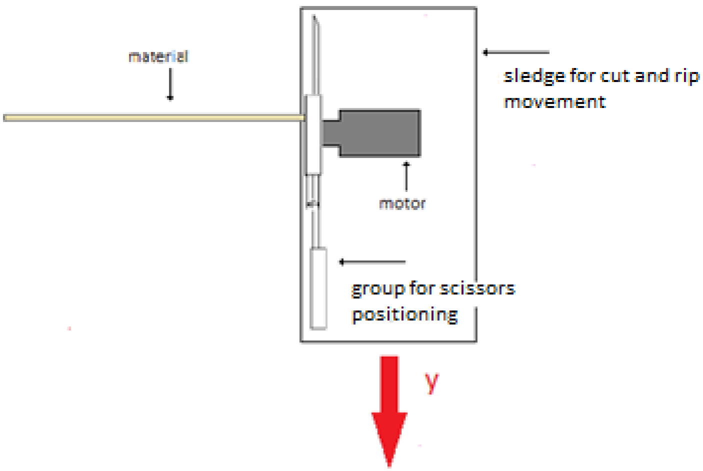


Figure 2.53 Movement of the motor for scissors opening/closure

Once that the correct position of the motor is identified two nylon bolts are used to fix the position.
The sledge which allows the movement on Y direction is made by Igus® "NK-02-80-01-200 LLZ" whose maximum load (torque) are depicted in the following Figure 2.58

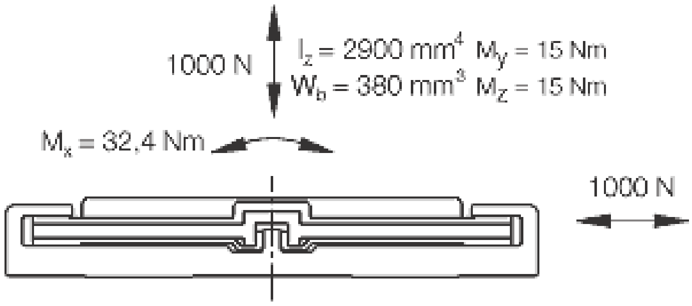


Figure 2.54 Allowable load on the NK-02-80-01-200 LLZ

Since is expected an arm (b) greatly lower than 0,170 m (Figure 2.61)

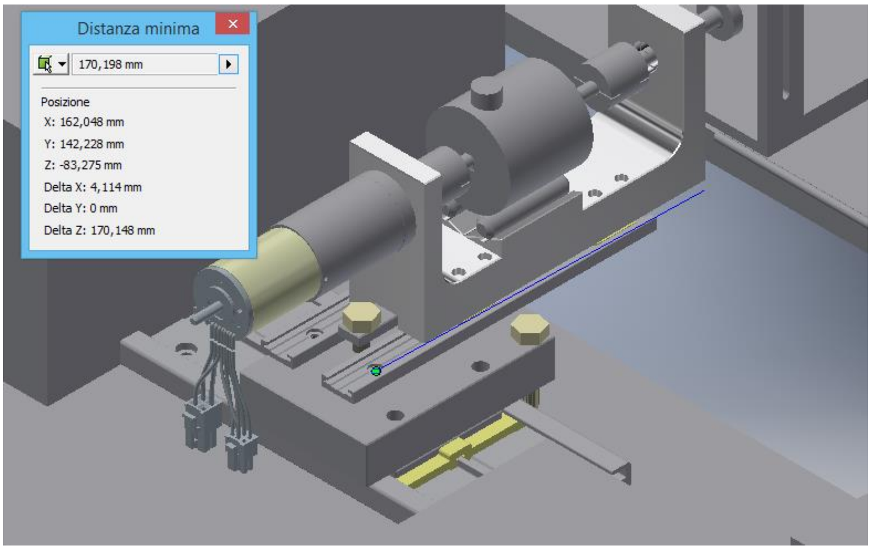


Figure 2.55 Arm expected

The allowable weight (W) that can be substained by the sledge is about

$$M_x = 32{,}4 = Wb$$

$$W = \frac{32{,}4}{0.170} = 190\ N$$

which corresponds to a mass of about 20 kg, a value definitely lower than the maximum weight of the structure.

2.5.5 Assembly of the components

The complete assembly of the previous discussed groups is depicted in the following Figure 2.62.

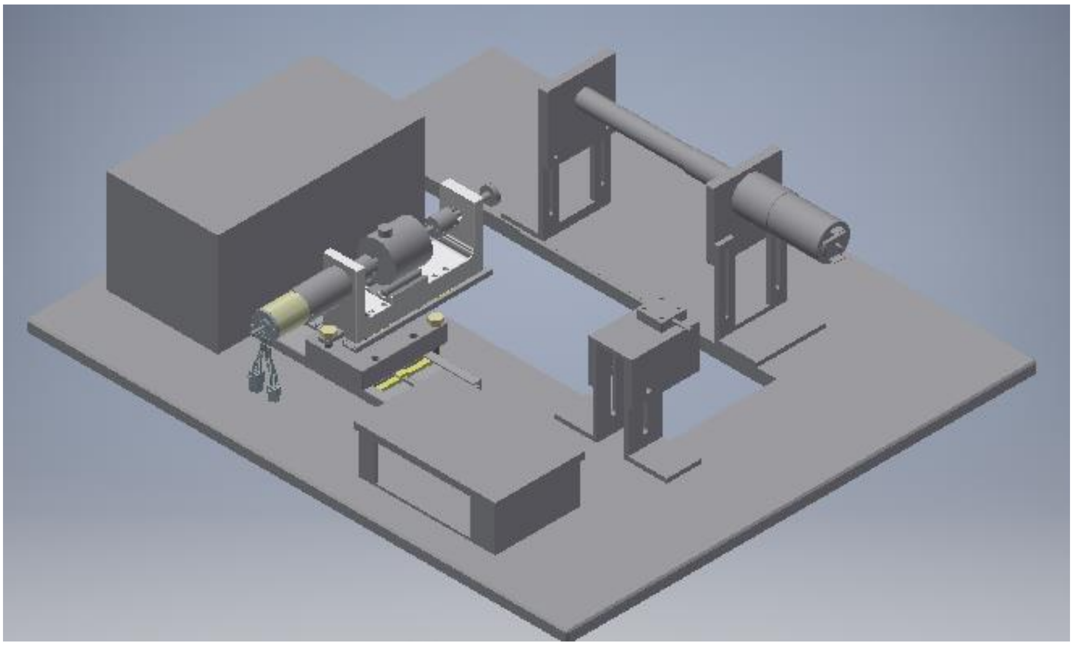


Figure 2.56 Assembly of the complete test bench

Note that a structure not discussed previously was added (a box in the bottom-right side of the plate). This device has no structural role, it is necessary only to contain, protect the control board and collect all the wires directed to the motors.

3 Experimental results

In this chapter it is described the experimental campaign which was carried out with multiple aims. The first task is to validate the whole measurement system (described in the previous chapter), which is composed by the static torsiometer and the acquisition chain. Then, it is necessary to check the correct behavior of the cutting device (proper working of the mechanical parts and correct running of the control software). Finally, it is of interest to analyze if there are some relevant parameters which can significantly influence the torque required to open and close a given pair of scissors. Before the presentation of the experiments, a description of all the instruments (and their connection) used during the test is provided.

3.1 Description of the system and setup

3.1.1 Introduction

Data acquisition (DAQ) is the process of measuring an electric or physical phenomenon, such as voltage, current, temperature, pressure, deformation, etc. A DAQ system is composed by sensors, measuring hardware and a programmable software for collecting, displaying and evaluating results (Figure 3.1).

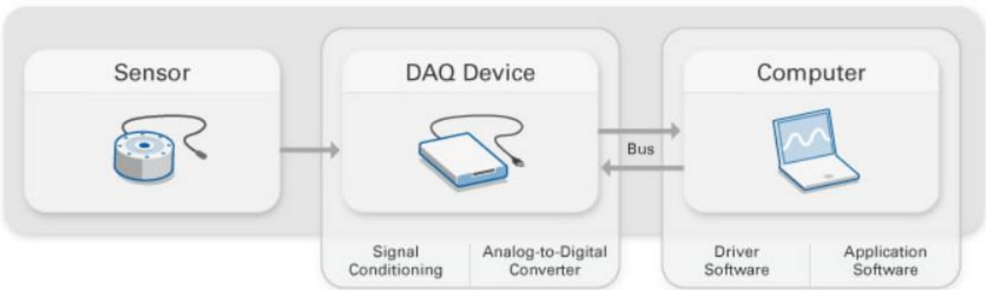


Figure 3.1 Data acquisition chain

Measuring a physical phenomenon starts necessary with the use of sensor. The DAQ hardware is the interface between the signals coming from the sensors and the digital world of computers; the role of the DAQ hardware is to filter, condition, digitalize signals and feed them to the programmable software. The computer with software is the final part of the measuring chain, it makes possible to visualize, elaborate and store the collected data. In the following Figure 3.2 what was described above with a block diagram is schematically represented.

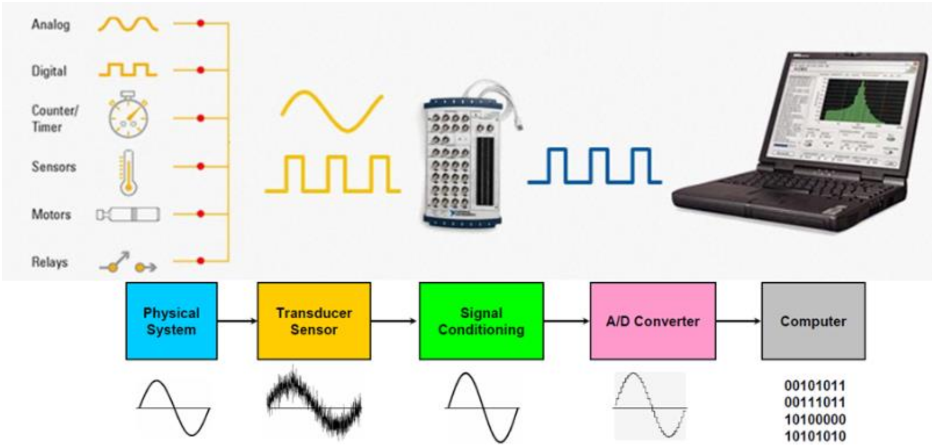


Figure 3.2 Data acquisition block diagram

3.1.2 Instrumentation and devices for the tests

The setup adopted for the tests reflects what already described in the previous section. The power supply feeds the DAQ system which collects signals coming from the measuring system. An additional system for signal conditioning and amplification is part of the set up and is not directly included in the DAQ device. All the data are sent from the DAQ to computer and evaluated via software. In the following a brief description of each component of the system is provided.

- Scissor actuation and measuring system

It is the system which applies the torque to the scissors: the torque is generated by mean of a motor; torque, angular position and current flowing in the motor windings are measured.

