Robotic gripper for the handling of non-stiffened fabric

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Abstract

This study takes a holistic approach to the problem of fabric gripping in the clothing making automation, through this approach it explores the factors influencing the performance and design of a gripper design and develops a design framework to guide this process. Finally, a gripper concept is also developed, capable of performing a two pice of fabric translation and alignement, and manipulate different materials.

To guide this study, a tailored triple diamond methodology was used, it is the result of the combination between the design research methodology and the double diamond methodology. This approach allowed to deepen the understanding of the project and the problem, generate innovative concepts and bridge the gap between theory and practice. Results of this process also highlight the importance of flexibility and control in gripper design, to grab different types of materials without damaging them or having to carry complex manipulations.

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1. Introduction

This chapter provides an outline of the study. It first focuses on the background and the context, then defines the problem before giving an overview of the project environment and especially the stakeholders, to then define the purpose and research questions of this study. Then the relevance of the project is explained according to the context and finally, the outlines and delimitations of this work are presented.

1.1 Background

The need for automation in the textile and clothing industry in industrialized regions like Europe, the USA, and Japan has been recognized since the early 1980s (Sun and Zhang, 2019). Since then, such automation has been studied and developed, but the handling of fabric by robots remained an ongoing challenge in the industry for the last 30 years (Kolluru et al., 1995), Ebraheem, Drean, and Adolphe (2020) state that the current handling systems lack the complexity and performance necessary to meet the complex requirements of clothing making. Indeed, the handling and especially gripping of flexible materials, like fabric, is considered to be one of the biggest challenges in the field of robot manipulators (Koustoumpardis, Zacharia, and Aspragathos, 2006). However, it has the potential to greatly increase productivity and reduce costs (Paraskevi, 2012). As a consequence, the development of sophisticated gripping systems for non-stiffened fabric has become crucial to meet the demands of the industry.

The Science Park Borås, located in Sweden, is actively working towards automating the cloth assembly process. This company is a collaborative platform that brings together a diverse group of stakeholders and companies to enable innovation in the Borås region. Their mission is to drive sustainable development in three areas: textiles, consumption, and societal development. Their collaborative approach allows the Science Park to create new solutions that address complex challenges and contribute to the development of a more sustainable future. The Science Park Borås works across borders and disciplines by bringing together researchers, businesses, and other stakeholders; which creates a fertile environment for the development of ideas and projects. This collaborative approach has led to the development of several successful projects, including new textile materials and manufacturing processes, sustainable consumption initiatives, and innovative solutions for societal development. In addition to its focus on sustainability, the company is also committed to innovation by leveraging new technology and business models. They recognize that the pace of change in the modern world demands constant adaptation and experimentation, and they are continually seeking new ways to create value for their partners and stakeholders. To achieve its goals and stay on the cutting edge of innovation, the company maintains a global network of national and international partners. Additionally, the Science Park Borås participates in multiple EU projects and is an active partner in the development of solutions linked to the EU Green Deal, which aims to make Europe the first climate-neutral continent by 2050.

One Eu project that the company participates in is the micro-factory project, which aims to enable the production of clothes in high-cost regions such as Sweden, with the help of automation and robotization of the production. This project originated from the growing need and interest in producing clothing locally, however, clothing manufacturing is a labor-intensive process that requires operators to perform complex tasks like sewing. This factor is what prevents the implementation of affordable and locally produced clothes in regions such as Europe because of their labor cost. Therefore, the goal of the micro-factory project is to offer solutions and insights for automation in the textile industry while enhancing the flexibility of the value chain and reducing overproduction. Moreover, the project also wants to present an image of what is possible today and gather relevant partners for further research and development.

The collaboration with the Science Park Borås for this study is not the first one as the author of this thesis already had the opportunity to collaborate twice with the company for different courses. The first collaboration took place during the first year's project methodology course during which a team carried out a small project of gripper design, the research extended for over a month with the intent of managing an innovative project. The results of this project consisted of simple 3D-printed mechanical grippers. This first collaboration is the foundation of this thesis project and is also the basis of the author's knowledge of textiles and robotics. Taking place within the company, the participation in the project was also great to develop an understanding of the micro-factory project as well as the Science Park Borås' way of working.

The second collaboration with the company was for the innovation and creativity management course, which focused on companies' management of innovation. During this course, a different group developed a tool to increase innovation. To do so, interviews were conducted within the company to understand the company's organization and mindset towards innovation, their way of working on projects but also their aspirations and goals.

The knowledge gathered through those collaborations was especially useful to map out this thesis project and its stakeholders.

1.2 Problem definition

The general robotization of material handling is a challenging task on its own due to various difficulties such as geometrical uncertainty and obstacle avoidance. However, handling and gripping flexible materials like fabric adds a layer of complexity due to their unpredictable, non-linear, and complex mechanical behavior in combination with their high flexibility and bending deformations (Koustoumpardis, Zacharia, and Aspragathos, 2006). These unique characteristics of fabric affect the automation of handling and gripping in various ways: this is especially due to the high variety of fabric's size, type, shape, and material characteristics. As a result, fabrics do not react the same way from one type of fabric to another. Ebraheem, Drean, and Adolphe (2020) even state that each textile and each technological operation should have a specialized gripper. Another major difficulty in automating the handling of fabric is its unpredictable behavior due to its low bending rigidity (Paraskevi, 2012). Ebraheem, Drean, and Adolphe (2020) also agree that the high bending flexibility of the fabric and its ability to change shape when it is handled makes automation of its handling a difficult task.

Despite these difficulties, the need for automation in textile and clothing manufacturing has been recognized for many years, and different solutions have been developed, bringing the industry closer to this goal. Yet, the practical difficulties in designing and implementing a reliable gripper to efficiently handle fabric remain (Sun and Zhang, 2019).

With the handling of clothing accounting for 80% of the total production time and it being the biggest issue when it comes to automatizing the making of clothes, this issue is full of challenges, from the gripping and holding of fabric to its manipulation, positioning, and more. Based on the author's background in mechanical engineering and product development, it was decided in hand with the partner company to focus on the development of a gripping concept that would allow to grab, hold and manipulate fabrics in between the manufacturing steps.

1.3 Stakeholder mapping

Before defining the purpose and goals of this study, a map of it and its different actors (that have an impact or are concerned with it) was created. The goal behind this mapping out was to understand the thesis environment to set a coherent purpose and goals, indeed Den Ouden (2013) states that "meaningful innovations aim to create a holistic value and that to do so, it is necessary to have an integrative approach and to consider the conflicting needs of the stakeholders and integrate them into one proposition".

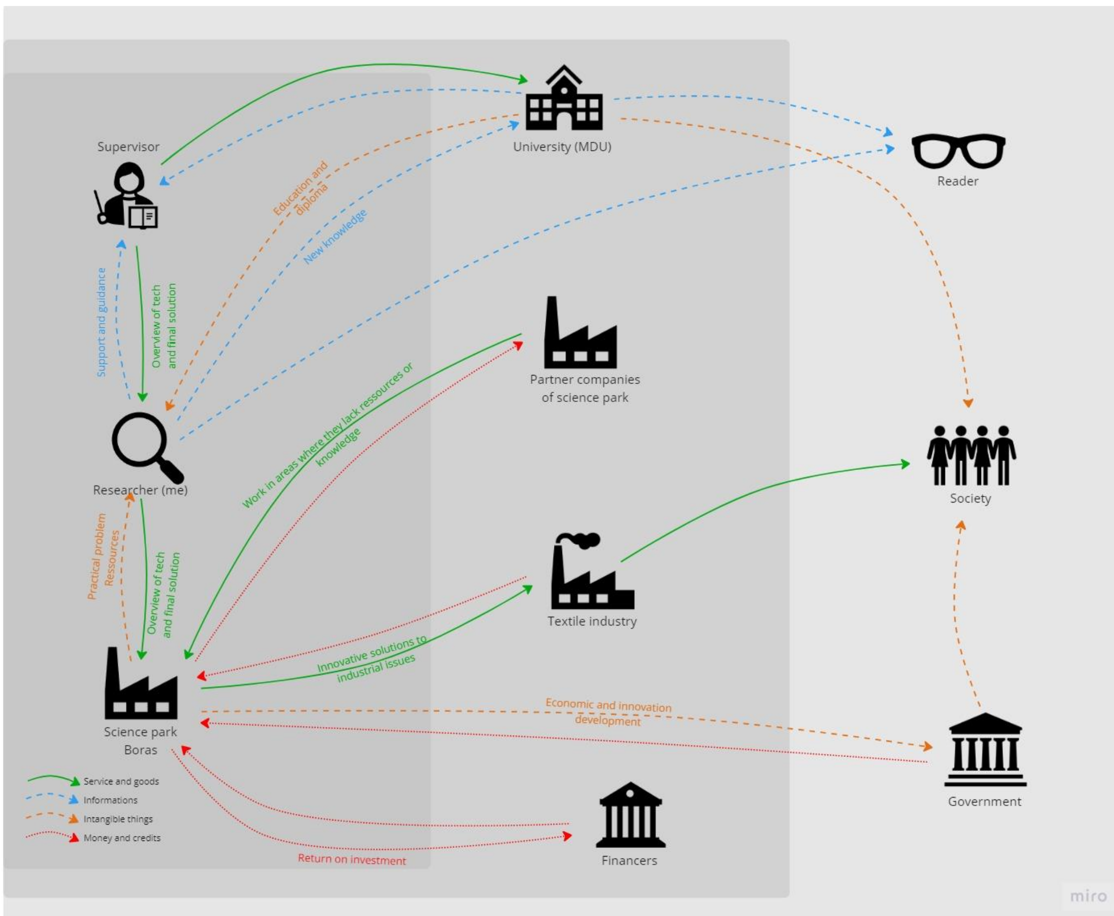
This stakeholder mapping was done in three steps detailed in section 3.2, the first of which consisted of a simple brainstorming to identify the 10 actors that are impacted or that impact this project as well as their goals. According to these, the identified stakeholders were then categorized by importance using the salience model, which better positioned the study in its environment (a combination of the results of those processes is visible in figure 1 below).