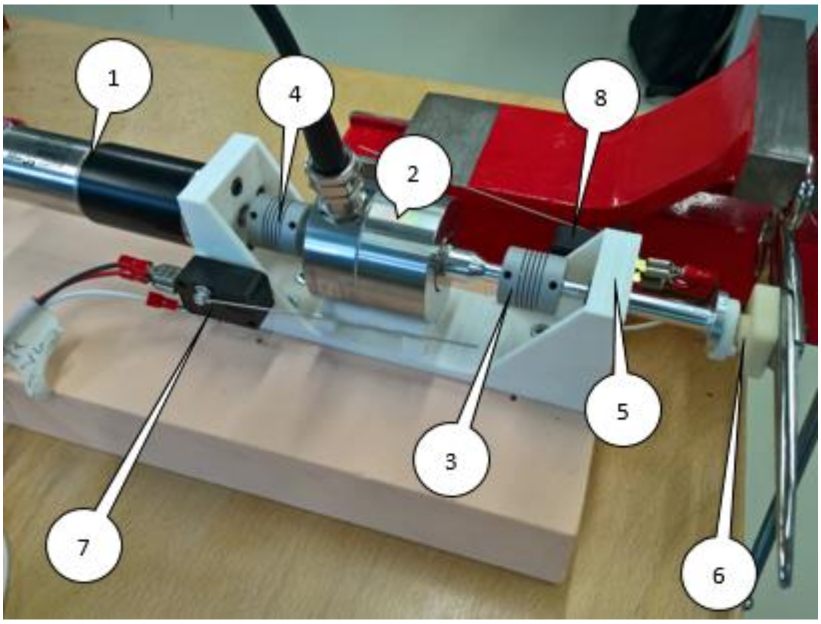


Figure 3.3 Scissors actuation and measuring system

The system is composed by:

a. One electric brushless motor with related encoder and gearbox (1).
b. One static torsiometer (2) to measure the torque applied to the scissor.

Dati Tecnici	*Technical Data*		
TORSIONE NOMINALE **STATICA**	*STATIC NOMINAL TORQUE*	0.5 – 2.5 Nm 5 - 10 Nm 25 Nm	50 – 100 Nm 250 – 500 Nm 1000 Nm
LINEARITA' e ISTERESI	*LINEARITY and HYSTERESIS*	$\leq \pm 0.2$ %	
EFFETTO DELLA TEMPERATURA (1°C): a) sullo zero b) sulla sensibilità	*TEMPERATURE EFFECT (1°C):* *a) on zero* *b) on sensitivity*	 $\leq \pm 0.02$% $\leq \pm 0.02$%	
SENSIBILITA' NOMINALE TOLLERANZA DI CALIBRAZIONE	*NOMINAL SENSITIVITY* *SENSIVITY TOLERANCE*	1 mV/V $\leq \pm 0.5$%	2mV/V $\leq \pm 0.5$%
ALIMENTAZIONE NOMINALE ALIMENTAZIONE MAX. RESISTENZA DI INGRESSO RESISTENZA DI USCITA RESISTENZA DI ISOLAMENTO BILANCIAMENTO DI ZERO	*NOMINAL POWER SUPPLY* *MAX. POWER SUPPLY* *INPUT RESISTANCE* *OUTPUT RESISTANCE* *INSULATION RESISTANCE* *ZERO BALANCE*	1-15V 18V 440 ± 20Ω 350 ± 5Ω >2 GΩ $\leq \pm 0.5$%	
VALORI MECCANICI LIMITE RIFERITI ALLA TORSIONE NOMINALE : a) torsione di servizio b) torsione limite c) torsione di rottura d) torsione altamente dinamica	*LIMIT MECHANICAL VALUES REFERRED TO NOMINAL TORQUE :* *a) service torque* *b) max. permissible torque* *c) breaking torque* *d) highly dynamic torque*	 100% 150% >300% 70%	
TEMPERATURA DI RIFERIMENTO TEMPERATURA DI ESERCIZIO TEMPERATURA DI STOCCAGGIO	*REFERENCE TEMPERATURE* *WORKING TEMPERATURE RANGE* *STORAGE TEMPERATURE RANGE*	+23°C -10/+70°C -20/+80°C	
CLASSE DI PROTEZIONE (EN 60529) MATERIALE PARTE SENSORE CONNESSIONE ELETTRICA	*PROTECTION CLASS (EN 60529)* *SENSOR EXECUTION MATERIAL* *ELECTRICAL CONNECTION*	IP40 INOX 17-4 PH Cavo / *Cable* 5m	
ATTACCO DI PROCESSO (UNI ISO 1174-1): 0.5 - 2.5 – 5 - 10 Nm 25 - 50 Nm 100 – 250 Nm 500 – 1000 Nm	PROCESS COUPLING (UNI ISO 1174-1): 0.5 - 2.5 – 5 - 10 Nm 25 - 50 Nm 100 – 250 Nm 500 – 1000 Nm	 ■ 1/4" ■ 3/8" ■ 1/2" ■ 3/4"	

Figure 3.4 Static torsiometer technical data

c. 2 helix couplings (3 and 4) to provide coupling between the torsiometer and the housing.
d. 2 roller bearings (5) to limit friction.
e. One Oldham coupling (6) to provide the attach for the tested scissors.
f. 2 switches (7 and 8) to limit the movement of the torsiometer.

- Motor for roller unwinding

The role of this motor is to unwind the roller of material in an automatic way; the same operation can be performed unwinding the roller by hand, but doing this way is for sure more complicated and burdensome in terms of required time.
The motor used is the same presented in the previous chapter: it is the model $E192\ \frac{12}{24}\ 67$ by Micromotrs.

- System for signal conditioning

The conditioning system is given by a Scout 55 (Figure 3.5), which is a measuring amplifier able to detect measures coming from passive transducers. Scout 55 most relevant features are listed below:

a. the transducers that can be connected are: strain gauges half and full bridge, inductive half and full bridge, linear variable displacement transducers (LVDT), piezo resistive and potentiometric transducers.
b. Amplification and filtering system.
c. Analog to digital and digital to analog converters.

What mentioned above is briefly schematized in the block diagram of Figure 3.6.

Figure 3.5 Scout 55

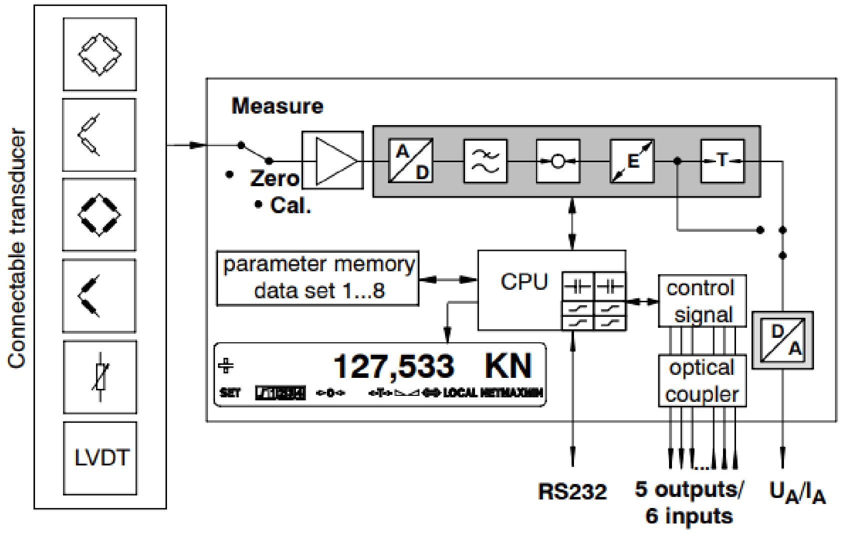


Figure 3.6 Scout 55 block diagram

In Figure 3.7 are represented the full specifications for Scout 55

Specifications

Type		SCOUT 55
Accuracy class		**0.1**
Mains connection / Supply voltage	V Hz	115/230, +6 %; −14 %; 48...60
Power consumption, max.	VA	8
Safety fuse (slow blowing)	mA	T 125 mA L (115 V) / T 63 mA L (230 V)
Amplifier		
Carrier frequency	Hz	4800 ± 0.32
Excitation voltage U_B (± 5 %)	V_{rms}	1 or 2.5
Transducers that can be connected		**U_B = 1 V_{rms}**
S.G. half and full bridge	Ω	40...5000
Inductive half and full bridge, LVDT's	mH	6...19
		U_B = 2.5 V_{rms}
		80...5000
		2.5...20
Permissible cable length between transducer and amplifier	m	max. 500
Measurement frequency range, adjustable (−1 dB)	Hz	0.05...500

Input level			**low**	**medium**	**high**
Measuring range	U_B=2.5 V	mV/V	0.2...4	2...40	20...400
	U_B=1 V	mV/V	0.5...10	5...100	50...1000
Bridge balance range	U_B=2.5 V	mV/V	± 4	± 40	± 400
	U_B=1 V	mV/V	± 10	± 100	± 1000
Noise voltage[1)]	0...200 Hz	µV/V_{PP}	0.5	1	10
	0...1.25 Hz	µV/V_{PP}	0.025	0.1	1
Effect of 10 K change in ambient temperature[1)]					
Autocalibration on / off					
Sensitivity		%	0.04 / 0.1	0.04 / 0.1	0.04/0.1
Zero point		µV/V	0.2/2	2/20	20/200

Measurement frequency range

Butterworth low-pass

Nom. val. fc (Hz)	-1 dB (Hz)	-3 dB (Hz)	Phase del. (ms)	Rise time (ms)	Overshoot (%)
1000	1010	1165	0.66	0.35	12
500	485	580	1.1	0.7	12
200	245	290	1.7	1.3	11
80	78	98	4.3	3.8	10
40	38	50	7.1	7.3	8
20	19	26	12	14	7
10	9.1	12.5	22	28	6
5	4.6	6.3	41	56	5

Bessel low pass

Nom. val. fc (Hz)	-1 dB (Hz)	-3 dB (Hz)	Phase del. (ms)	Rise time (ms)	Overshoot (%)
900	900	1550	0.49	0.28	4.1
400	400	750	0.8	0.6	2
200	215	395	1.3	1.0	2
100	111	190	2.5	2.1	2.5
40	39	68	5	5.5	1.1
20	21	37	8.1	10	1
10	11	19	14	19	0.7
5	5.3	9.7	25	38	0.3
2.5	2.7	4.9	48	75	0
1.25	1.4	2.4	90	150	0
0.5	0.7	1.2	180	300	0
0.2	0.17	0.3	700	1200	0
0.1	0.09	0.16	1400	2300	0
0.05	0.044	0.075	2900	4700	0

Max. permissible common-mode voltage	V	± 5 V
Common-mode rejection	dB	typically 110
Max. differential voltage DC	V	± 10
Linearity deviation	%	typically 0.05
Long-term drift over 48 hours, Meas. range 2 mV/V		Autocalibration on / off
30 minutes after switching on (warm-up time)	µV/V	<0.2 / <0.4

1) For U_B=2.5 V, relative to the input

Analogue output		
Applied voltage	V	± 10 V (asymmetric)
Permissible load resistance, min.	kΩ	5
Internal resistance, max.	Ω	1.5
Applied current	mA	± 20; 4...20
Permissible load resistance, max.	Ω	400
Internal resistance, min.	kΩ	100
The analogue output can show gross, net, positive and negative peaks and peak/peak values.		
Interference voltage at the output, typ.	mV_{PP}	4
Residual carrier voltage 38.4 kHz	mV_{PP}	3
Residual carrier voltage 4800 Hz	mV_{PP}	2
Long-term drift (over 48 h)		
(30 minutes after switching on)	mV	< 3
Effect of 10 K change in ambient temperature		
(additional effect to digital value)		
Zero point	mV	< 3
Sensitivity	%	< 0.05
Limit value switch		
Number		4
Reference level	V	Gross, Net, Peak value
Reference voltage (independently adjustable)	V	−10 ... +10
Factory settings, hysteresis	V	0.1
Adjustment accuracy	mV	0.33
Response time	ms	0.83 (all Butterworth filter frequencies and Bessel filters >1.25 Hz. The values double each time for the next lower measurement frequency)
Peak value stores		
Number		2
Function		positive; negative; peak-to-peak
Update rate	ms	0.03 (with Butterworth filter and Bessel filter ≥ 100 Hz)
Clearing the peak value store	ms	3.3 (control inputs)
Recording of the current value/peak value	ms	3.3 (control inputs)
Time constant for envelopes	ms	100 ... 60 000 (± 6 %)
Control outputs (limit value 1...4, Warning V_{CTRL})		5
Nominal voltage, external power supply	V	24
Permissible supply voltage range	V	11...30
Output current, max.	A	0.5
Short-circuit current, typ.	A	0.8
Short-circuit period		unlimited
Isolation voltage, without transients	V_{rms}	< 60
Control inputs		6
Input voltage range, LOW	V	0...5
Input voltage range, HIGH	V	10...24
Input current, typ., HIGH level = 24 V	mA	12

Figure 3.7 Scout 55 technical data

It is important to notice in the section of analogue output that the applied voltage assumes values between +10 V and -10 V. This value must be compared to the available input voltage of the control board to have a coherent measurement.