Stakeholder	Goal
Definitive	
Science Park Borås	Create innovative solutions to fulfill the textile industry's needs
Author/researcher	Generate new knowledge and gripper concepts while fulfilling the course goal
Supervisor	Accompagny students to accomplish his work and make sure the student is on track with course requirements
Expectant	
Textile industry	Get new solutions to solve their current issues
Partner companies	Contribution to project
Financers	Get a return on investment and contribution to the industry
MDU	Investigate existing knowledge and generate new one to educate
Latent	
Government	Improve economy and innovation Educate population
Society	Have affordable and sustainable clothes
Reader	Learn and understand the process

▼ Figure 1. Table of the stakeholders' classification and their individual goal

As seen in figure 1, stakeholders can be categorized into three levels of importance. The lowest level is latent stakeholders, which include society, readers, and the government, who have low power and urgency, however, their needs should still be considered because of their legitimacy.

The second level is expectant stakeholders, which includes dominant stakeholders such as the university, dependent stakeholders like the textile industry and partner companies, and dangerous stakeholders like financers. These stakeholders, and especially the dangerous ones have an important impact on the project, meaning that they have to be managed and considered closely. The highest level is definitive stakeholders, they have all three attributes; power, legitimacy, and urgency. In this case, the partner company, the supervisor, and the author, who have power, legitimacy, and urgency are definitive stakeholders, and they require the most attention.



▼ Figure 2 Value flow model of the study's stakeholders adapted from Den Ouden (2013)

Additionally, to go further and better define the goal of this study in accordance with its environment, a value flow model was created (figure 2 above). This process highlighted the links and the nature of the relationship between stakeholders, which was great to understand how they are related and what they expect from each other, but also to understand what they expect from this study and therefore, what should be the goal of this project.

1.4 Purpose and Research question

Based on the stakeholders' mapping presented in the previous section, the purpose of this thesis study is in two folds. First of all, by making use of a literature review and interviews, it aims to create a design framework for the design of robotic grippers. The study behind this framework focuses on the main aspects that affect the gripping of fabric by robots. On an academic level, this will generate knowledge about the principles to consider for the gripping of fabric, moreover, on a collaborative level, this framework will allow the Science Park Borås to have a holistic understanding of fabric gripping, which can be useful for them to develop other solutions or to further develop the concept designed in this study.

Secondly, based on these previous findings, this study aims at designing a practical concept of a robotic gripper to handle fabric. On an academic level, doing so will allow the author of this thesis to use his knowledge and show his abilities in innovation and design by solving a complex problem, using a critical and creative approach as well as adequate research methods to integrate existing knowledge, while considering and supporting different perspectives. On a collaborative level, the author provides the Science Park Borås with a concept of an innovative gripping solution that if further developed can solve the fabric handling and gripping issues in clothing manufacturing automation.