- Power supply

The power supply provides the necessary DC voltage to feed the control board and it is done using an Eutron bv170

- Computer

A personal computer is used to run the LabVIEW® based software for the data acquisition and the motion of the motor, and the Maxon software for additional, but not necessary, monitoring of the evaluation board.

- Data acquisition device (DAQ)

As acquisition and control board the Epos 2 evaluation board and the 36/2 controller produced by Maxon was selected.

In Figure 3.8 are specified the Electrical data for the control board Epos 2 module 36/2

Electrical Data

Rating	
Nominal power supply voltage V_{CC}	11…36 VDC
Nominal logic supply voltage V_C (optional)	11…36 VDC
Absolute minimum supply voltage	10 VDC
Absolute max. supply voltage	40 VDC
Max. output voltage	0.9 • V_{CC}
Max. output current I_{max} (<1sec)	4 A
Continuous output current I_{cont}	2 A
Switching frequency	50 kHz
Max. efficiency	93%
Sample rate PI – current controller	10 kHz
Sample rate PI – speed controller	1 kHz
Sample rate PID – positioning controller	1 kHz
Max. speed @ sinusoidal commutation (motors with 1 pole pair)	25 000 rpm
Max. speed @ block commutation (motors with 1 pole pair)	100 000 rpm
Built-in motor choke per phase	10 μH / 2 A

Table 3-4 Electrical Data – Rating

Inputs	
Hall sensor signals	Hall sensor 1, Hall sensor 2 and Hall sensor 3 for Hall effect sensor ICs (Schmitt trigger with open collector output)
Encoder signals	A, A\, B, B\, I, I\ (max. 5 MHz) internal line receiver EIA RS422 Standard
Digital Input 1 (“General Purpose”)	+3…+36 VDC (Ri = 12 kΩ)
Digital Input 2 (“General Purpose”)	+3…+36 VDC (Ri = 12 kΩ)
Digital Input 3 (“General Purpose”)	+3…+36 VDC (Ri = 12 kΩ)
Digital Input 4 (“General Purpose”)	+3…+36 VDC (Ri = 12 kΩ)
Digital Input 7 (“High Speed Command”)	internal line receiver EIA RS422 Standard
Digital Input 8 (“High Speed Command”)	internal line receiver EIA RS422 Standard
Analog Input 1	resolution 11-bit 0…+5 V (Ri = 34 kΩ)
Analog Input 2	resolution 11-bit 0…+5 V (Ri = 34 kΩ)
CAN ID (CAN identification)	ID 1…127 configurable by external wiring

Table 3-5 Electrical Data – Inputs

Outputs	
Digital Output 1 (“General Purpose”), open collector	max. 36 VDC (I_L <50 mA)
Digital Output 2 (“General Purpose”), open collector	max. 36 VDC (I_L <50 mA)
Digital Output 5 (“High Speed Command”), push-pull	max. 3.3 VDC (I_L <10 mA)

Table 3-6 Electrical Data – Outputs

Voltage Outputs	
Encoder supply voltage	+5 VDC (I_L <100 mA)
Hall sensors supply voltage	+5 VDC (I_L <30 mA)

Table 3-7 Electrical Data – Voltage Outputs

Motor Connections	
maxon EC motor	**maxon DC motor**
Motor winding 1	+ Motor
Motor winding 2	− Motor
Motor winding 3	

Table 3-8 Electrical Data – Motor Connections

Interfaces		
RS232	RxD; TxD	max. 115 200 bit/s
USB 2.0 / USB 3.0	external transceiver necessary	
CAN	CAN_H (high); CAN_L (low)	max.1 Mbit/s

Table 3-9 Electrical Data – Interfaces

Status Indicators	
Operation	green LED
Error	red LED

Table 3-10 Electrical Data – LEDs

Connections	
On board: Suitable plug: Suitable retainer:	Card edge connector PCI Express (PCIe) Connector 2x32 Pin vertical or horizontal, 1 mm pitch Tyco 2-1775801-1 (vertical) / Tyco 1761465-2 (horizontal) FCI 10018783-11111TLF (vertical) Meritec 983172-064-2MMF (horizontal) FCI PCI express retainer, blue, 10042618-002LF

Table 3-11 Electrical Data – Connections

Figure 3.8 Epos 2 Module 36/2 electrical specifications

As previously mentioned it is important to check the voltage limits for the input channels. Both the analog input channels 1 and 2 work with a voltage range between 0 V and 5 V; this means that in case negative values are read by the Scout 55 amplifier (voltage range ± 10 V), they are not correctly fed to the control board. It is necessary to set the zero of the Scout 55 to a positive value, so that even the values that would result negative are instead interpreted as positive and can be successfully fed to the control board.

3.1.3 Wiring of the devices

In Figure 3.9 a general picture of all the devices involved in the measuring system and their connections is shown. In the following wirings of all the components will be analyzed.

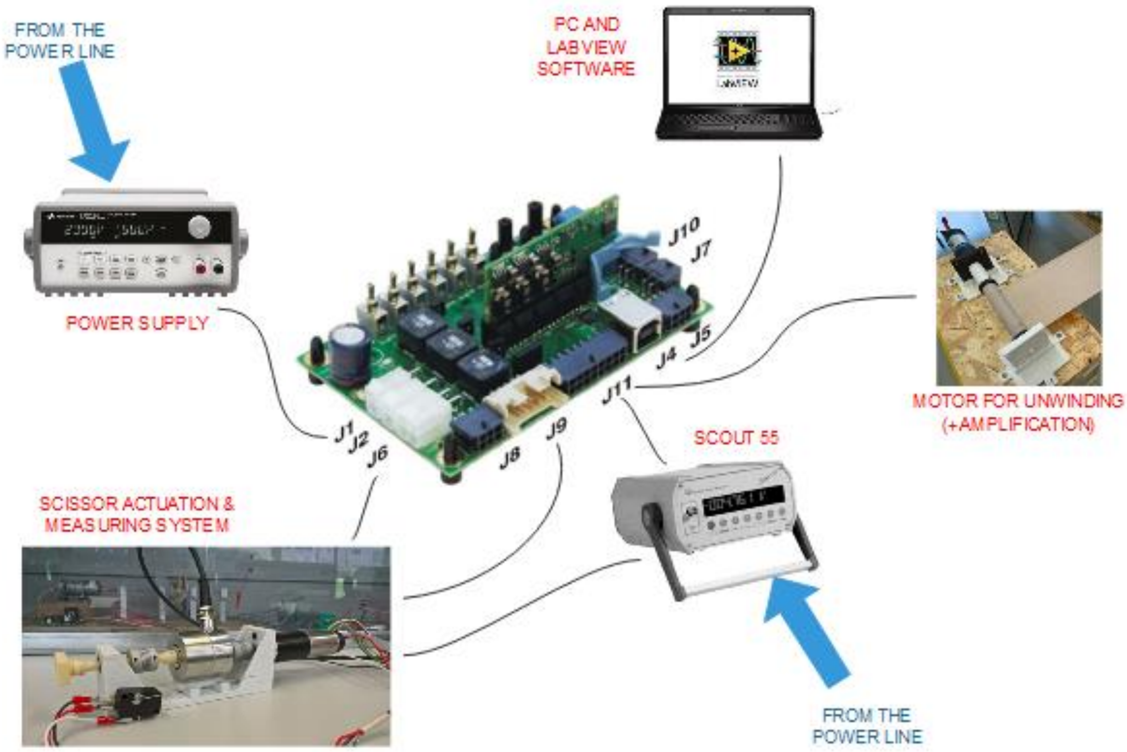


Figure 3.9 Scheme of connected devices

In the following are explained all the devices and connections introduced in Figure 3.9, to have an idea of all the connections involved in the system.

a. Control board

In Figure 3.10 the evaluation board Epos 2 36/2 with all its connectors and interfaces is shown, anyway not all the connectors are used for the test of the scissors.

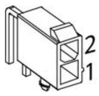
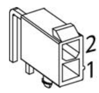
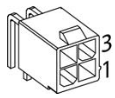
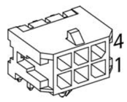
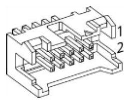
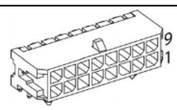
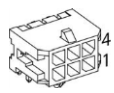
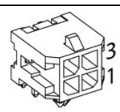
INTERFACE	NAME	IMAGINE
J1	Power connector	
J2	Logic supply connector	
J6	Motor connector	
J8	Hall sensor connector	
J9	Encoder conector	
J11	Input/Output connector	
J4	USB connector	
J5	RS232 connector	
J7, J10	CAN connector	

Figure 3.10 Epos 2 36/2 and connectors

b. Power supply

The power supply provides a DC voltage of 15.0 V directly to the control board Epos 36/2 by mean of the connector J1 (pay attention that a higher voltage would damage the control board). The power supply is fed by the power line of the laboratory.

c. Scout 55

Scout 55 is linked to the power line by mean of the ”mains connection” (Figure 3.11). The connection between the device and the static torsiometer is made through the “transducer connection” (Figure 3.11)

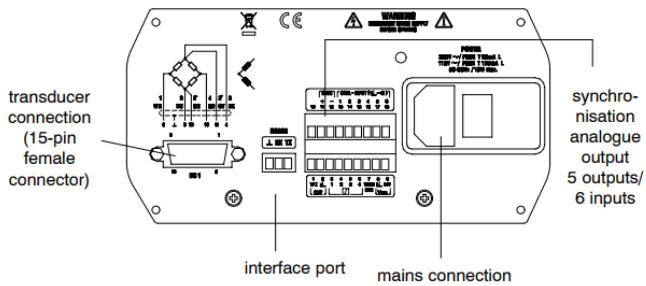


Figure 3.11 Back of Scout 55

The “transducer connection” offers a variety of trasducer to be attached to Scout 55 as depicted in Figure 3.12 (strain gauges half and full bridge, inductive half and full bridge, linear variable displacement transducers, piezo resistive and potentiometric transducers). For testing the scissors the strain gauge full bridge piezoresistive transducers are used.

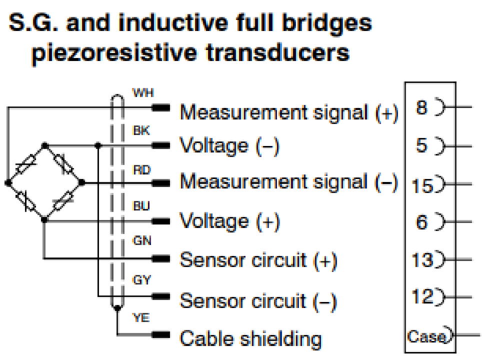


Figure 3.12 Connecting different type of transducers

The analog output signal is available as voltage (10 V). The analog output is sent from the front of the Scout 55 to pin J11 of the control board Epos 2 36/2 by mean of a BNC connector

d. Pc and Labview® software

The pc is connected to the control board using simply the USB interface J4. Control of the motor and data acquisition is performed using the National Instruments software LabVIEW®.

e. Scissor actuation and measuring system

The scissor actuation and measuring system is connected to the control board by mean of the interface J6 to connect the motor, the interface J11 to connect the static torsiometer and the connector J9 to connect the encoder.

f. Motor for roller unwinding

The motor for the unwinding operation is connected to an amplifier stage which is connected to the digital output connector J11 of the control board. The most logic solution would be connecting the motor directly to an analog output of the control board, but, since no analog output were available, this temporary solution was adopted. It is expected that when a new control board will be bought the solution adopted will be revisited and the amplification stage eliminated.