To fulfill these different goals, the study is revolving around the following research questions:

- What parameters need to be considered in the design of a robotic fabric gripper and how to integrate them in a design framework?
- How to design a concept of fabric gripping device to handle non-stiffened fabric?

1.5 Relevance of study

The relevance of this study lies in its contributions to both the theoretical and practical parts of gripper design. Indeed, this study develops new gripper concepts based on a design framework created from previous research and experts' knowledge.

The final concept developed is an innovative solution that can be used in different applications where current technologies are not sufficient. Therefore, it has the potential to move the current state of robotics in clothing-making forward by filling a gap in the industrial market. On a theoretical aspect, this study provides a comprehensive design framework that takes into account different external factors that impact the design of a gripper. This framework not only highlights the main factors to consider but also explains how they can be integrated into the design of a gripper in the form of requirements.

In addition to this design framework, this study deepens the understanding of gripping principles by exploring their pros, cons, and their recommended applications based on fabric characteristics and handling actions. This knowledge can be applied to a wide range of textile industries such as the cloth, furniture, or car interior industries, where requirements are very different.

1.6 Scope and delimitation

As mentioned earlier, the automation of clothing manufacturing is still undergoing development because of the many challenges engendered by fabric. The handling of fabric and especially its grasping is one of the challenges that need to be solved to enable the automation of clothing manufacturing. However, more research on the topic is necessary to create practical solutions. Therefore, the goal of this study is to create a concept of a gripper's design to grab, hold and manipulate fabrics in between the main steps of the manufacturing system (here, it is important to make a difference between the robotic arm that moves the gripper and the gripper that is fixed on a robotic arm and grips the fabric).

To do so, this study investigates 4 topics: the clothing assembly/making process to understand the environment in which the solution will be implemented, the handling task that a gripper needs to achieve in an automatized clothing production, the impact of the fabric specifications to set requirements for the design and finally, the different gripping technologies and concepts that exist as of today. Due to the limited amount of information on the topic, those subjects have been investigated over the last 30 years only.

Based on the limited time constraint of this study and within the company, the development of the final concept into a physically finished solution has been excluded from this study.

2. Theoretical framework

Because of the holistic approach of this project, the goal of this theoretical framework is to provide an overall understanding of fabric gripping and the evolution of research in the domain. According to Ragunathan and Karunamoorthy (2008), such an understanding requires the integration of fabric features and behavior and an analysis of gripping and handling tasks (manipulation, transportation tasks, etc.). Therefore, this chapter provides an understanding of the clothing-making process; a definition and analysis of factors that affect the gripping of fabric and the design of a gripper: the handling task themselves, as well as the fabric characteristics. It also gives an overview and deep understanding of the basic gripping principles that inspire current concepts and gives an outline of the research evolution.

2.1 Clothe manufacturing/production

According to Nilsson (1983), to automate the sewing process, it is essential to first focus on the clothing-making process itself. Even though the focus of this study is not on the automation of the whole cloth assembly process but rather the gripping to enable the automation of this process, the understanding of it was still considered necessary.

According to Mok et al. (2011), apparel manufacturing is a sequential process that usually consists of the same steps, with exceptions made for custom products. These steps can be simplified in the following way (Mok et al. 2011; Sun et al. 2021; Kim and Kim, 2020; Mendes and Dos Santos, 2017):

- Cutting: During this step, the fabric is transported to the cutting machine before being cut into the different pieces that compose the product, and then stored. Current cutting machines use vibrating blades, rotary knives, or lasers which create highly precise and neat cuts. Cutting is known as the bottleneck of the production cycle because it supplies the rest of the process.
- Sewing: This step usually takes place in different steps depending on the number of pieces the cloth is composed of. Therefore, a first sewing step called module assembly usually occurs during which secondary components of a garment are assembled like the sleeves, collar, label, pockets, and more; then all elements of the clothe are assembled to create the final product. Both of these operations can however be completed within a single sewing unit.
- Final processing: Once the clothes are assembled, the final processing steps are applied to them, these steps usually include processes such as washing, finishing (water repellant, …), and ironing. Most of these individual processes are automated.
- Stacking: Finally, once the clothes are ready, they get stacked up in piles to prepare for shipping and distribution.