3.1.4 Torsiometer calibration

The procedure of calibrating the static torsiometer is necessary to obtain a relationship that links the output voltage (which is visualized and stored by the LabVIEW software and the Scout 55) and the effective physical torque applied on the torsiometer. It would be possible to obtain this multiplicative factor, expressed in [Nm/V], with calculations that involve all the chain of measurement and conditioning of the signal, but the fastest and most accurate way to get the sensitivity value is to perform an experiment.
A rod of about 100 mm length is linked to the torsiometer, a plate is hung at a distance of 93,05 mm from the fulcrum of the instrument. The plate can be loaded with masses ranging from five grams to one kilogram. The torsiometer is connected to the LabVIEW program which visualizes and stores the values of voltage in output from the torsiometer. In Figure 3.13 is depicted the test setup.

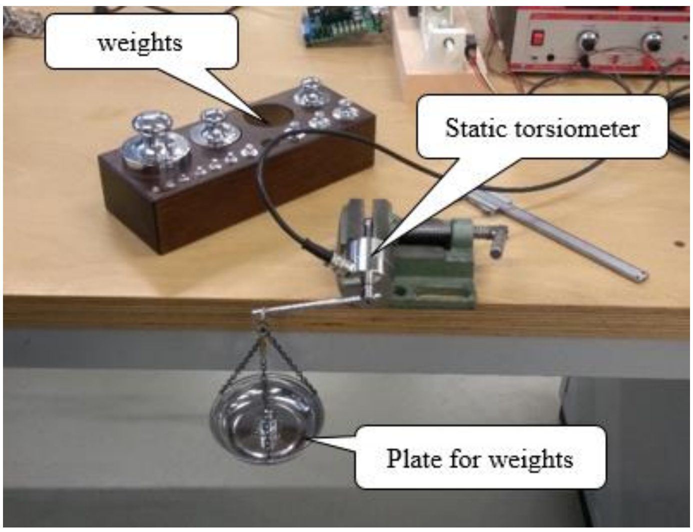


Figure 3.13 Apparatus for the calibration of the static torsiometer

The experiment is carried out loading additional weights on the plate up to a value of 650 g in order not to saturate the Scout 55 and to respect the torsiometer limitations on the maximum measured torque. The test is repeated a total of four times as it follows. The rod is connected to the torsiometer in order to generate a counter-clockwise rotation, then weights are added up to 650g and the values of the voltage generated are collected (test1). Once that the load of 650g is reached the procedure is repeated unloading the plate up to the reaching of 0g on the plate (test2). Finally, the two mentioned tests are repeated connecting the rod in order to generate a clockwise rotation (test3 and test4). To every value of voltage is associated the corresponding value of torque calculated by the multiplication of the weight force applied and the distance of 95,05 mm.
From the obtained results it is easy to notice the correspondence of values between the tests and the linear relationship that links the voltage and the torque applied on the torsiometer.

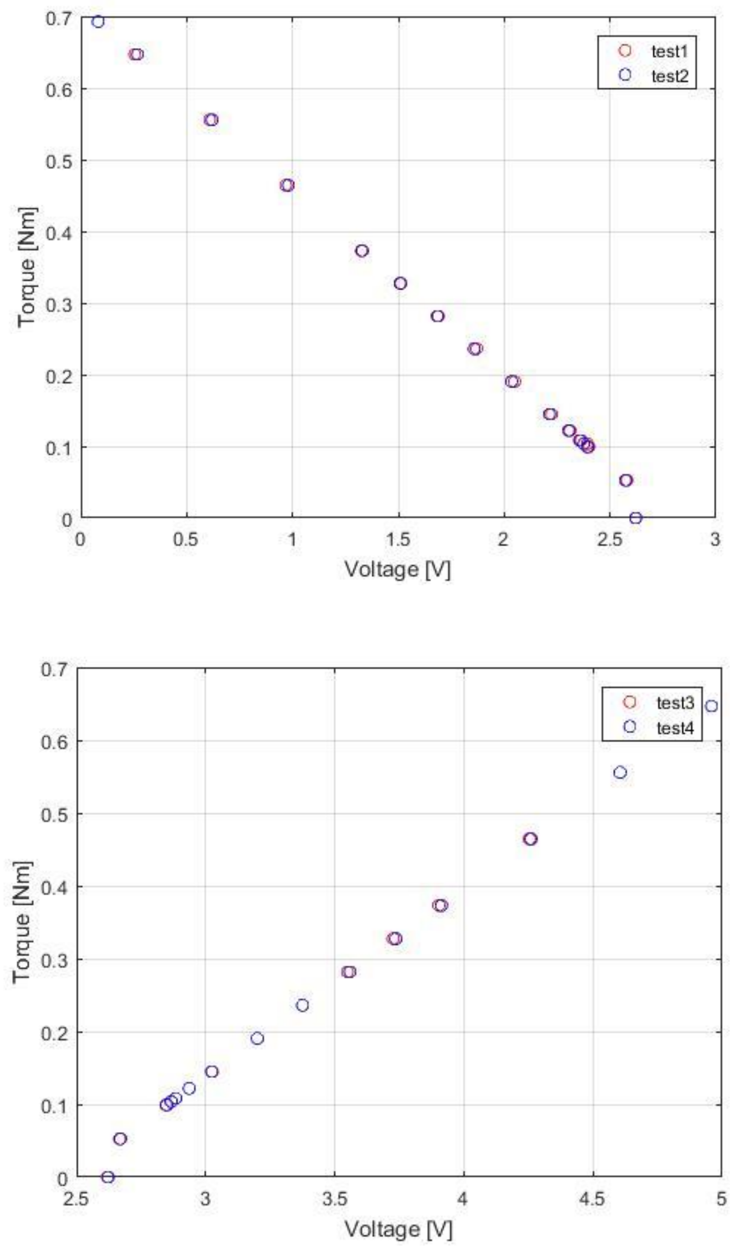


Figure 3.14 Linear relationship between torque and voltage

Simply using a linear regression for all the four tests performed is possible to evaluate the sensitivity of the torsiometer. The linear equation is given by: $y = ax + b$, where:

Table 3.1 Values of the linear regression

TEST	a	b
Test1	-0,2590	0,7160
Test2	-0,2611	0,7188
Test3	0,2640	-0,6578
Test4	0,2636	-0,6572

Since all the four tests provide results that are almost identical, the value of

$$\frac{0{,}2590+0{,}2611+0{,}2640+0{,}2636}{4} = 0{,}2620 \text{ [Nm/V]}$$

is considered as the multiplicative factor to obtain the torque from the voltage measurement.

3.2 Tests

In this section, all the tests carried out to analyze the behavior of the cutting torque as function of some parameters and working conditions are presented.
The tests are structured in the following way:

The first two analysis have the goal of testing the effectiveness of the mechanical system and of the control software analyzing the repeatability and reproducibility of the results of consecutive cuts:

1) Repeatability of consecutive cuts
2) Repeatability of consecutive cuts (with re-positioning)

In the following some test are provided to analyze the effects of some parameters which can affect the working conditions (and so the cutting torque):

3) Influence of pre-tensioning of the material
4) Velocity influence
5) Effect of a nick on the blade
6) Wear of the scissors (short duration test)
7) Wear of the scissors (long duration test, PREMAX scissors)
8) Wear of the scissors (long duration test, common scissors)
9) Influence of the cut material

3.2.1 Descriptors

To analyze the cutting torque three options are considered: to use the complete time history of the torque generated, to use exclusively the peak values (maxima) of the cutting torque or to use the torque RMS value. The first alternative could be burdensome in terms of computational power the second one could generate errors since the maximum value of the torque is a punctual parameter and it can be affected by localized noise. Therefore, the best alternative is to use the RMS value, which can describe the entire time history with the use of one single parameter. The RMS value is mathematically defined in the case of discrete systems as:

$$RMS = \sqrt{\frac{1}{N}\sum_{i=1}^{N} {x_i}^2}$$

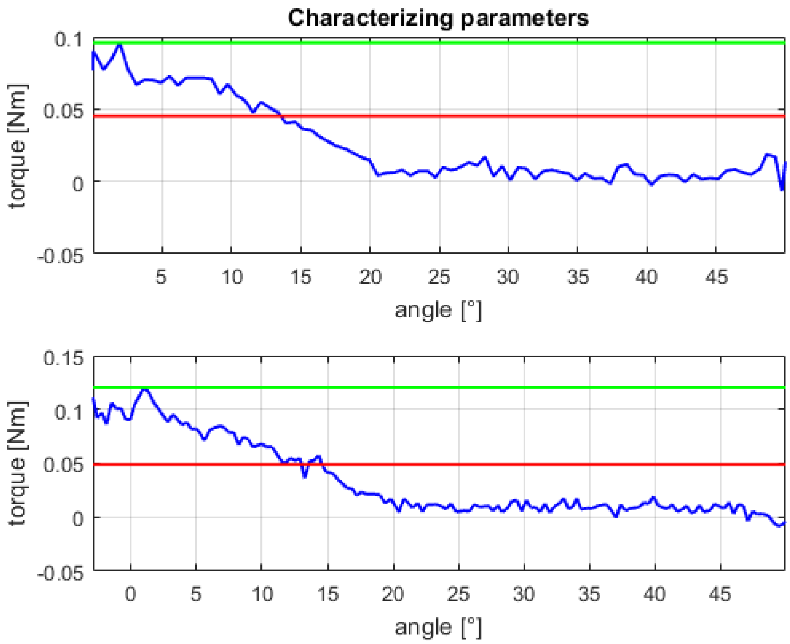


Figure 3.15 Definition of RMS value and maximum value

In the Figure 3.15 the full-time history of a cut (blue line) is displayed with the relative maximum value (green line) and the RMS value (red line).

3.2.2 Repeatability of consecutive cuts

The aim of the test is to perform consecutive cuts with the same pair of scissors and monitoring the evolution of the RMS value. It is expected that for a low number of cuts the RMS value of the torque should exhibit negligible variations and thus the cuts can be considered as nominally equivalent. The tests are performed using two different options to unwind the material subjected to the cut: unwinding using an electric motor and unwinding by hand. Two different tests have been performed.

The first test is characterized by:

- Not completely new scissors (few cuts performed before the test).
- Unwinding operation performed firstly using the electric motor and then by hand.
- 25 cuts performed for each test (number near enough to the statistical meaning for the identification of mean and standard deviation parameters, since it is a random disturbance is reasonably a Gaussian noise).
- Tension applied to the material of 1.96 N.
- Trapezoidal (symmetric) law of motion for scissors opening/closure (ϑ=50°, v=60 rpm, a=164 rpm/s, d=-164 rpm/s).

The second test is equal to the previous one, except for the fact that unwinding by hand and motor are switched in this case; the test is characterized by:

- Completely new scissors (few cuts performed before the test).
- Unwinding operation performed firstly by hand and then using the electric motor.
- 25 cuts performed for each test (identification of mean and standard deviation parameters).
- Tension applied to the material of 1.96 N.
- Trapezoidal (symmetric) law of motion for scissors opening/closure (ϑ=50°, v=60 rpm, a=164 rpm/s, d=-164 rpm/s).

3.2.3 Repeatability of consecutive cuts (with re-positioning)

The aim of this test is to understand if the operation of re-positioning the target material and the weights hung to the free-falling edge of the strip of material (to provide the tensioning to the material) could disturb the value of the maximum cutting torque. Once that the roller of cloth is unwind and several cutting operations are performed, the hung weights get closer and closer to the ground. To avoid contact between the weights and the floor, the cutting operation is stopped and the weight is re-positioned further up on the material. When the re-positioning is performed, the test resumes from where it was stopped. To quantify the effects of the re-positioning two tests are performed.

The first test is characterized by:

- Not completely new scissors (few cuts performed before the test).
- Tension applied to the material of 1.96 N.
- Trapezoidal (symmetric) law of motion for scissors opening/closure (ϑ=50°, v=60 rpm, a=164 rpm/s, d=-164 rpm/s).

Firstly 25 consecutive cuts are performed and 25 values of T_{rms} are computed; each of these value is compared to the next one to depict only the variation of the cutting power required to perform the cut.
Then 25 cuts with re-positioning are performed and the relative 25 values of T_{rms} are computed.
For both cases mean and standard deviations are analyzed.

A second similar test is performed to verify the consistency of the results. If the trend is closer to the previous case, since the number of cuts considered is statistically relevant, the test will be considered significative.
The second test is characterized by:

- Not completely new scissors (few cuts performed before the test).
- Tension applied to the material of 1.96 N.
- Trapezoidal (symmetric) law of motion for scissors opening/closure (ϑ=50°, v=60 rpm, a=164 rpm/s, d=-164 rpm/s).

Firstly 25 cuts are performed (and 25 values of T_{rms} are detected) with re-positioning; each value of the cutting torque is compared to the next one so to depict the variation of the maximum cutting torque for the entire time history.
Then 25 cuts are performed (and 25 values of T_{rms} are detected) with no kind of re-positioning; each value of the cutting torque is compared to the next one so to depict the variation of the maximum cutting torque for the entire time history.
For both the situations means and standard deviations are analyzed.

3.2.4 Influence of pre-tensioning of the material

This series of tests is dedicated at investigating if the tension applied to the material before the cutting operation could generate significative changes on the RMS value of the torque. In the following Figure 3.16 the setup used to perform the experiments is shown.

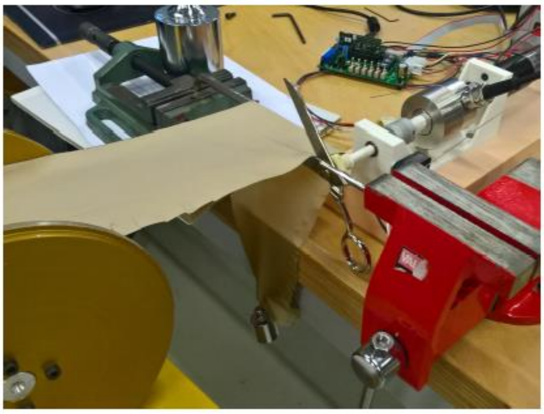


Figure 3.16 Set up to vary the pre-tensioning

The tension on the strip of material is generated hanging to the free-falling end of the strip of cloth a measured weight (with one or more masses). The value of the weight varies from 50 g to 500 g in all the test and 1000 g in the last one. This test is performed under the assumption that, for a low number of tests, the dulling of the blade has negligible influence on the cutting capability. Two different tests are performed.

The first test characteristics are:

- Completely new scissors (f13).
- 1 single acquisition containing all the different values of the tension applied to the material.
- Trapezoidal (symmetric) motion law for scissors opening/closure operation (ϑ=50°, a=164 rpm/s, d=-164 rpm/s).
- Random order of the tensions applied to the material.
- 10 cuts for each value of the pre-load (identification of mean and standard deviation parameters).

The characteristics of the second test are:

- Partially used scissors (f14).
- 1 single acquisition containing all the different values of the tension applied to the material.
- Trapezoidal (symmetric) law of motion for scissors opening/closure (ϑ=50°, a=164 rpm/s, d=-164 rpm/s).
- Random order of the tensions applied to the material.
- 5 cuts for each value of the pre-load (identification of mean and standard deviation parameters).

A third test is performed (using a new pair os scissors f19) with a pre-load up to 1kg in order to verify if a treshold value exists over which the influence of the pre-load becomes significative.

3.2.5 Velocity influence

The aim of these tests is to analyze if the cutting velocity affects in some way the RMS value of the torque. Two different tests have been performed also for these experiments.

The first test characteristics are:

- Completely new scissors.
- No re-positioning actions performed.
- Trapezoidal (symmetric) law of motion for scissors opening/closure (ϑ=50°, a=164 rpm/s, d=-164 rpm/s).
- Tension applied to the material of 1.96 N.
- One single acquisition containing all the velocity ranges.
- Random order of the different velocities.
- 4 cuts performed for each value of the velocity (identification of mean and standard deviation parameters).

The second test is characterized by:

- Partially used scissors.
- Before each changing of the velocity parameter, a re-positioning action is performed.
- Trapezoidal (symmetric) law of motion for scissors opening/closure (ϑ=50°, a=164 rpm/s, d=-164 rpm/s).
- Tension applied to the material of 1.96 N.
- One single acquisition containing all the velocity ranges.
- Random order of the velocities.
- 4 cuts performed for each value of the velocity (identification of mean and standard deviation parameters).

3.2.6 Effect of a nick on the blade

The aim of this test is to verify if a damage or a nick on the blade of the scissors could influence the cutting torque.
The test showed that when the blade of the scissors is nicked (even if the damage is hardly visible as showed in the following Figure 3.17)

Figure 3.17 Nick on the blade

3.2.7 Wear of the scissors (short duration test, PREMAX scissors)

The aim of this test is to analyze the duration of scissors and if they can maintain their cutting capability after having performed several cutting cycles. For this test 3000 cuts on the target material are performed, for a total test time of more than 3 hours.

The test characteristics are:

- Completely new PREMAX scissors.
- Tension applied to the material of 1.96 N.
- Trapezoidal (symmetric) law of motion for scissors opening/closure (ϑ=50°, v=60 rpm, a=164 rpm/s, d=-164 rpm/s).
- 3000 cutting cycle analyzed.

The idea is to verify if after 3000 cycles the scissors exhibit symptoms of wear or damages (on the blades or on their fulcrum) computing the RMS value of the torque applied.

3.2.8 Wear of the scissors (long duration test, PREMAX scissors)

As previously mentioned the idea of this test is to analyze if largely increasing the number of cycles makes the blades exhibit relevant wearing phenomena. For this reason, the number of cycles will be raised from 3000 to 30000. The procedure is to perform 10 cuts on the cloth and analyze the RMS value (mean value and standard deviation), then perform 2000 opening/closure movements with no cut on the material (and no analysis of the RMS value) and repeat the procedure for 15 times.

The other test parameters remain the same as in the previous test:

- Completely new scissors (scissors by PREMAX f24).
- Tension applied to the material of 1.96 N.
- Trapezoidal (symmetric) law of motion for scissors opening/closure (ϑ=50°, v=60 rpm, a=164 rpm/s, d=-164 rpm/s).
- 30000 opening/closure operations analyzed.

3.2.9 Wear of the scissors (long duration test, common scissors)

The idea of this section is to repeat the same type of test of the previous section but using a commercial pair of scissor. The test procedure is the same as the previous one: 10 cuts are performed on the cloth and the RMS value is analyze (the mean value and standard deviation), then perform 2000 blank cuts are performed (no analysis of the RMS value) and the procedure is repeated for 14 times.

The test characteristics remains the same of the previous test:

- Completely new scissors (common scissors bough at supermarket/stationery).
- Tension applied to the material of 1.96 N.
- Trapezoidal (symmetric) law of motion for scissors opening/closure (ϑ=50°, v=60 rpm, a=164 rpm/s, d=-164 rpm/s).
- 28000 opening/closure operations analyzed.

3.2.10 Influence of the cut material

With this test the influence of the material to be cut on the torque is analyzed. To carry out the test it was decided to use sheets of paper with different weights (ranging from 80 g to 300 g). Two different type of scissors were tested, one partially used scissor by PREMAX and one completely new scissor (not manufuactured by PREMAX)

The first test characteristics are:

- Partially used scissors (PREMAX scissors).
- No tension applied to the material.
- Trapezoidal (symmetric) law of motion for scissors opening/closure (ϑ=40°, v=60 rpm, a=164 rpm/s, d=-164 rpm/s).
- 6 different weight of paper were used: 80g, 100g, 120g, 160g, 200g and 300g.
- 10 cuts performed on each sheet of paper plus 10 unladen cuts.
- Radom order of the cut paper sheets.

The second test characteristics are the same of the previous one except for the type of scissors:

- Partially used scissors (common scissors bough at supermarket/stationery).
- No tension applied to the material.
- Trapezoidal (symmetric) law of motion for scissors opening/closure (ϑ=40°, v=60 rpm, a=164 rpm/s, d=-164 rpm/s).
- 6 different weight of paper were used: 80g, 100g, 120g, 160g, 200g and 300g.
- 10 cuts performed on each sheet of paper plus 10 unladen cuts.
- Radom order of the cut paper sheets.

3.3 Results

This section presentes all the results obtained from the tests described in the previous section. The analysis on the test results will be developed using the MATLAB® algorithms developed by Davide Magnani.

3.3.1 Repeatability of consecutive cuts

Considering the first test presented:
the following two figures show the RMS value of each cutting operation. The first one (Figure 3.18) refers to the test performed with hand-unwinding, the second one (Figure 3.19) with the unwinding using an electric motor.

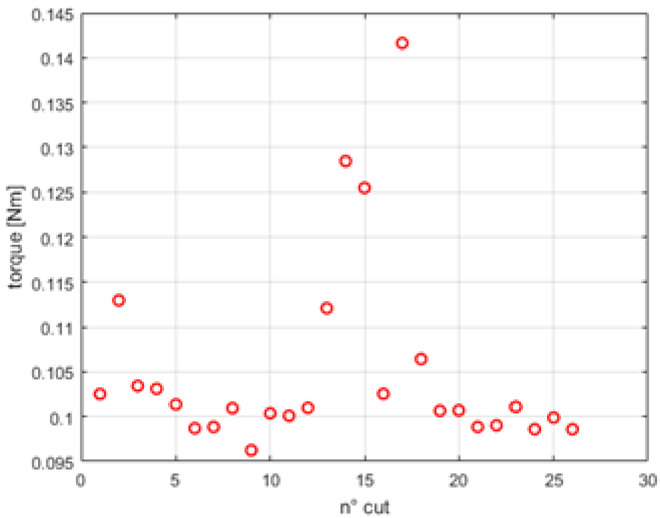


Figure 3.18 Repeatability of consecutive cuts 1: torque RMS, hand unwinding

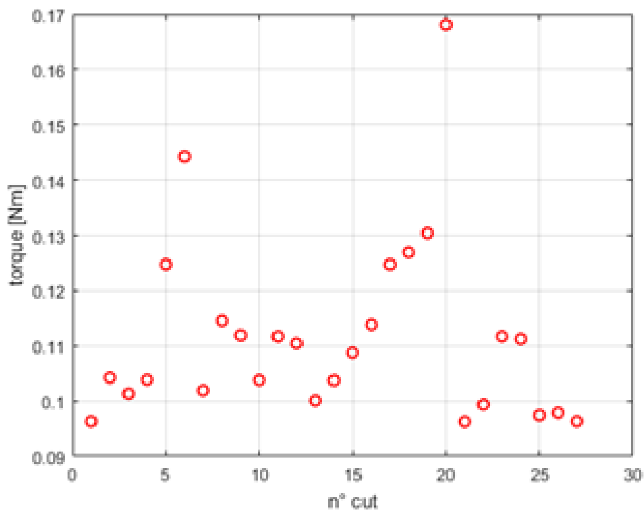


Figure 3.19 Repeatability of consecutive cuts 1: torque RMS, motor unwinding

The previous results can be collected in the following Figure 3.20, which show that the mean values are almost the same for the two unwinding alternatives (variations in the range 0,1-0,11 Nm), moreover the two standard deviations are low and not relevant.