Some of these steps including cutting and processing are automated and some are automated or partially automated. Moreover, the transfer of garments between each step is carried forward by more or less automated transfer equipment such as overhead hanging or conveyors (Nilsson, 1983). In consequence, the main steps of the clothing-making process are automated and the need for automation is in the handling of the fabric during the intermediate steps that link those automated steps. Those intermediate steps engender different handling tasks described in the following part.

2.2 Fabric handling tasks

According to (Koustoumpardis, and Aspragathos, 2004) handling operations account for about 80% of a production line time, therefore it is logical to see that many researchers such as Paraschidis et al. (1995); Moulianitis, Dentsoras, and Aspragathos (1999); Koustoumpardis, Zacharia, and Aspragathos (2006); Sun and Zhang (2019); and Ebraheem, Drean, and Adolphe (2020) talk about considering the handling operations in the design of their grippers. Yet, all of them have a different classification of the handling tasks, however, a common base can be found throughout those classifications, that is:

- Separation; is the process of separating the garment or pieces of fabric from the stack of fabric. This step is important to avoid any creasing or damage to the fabric during the handling process. A common challenge with this step is to manage to pick only the number of layers wanted, indeed if two layers of fabric are picked up instead of one, the whole process will be affected.
- Picking; during this step, the fabric is picked up from a surface, this surface can be a cutting machine or a surface like a workbench. A challenging aspect of this task is related to the variety of sizes and possible locations of the fabric, meaning that the edge or center of a piece of fabric is not always located in the same spot and that the robotic arm has to adapt.
- Translation; involves moving the fabric from one place to another. A translation could simply be about lifting the fabric and moving it to a different location, or it could involve more complicated actions such as folding or rolling the fabric.
- Laying; is when the fabric is placed down on a surface, usually in a particular way. This could involve laying the fabric flat to later sew it, or it could involve folding the fabric to stock it or even draping it over a form or object. A challenge during this step is to lay the fabric down flat, without creating any unwanted folds or wrinkles as it can affect other steps.
- Positioning; is about moving the fabric around and placing it in a specific manner for a specific purpose. This step is usually achieved to allow the processing of the fabric like sewing or cutting. The main complexity of this step is accuracy.

The classification above is chronological, according to the order in which the different tasks are usually performed; which can make them look like steps, however depending on the overall process the fabric has to go through, most steps take place multiple times and in different orders.

As for the individual complexity and difficulty of these tasks, it is hard to rank them as findings on the topic are contradicting one another, as a matter of fact, Sun and Zhang (2019) state that the main difficulty in handling fabric seems to be finding a reliable way of picking up fabric, whereas Koustoumpardis, Zacharia, and Aspragathos, (2006) suggest that the most sophisticated handling task is the fine translation and alignment of flat fabric (for sewing for example).

2.3 Fabric properties

As said earlier, the complexity of the fabric, including its size, type, shape, and material properties, makes it challenging to introduce flexible automation in the textile industry (Koustoumpardis, Zacharia and Aspragathos, 2006 and Shibata et al. 2008). Ebraheem, Drean, and Adolphe (2020) even state each type of textile and/or process operation should require its own specialized gripper because of the varying shapes and properties of textile products. Indeed, textiles can be split into eight categories: permeable, waterproof, tights, light, heavy, thick, thin, and release (Ebraheem, Drean, and Adolphe, 2020). This classification is a traditional way of classifying fabric, but it is based on the different materials' specifications (Koustoumpardis, Zacharia, and Aspragathos, 2006); in fact, materials may have specifications in common, however, they have unique combinations of characteristics, which creates various types of fabric. Therefore, for more accuracy and a better understanding of fabric, the focus of this part is on the individual specifications of the fabric and their effect on gripping.

According to Moulianitis, Dentsoras, and Aspragathos (1999), fabric specifications can be categorized into two groups: properties and characteristics. A property is a static aspect of a material that cannot change and characteristics are dynamic physical parameters of fabric resulting from outside changes to the fabric. For instance, the weight, or the fiber length of a fabric are properties, while its air permeability or tearing strength are characteristics of a fabric (in this case, impacted by the manufacturing process and manufacturing parameters of the fabric). Some of these specifications are general and may need to be considered in the design of clothing but not the design of a gripper, but some are highly specific and need to be considered for the design of grippers. Moulianitis, Dentsoras, and Aspragathos (1999) give the example of porosity, which may not be important for an electrostatic gripper but a vital factor for pin grippers.