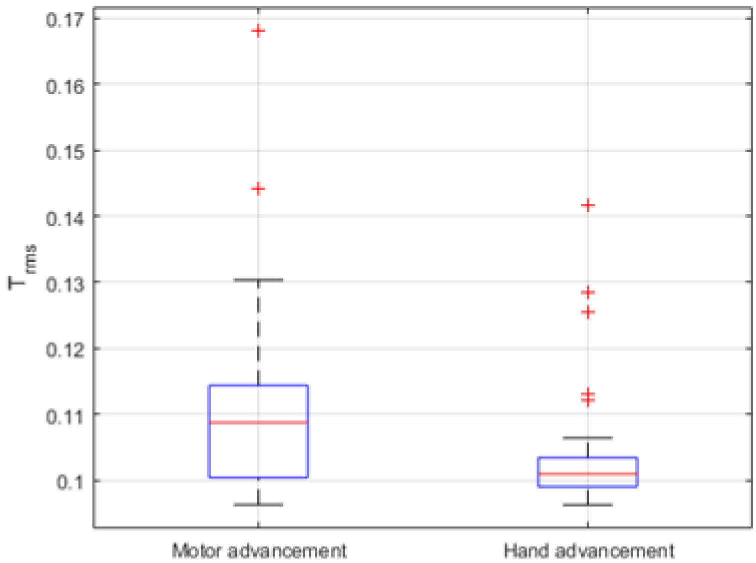


Figure 3.20 Repeatability of consecutive cuts 1: torque RMS comparisons

Considering the second test presented:
Even in this case Figure 3.21 and Figure 3.22 depict the RMS values of the torque considering the two types of unwinding.

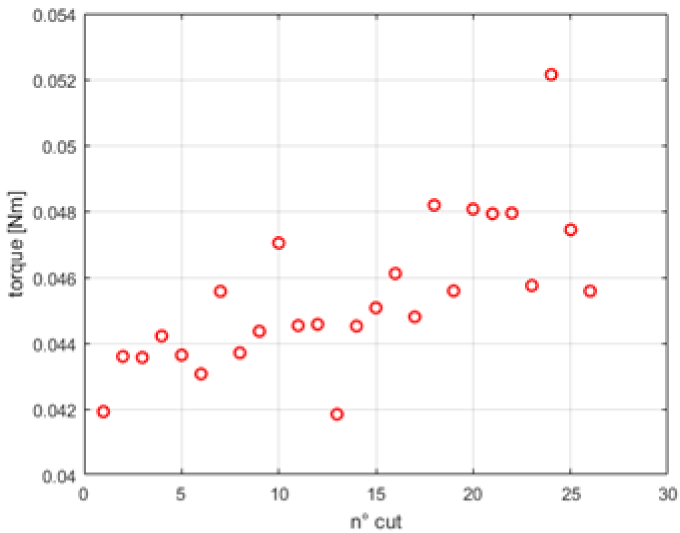


Figure 3.21 Repeatability of consecutive cuts 2: torque RMS, hand unwinding

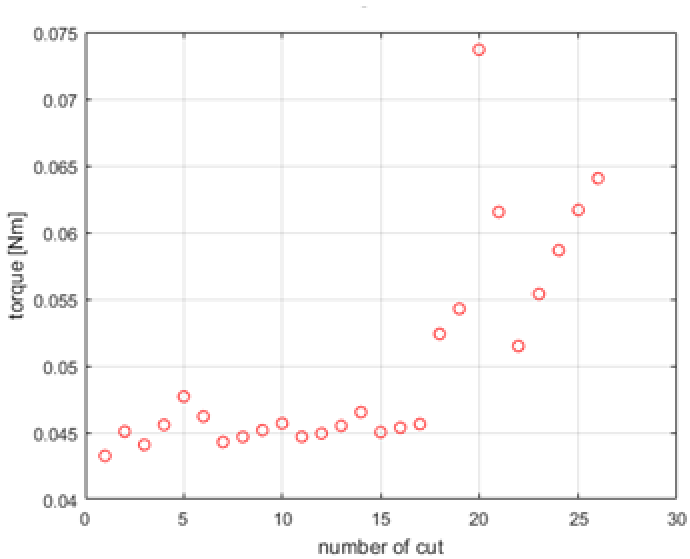


Figure 3.22 Repeatability of consecutive cuts 2: torque RMS, motor unwinding

The results obtained show that, even in this case, the mean values are almost the same for the two unwinding alternatives (about 0,045 Nm) and, again, the two standard deviations are low (Figure 3.23).

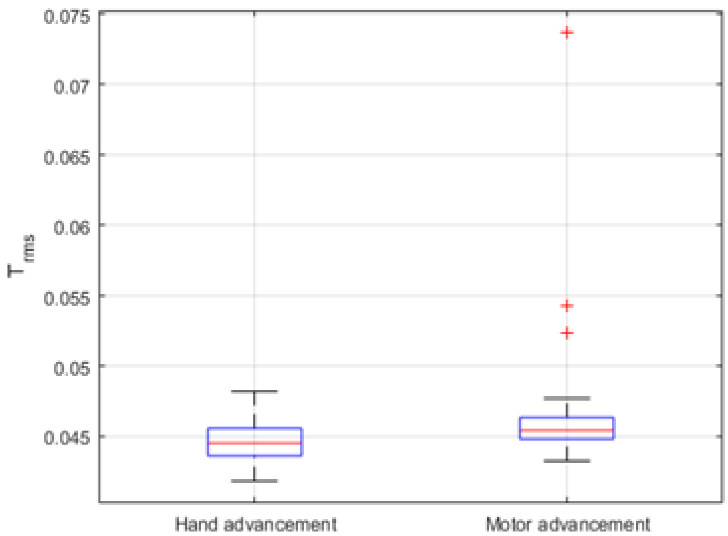


Figure 3.23 Repeatability of consecutive cuts 2: torque RMS comparisons

3.3.2 Repeatability of consecutive cuts (with re-positioning)

The results for the two different tests are shown in the following Figure 3.24 and Figure 3.25

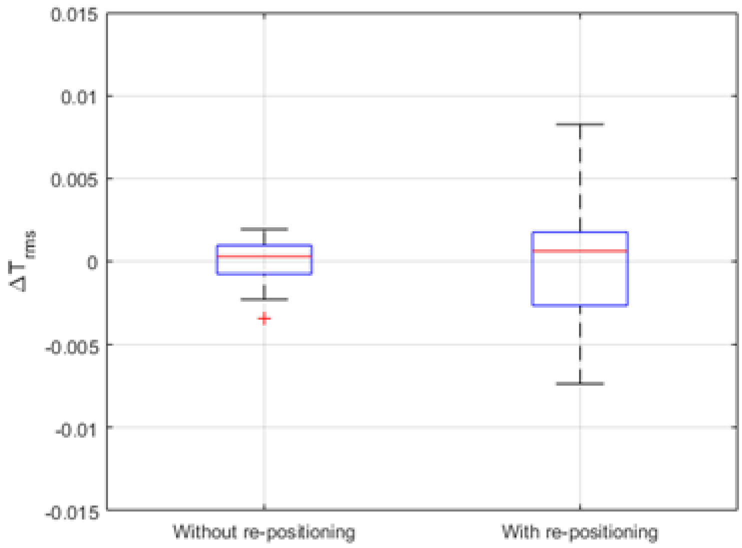


Figure 3.24 Repeatability of consecutive cuts (re-positioning) 1: torque RMS comparison

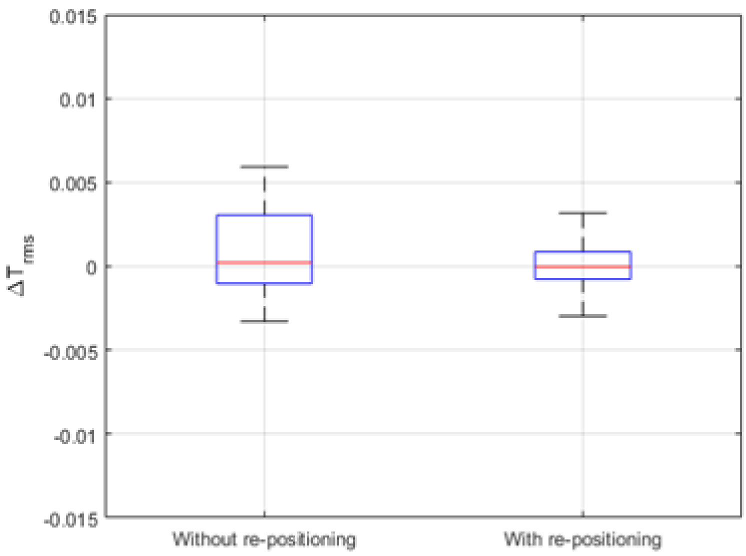


Figure 3.25 Repeatability of consecutive cuts (re-positioning) 2: torque RMS comparison

It is possible to see that the mean value of both tests is almost identical (its value is about 0 Nm meaning that there's no sisgnificative variation of the torque between consecutive cuts) considering or not the re-positioning actions. The standard deviation slightly increases, as expected, the re- positioning could generate disturbances on the system (for example during re-positioning the orientation of the strip of material, the bending of material, distribution of tension on the material can change).

3.3.3 Influence of pre-tensioning of the material

The results for the two test are shown in the following Figure 3.26 and Figure 3.27. The RMS value of the torque is plotted as fucntion of the pre-load applied and of the number of the test.

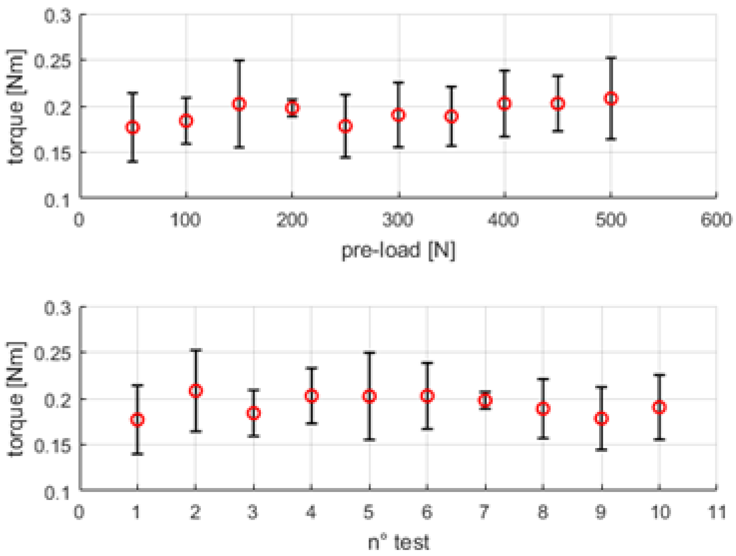


Figure 3.26 Influence of pre-tensioning 1: torque RMS

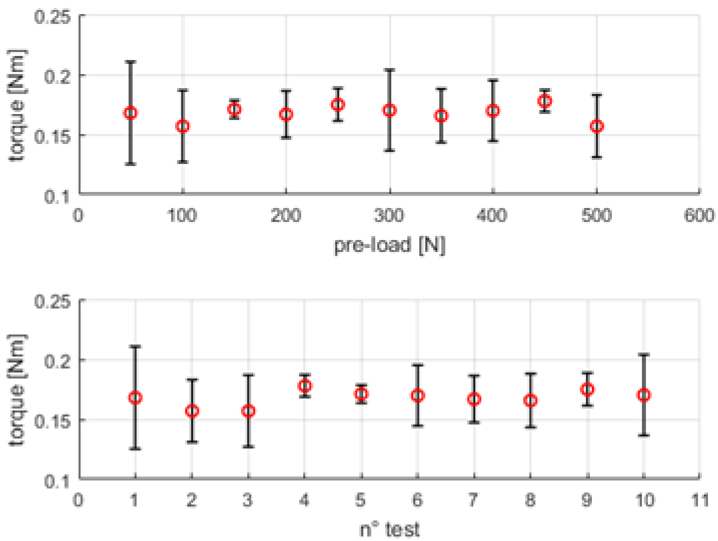


Figure 3.27 Influence of pre-tensioning 2: torque RMS

It is important to notice that both the test ended up with the same conclusion: the cutting torque (power) is not significantely influenced by the tension appllied to the material, in fact no particular trend can be observed on the torque diagrams as function of the pre-load.