Through this literature review, five fabric specifications that need to be considered in the design of gripper were identified; this selection has been made based by crossing the findings of Bunsell (2018), Shibata et al. (2008), and Taylor (1994) as cited in Moulianitis, Dentsoras, and Aspragathos (1999), and Jabbar and Shaker (2016):

- Mass: The mass of a fabric refers to the amount of material it contains. This mass is affected by the thickness of the threads the fabric is made of, the density of the knit, and its composition (material). The mass is often expressed in grams or ounces.
- Elasticity: The elasticity of a fabric expresses the maximum stress it can support and return to its original shape without being deformed. This amount of stress is referred to as elongation and is measured in percent per meter, going over the elongation limit can deform the fabric or damage it.
- Strength: The strength of a fabric characterizes the load it can support until breaks. This specification can remind us of elasticity; however, it is different as it represents the limiting load-bearing capacity of a fabric. Furthermore, the strength of a fabric will affect its resistance to use and wear.
- Texture/friction coefficient: The texture of a fabric describes the feel or quality of its body and surface. The texture is often described as rough, smooth, or soft.

- Permeability: The permeability of a fabric refers to its ability to allow a penetrant such as air or gas, liquid or even solid to pass through it

Mass	Heavy fabrics: canvas, leather, wool, denim	Light fabrics: silk, cotton, linen, chiffon
Elasticity	Elastic fabrics: spandex, stretchy cotton, stretch velvet	Non-elastic fabrics: denim, canvas, wool, corduroy
Strength	Strong fabrics: canvas, denim, leather, wool	Weak fabrics: silk, chiffon, lace, gauze
Texture	Rough fabrics: corduroy, burlap, canvas, wool	Smooth fabrics: silk, satin, chiffon, cotton
Permeability	Permeable fabrics: mesh, knit, lace, gauze	Non-permeable fabrics: denim, canvas, leather, wool

▼ Figure 3 Table of material specifications and examples of materials adapted from Jabbar and Shaker (2016)

The mass, elasticity, texture, strength, and permeability of a fabric determine how the fabric behaves, and according to Ebraheem, Drean, and Adolphe (2020) how the gripper should be designed to handle it effectively and efficiently. Naturally, these specifications are important to consider in the design of a gripper for fabrics because they will directly impact its performance and functionality.

2.4 Gripping principles

Some concepts and solutions have already been developed over the years and even if those solutions are not good enough to be used in the industry, there is a lot to learn from them. One thing that seems to be common between those solutions and that is still developed today is an array of gripping principles. In clothing manufacturing automation, a gripping principle refers to the method used to grip or hold fabrics. Gripping principles are important in automation because they allow the fabric to be handled and manipulated by machines without causing damage or distortion to the material. Moulianitis, Dentsoras, and Aspragathos (1999) divide the main gripping principles into three classes:

- Mechanical surface, which describes principles that grab the fabric using a mechanical action such as clamping or pinching the fabric between gripper fingers.
- Intrusive, which is when the fabric is held on by pins or needles that are driven into the surface of the fabric
- And lastly, surface attraction, which represents solutions that stick to the fabric thanks to adhesive, electrostatic, or suction principles

Mechanical		Intrusive	Attraction		
Gripping	Friction	Penetration	Adhesion	Suction	Electrostatic

▼ Figure 4 Table of the main gripping categories and sub principles

Mechanical

- The gripping principle is based on prehensile modes like clamp, pinch, and grasp (Kolluru et al., 1995), these principles are often designed for simulating how humans' hands interact with fabric (Sun and Zhang, 2019). The pinching principle can be compared to how human fingers pick up fabric as the material is either clamped or pinched between robotic fingers while gripping uses the same principle but from the edge of the fabric (Ebraheem, Drean, and Adolphe, 2020). One disadvantage of this method highlighted by Sun and Zhang (2019) is that the fold generated on the fabric by the pinching can deform the fabric and cause difficulties in the handling tasks, still, this principle can handle a wide variety of fabrics at a low cost and reliably (Sun and Zhang, 2019; and Ebraheem, Drean and Adolphe, 2020).

- Friction can be seen as part of the pinching and clamping principles detailed above as it is not possible to maintain the fabric in a gripper without it. But new concepts are focusing on this specific principle to create innovative solutions such as the bio-inspired gecko adhesion gripper, which combines soft materials with a high friction surface inspired by gecko skin (which allows them to stand upside down) (Hoang et al., 2021). Limitations of this principle are led to evolve as its use is still new but an already known advantage is that this principle can handle fabrics without damaging them (Hoang et al., 2021).