Considering the previous figures and analyzing the torque diagrams as function of the

number of test, it can be observed that the values of the mean value do not exhibit significative variations, meaning that, at least for a low number of cuts, the blades of the scissors do not undergo an appreciable wearing phenomena.
In the following Figure 3.28 are shown the results obtained from the third test; even in this case the results lead to the same conclusion of the previous tests.

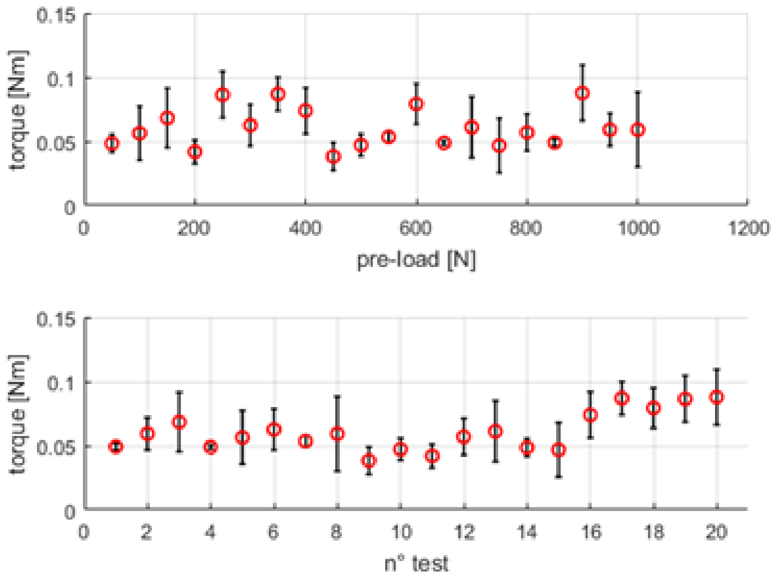


Figure 3.28 Influence of pre-tensioning 3: torque RMS

3.3.4 Velocity influence

The tests showed that the RMS value is not depending on the maximum cutting velocity (Figure 3.29).

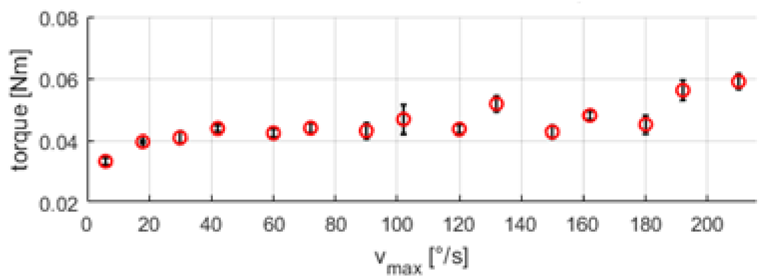


Figure 3.29 Velocity influence: torque RMS

Even the second kind of test was shown that the RMS value is not function of the maximum cutting velocity (Figure 3.30).

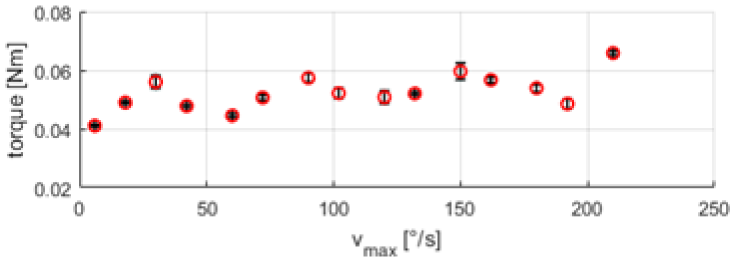


Figure 3.30 Velocity influence 2: torque RMS

3.3.5 Effect of a nick on the blade

By the resulsts of the test a peak in the torque value between one cut and the subsequent one can be detected. The peak occurs for a value of the closing angle equal to the value of the angle at which the nick is located (Figure 3.31).

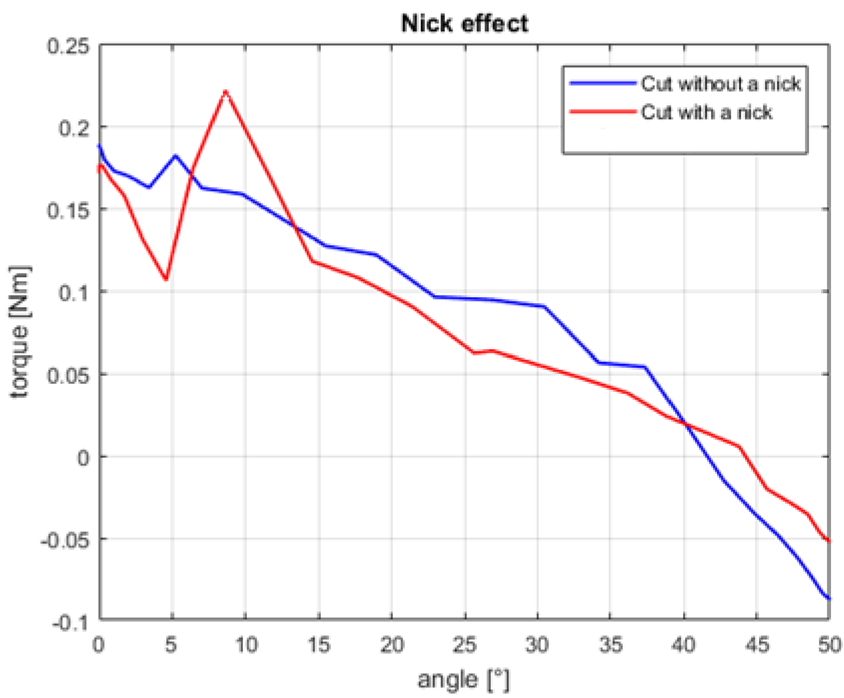


Figure 3.31 Effect of a nick on the cutting torque

This kind of result confirms the results already obtained in the case of knives.

3.3.6 Wear of the scissors (short duration test, PREMAX scissors)

As it can be observed in the following Figure 3.32 the variation of the RMS for 3000 cycles is of the order of 0,03 Nm which can be considered a value acceptable and satisfying to assert that not relevant wearing phenomena generate on the blade of the scissors.

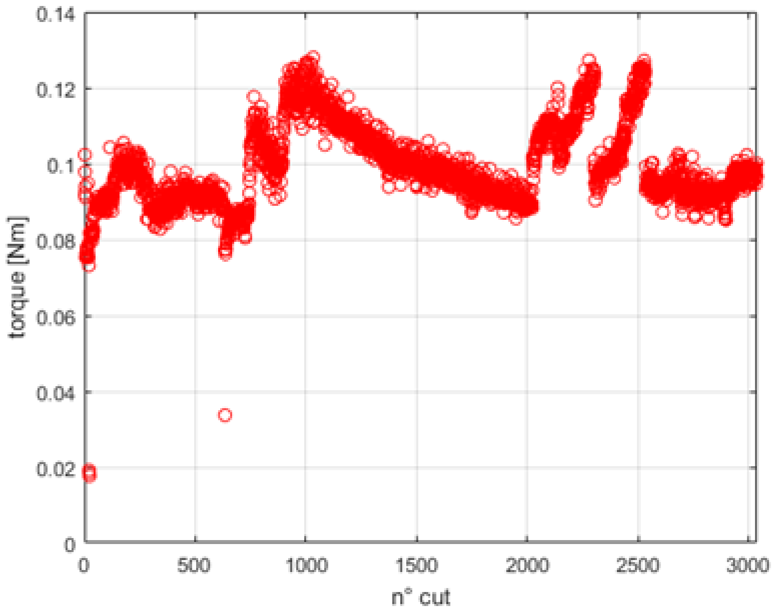


Figure 3.32 Wear of the scissors (short duration test): torque RMS

The tested scissors can be considered as new even after they have performed 3000 cut cycles. The next step is to greatly increase the number of cycles by doing many blank closures alternated with groups of cuts on cloth that are used as control parameter.
The values in the bottom-left zone of the graph greatly differs from all the other values, because of a malfuntioning of the masurement system and so they can be discarded.

3.3.7 Wear of the scissors (long duration test, PREMAX scissors)

The results obtained, shown in the following Figure 3.33, clearly exhibit (excluding the first measurement which can be discarded considering that the cutting system has to reach a steady-state condition) a decreasing trend of the cutting torque as the number of cycles increases.

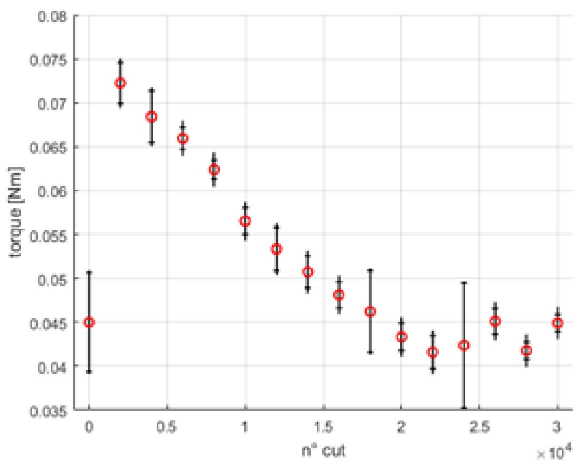


Figure 3.33 Wear of the scissors (long duration test, PREMAX scissors): torque RMS

From the obtained results is possible to assert that:

- the 3000 cycles of the previous test, were largely insufficient to detect possible wearing phenomena of the blades, which can withstand much more cuts without losing their cutting capability.
- A decrease of about 0,04 Nm is clearly visible after 25000 cycles of work. The reason of such behavior could be a gradual loosening of the pivot-bolt of the scissors or the effective wearing and damage of the blade which are no more able to impress the torque they impressed when were new

Even analyzing the values of the maximum torque (Figure 3.34), a decreasing trend of the cutting torque can be observed.

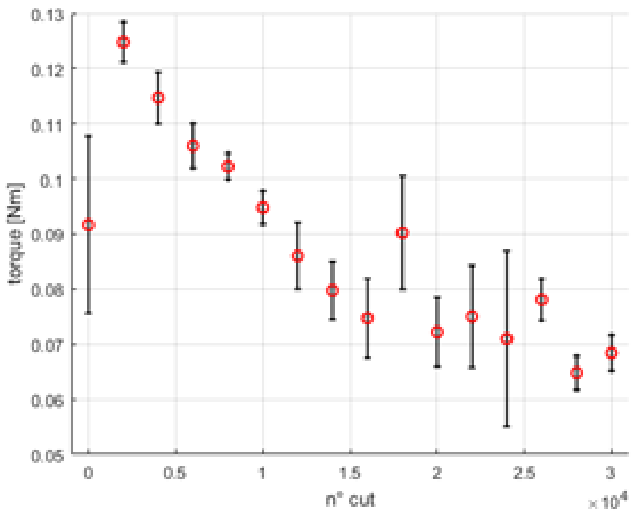


Figure 3.34 Wear of the scissors (long duration test, PREMAX scissors): maximum torque

To prove what mentioned previously, while performing the wear test, it was observed the angular variation of the pivot bolt of the scissors from the initial condition of the test, after that 22000 cuts were performed and once that the test was finished (Table 3.2).

Table 3.2 Angular values of the pivot bolt

Parameter	Symbol	Value
Screw angle before the test	α_{before}	22.6°
Screw angle after 22000 blank cuts	α_{22000}	23.8°
Screw angle after the test	α_{after}	23.5°

The observation of the angular variation of the pivot bolt effectively confirms a little variation of the screw angle.

3.3.8 Wear of the scissors (long duration test, common scissors)

The results obtained are shown in Figure 3.35.

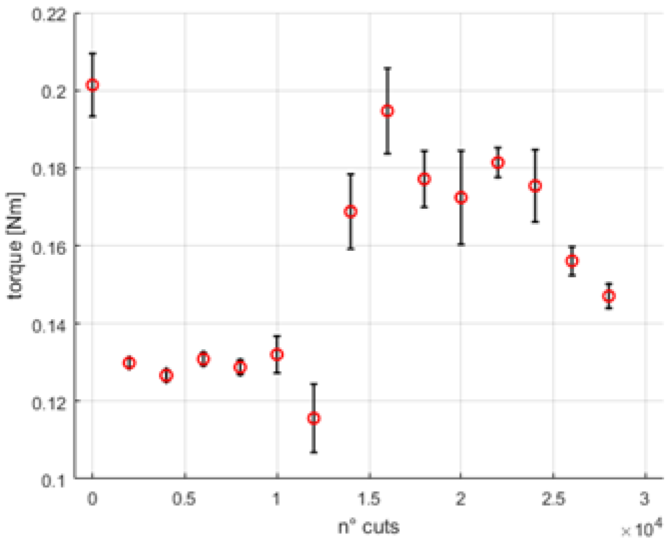


Figure 3.35 Wear of the scissors (long duration test, common scissors): maximum torque

Even in this case it is possible to discard the first series of data since the system is supposed to reach its steady-state condition. A sudden decrease of the cutting torque in 7th series of data can be seen. This is due to a crash on the pc and control software. For this reason, the mentioned series of data is discarded.
From the previous figure it is possible to observe an increasing trend of the cutting torque for all the cycles except for the last two. The increasing trend (of about 0,06 Nm in 25000 cycles) can be justified by a wear problem of the scissors with the subsequent probability of a hard closure and blocking (this kind of problem was already introduced in the first chapter of the thesis).

In conclusion, from the obtained results is possible to assert that:

- A decrease of 0,03 Nm (average value) is clearly detected after almost 25000 cycles of work. The reason of such behavior could be given by the aging process of the scissors. Such kind of situation could lead to the hard closure and blocking of the scissors, a kind of problem which is as important as its opposite of loosening of the bolt, in fact both generate a malfunctioning of the scissors.

3.3.9 Influence of the cut material

The results obtained from the two tests are shown on the following Figure 3.36 and Figure 3.37 (considering the maximum cutting torque).

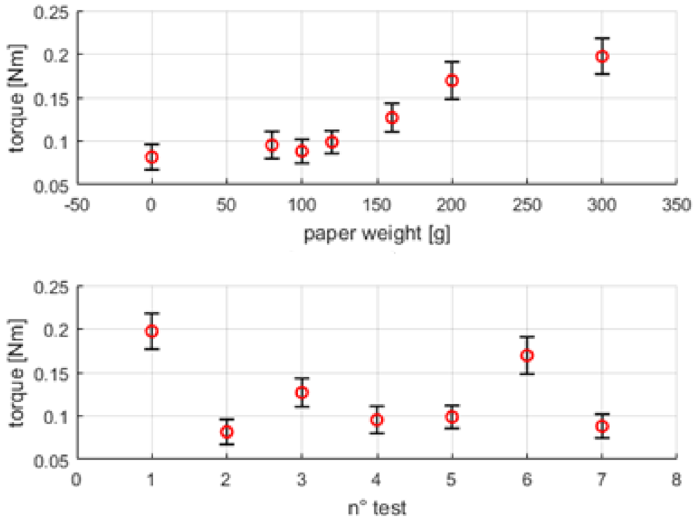


Figure 3.36 Influence of the cut material 1: maximum torque

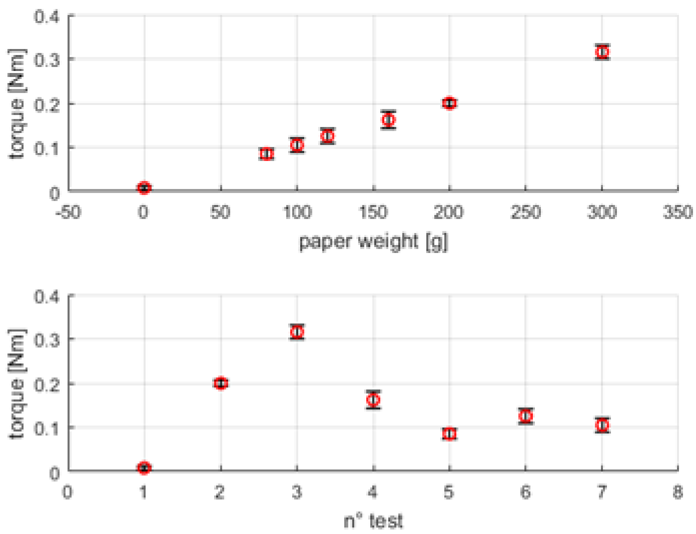


Figure 3.37 Influence of the cut material 2: maximum torque

From the results is possible to observe that an increasing trend is detected increasing the weight of the cut paper. Is possible to draw the same conclusion analyzing the RMS value of the torque (Figure 3.38 and Figure 3.39).

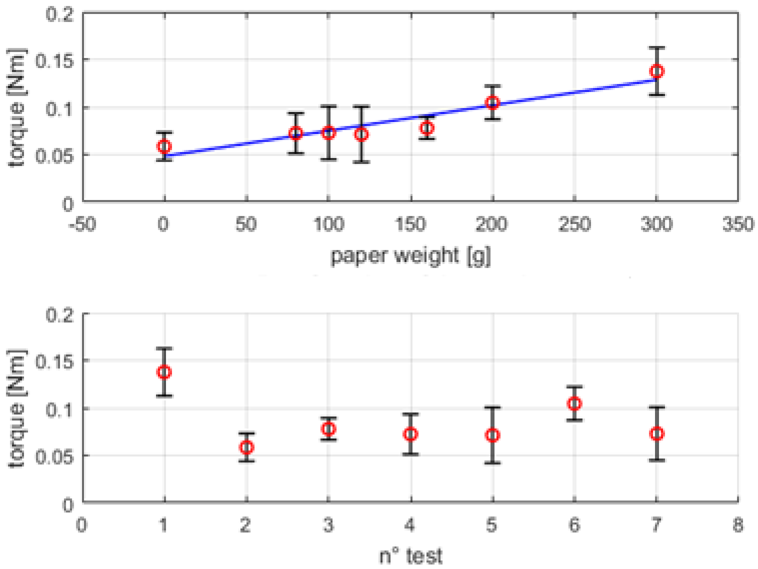


Figure 3.38 Influence of the cut material 1: RMS torque

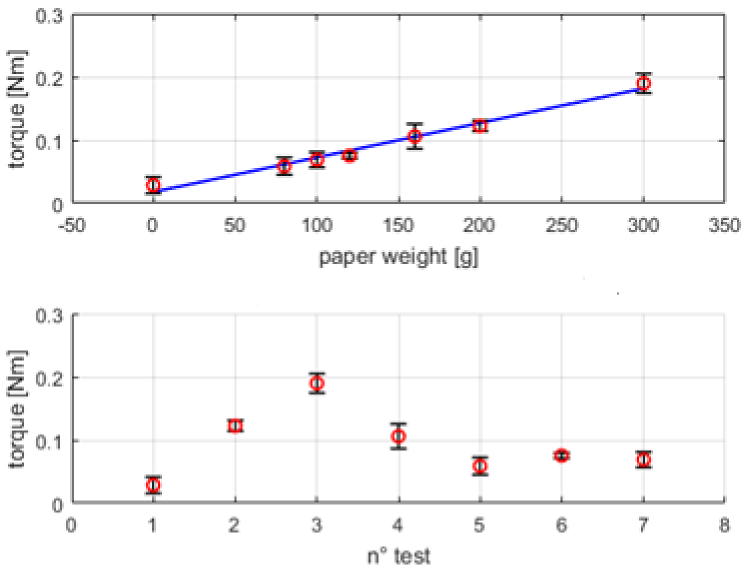


Figure 3.39 Influence of the cut material 2: RMS torque

In this case it is possible to observe that the increase of the torque is linear respect the increase of the paper weight (blue line in the graphs).

4 Discussion and Conclusions

The design of the machine proposed in the thesis fully satisfies the functional requirements identified by PREMAX. One of the most challenging requirements was the necessity of testing different types of scissors, with large differences in geometry and dimensions. Thanks to the regulation system proposed in this work, all the scissors provided by PREMAX can be mounted on the machine and can be tested. All the functional groups (winding and unwinding motors, system for material tensioning, holding system for scissors, motor for opening and closure of the scissors) were seen as individual elements which can be placed on the housing of the machine. An important feature of the proposed design for the machine is the simplicity of realization, since all the described parts can be easily manufactured using standard bars and profiles. This design choice also reflects on the global cost of the machine keeping it in an affordable range (the global cost for the realization of the full-operative machine is supposed not to overcome 3000 €).

The experimental campaign highlighted some interesting results which can easily be dropped into the design context. The tests on the repeatability of the cuts showed that the simple test bench was correctly working; for this reason, is expected that the realization of the test bench with metallic parts instead of the 3D printed ones could lead to more repeatable results. The tests on the influence of pre-tensioning of the material showed a very important result, leading to the conclusion that the tension applied to the material to be cut does not influence the cutting torque. Consequently, it is possible to re-evaluate the role of the winding motor controlled in torque; in fact, the presence of a torque control implemented on this motor may no longer be necessary, greatly simplifying the overall machine complexity. Experimental results also showed that the cutting torque is not influenced by the opening and closure velocity of the scissors and, for this reason, is suggested not to make the machine work with a cutting frequency above 1 Hz, in order to avoid overheating of the scissors fulcrum and of the mechanical parts involved in the system for scissors holding.

Even if of great efficiency, reliability, easiness of use and low cost the proposed design could suffer of some limitations. Firstly, as already explained, the regulation of all the devices composing the machine is not automated and passes necessarily through a set-up action performed by an operator. Another limitation of the proposed design is given by the possibility of cutting only rollers of material or materials which can be turned into rollers form; anyway, since is expected that the cut material will be mostly cloth or paper, such limitation is not seen as a relevant problem.

Future developments of the project surely include the design of a frame for the prototype test bench; such operation will be important even to have an idea of the size of the machine and its size. It will be also necessary to realize the mechanical parts that compose the cutting and ripping system which is not already mounted in the prototype test bench. Once that a full test bench is manufactured it should be easy to translate such system into a first prototype of the machine. Moreover, if the winding motor is not eliminated from the design of the machine, it will be necessary to develop the control of the mentioned motors using a LabVIEW® based software in order to adapt to the control of the motor that opens/closes the scissors. For what previously mentioned it would be interesting, but also very impacting on the final cost of the machine, to automate all the regulation systems of the various devices composing the machine using pneumatic or electric actuators. If such path is taken it will be necessary to develop a PLC system for sequencing all the operations.

5 References

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