Intrusive

- The intrusive principle describes penetration devices that use incisive needles to pierce into fabric surfaces, move to lock into them, and have a grip on them (Kolluru et al. 1995; Moulianitis, Dentsoras, and Aspragathos, 1999). The use of needles to grasp fabric however generates disadvantages as the needles are likely to damage the fabric surface, especially the non/poorly permeable fabrics (Sun and Zhang, 2019). In a setup where the gripper is used to pick up fabric from a stack, Ebraheem, Drean, and Adolphe (2020) also highlight the difficulty of adjusting the depth penetration, which can lead to picking up several fabrics at once. Still, this solution is affordable and very reliable with permeable materials (Ebraheem, Drean, and Adolphe, 2020).

Attraction

- The adhesion principle is based on the use of resins or adhesive glues to pick up pieces of fabric by pressing the adhesive on the fabric and releasing it using a stripping mechanism (Kolluru et al. 1995; Ebraheem, Drean, and Adolphe, 2020). Sun and Zhang (2019) state that using glue or resins though can affect the surface of the fabric and create irregularities, moreover, as it is hard to control adhesives, problems can occur when releasing the material (Ebraheem, Drean, and Adolphe, 2020).

- The suction/pneumatic principle uses vacuum or differential pressure as the operating principle, this method is widely used in the textile industry for its reliable grip (Sun and Zhang, 2019; Kolluru et al, 1995; Ebraheem, Drean and Adolphe, 2020). However, it requires relatively complex devices such as vacuum pumps, pipes, and other peripheral units, making it an expensive technique that requires large installations. Additionally, this principle does not work well with permeable fabrics as the air can go through the fiber, but when it comes to less permeable fabric, this solution is very reliable and offers a solid grip (Ebraheem, Drean, and Adolphe, 2020)

- The electrostatic principal functions by electrically polarizing the structure of the fabric, which creates an electric field between the gripper and the fabric and therefore an attraction force (Ragunathan and Karunamoorthy, 2008; Ebraheem, Drean, and Adolphe, 2020). According to Sun and Zhang (2019), this method is greatly suitable for fabric gripping as it does not damage the fabric and maintains it wrinkle-free, yet (Ragunathan and Karunamoorthy, 2008; Ebraheem, Drean and Adolphe, 2020) raise the issue of high voltage involved for this principle to work, which means that the working environment needs to be secured, otherwise, workers could be endangered.

2.5 Evolution of research

Early research on the development of robotic grippers to handle textiles was single-focused, with researchers focusing on either the fabric properties or on specific gripping actions. This narrow focus often resulted in solutions that did not fully consider the complexity of clothing manufacturing and that were not good enough. For example, a gripper designed around a specific type of fabric might not be effective on other types of fabrics, in different manufacturing settings, or for specific handling actions. Still, a lot was learned during that early research, and most design principles such as mechanical ones, adhesive, and attraction ones emerged from it.

However, recent approaches to gripper design have taken into account multiple factors at the same time, resulting in new and innovative concepts. For example, the gecko-inspired concept, which mimics the microscopic hairs on gecko feet to create a strong grip, considers not only the properties of the fabric being handled but also the surface on which it will be handled, as well as the specific actions involved in the fabric manipulation (Hoang et al., 2021). By taking a holistic approach to gripper design, researchers have been able to develop solutions that are more adaptable and effective in a range of manufacturing settings.

Looking to the future, some experts (Sun and Zhang, 2019; Ebraheem, Drean, and Adolphe, 2020) predict that the next major development in the automation of clothing manufacturing and gripping will be the mimicking of human gripping, and handling motions. This approach would involve developing grippers and automation systems that replicate the movements and actions of human workers in fabric factories. The advantage of this approach is that it would allow for greater flexibility and adaptability with a big range of fabric types and shapes, without requiring reprogramming or redesigning of the gripper systems. However, there are also challenges to be overcome in replicating human gripping. A major one is to replicate the dexterity and sensitivity of the human hand and fingers, which are essential. Another challenge is to develop systems that can adapt to different fabric specifications, such as texture, thickness, or elasticity.

3. Methodology and approach

This chapter gives an overview of the process followed during the project, including the methods for data collection and analysis as well as the development method for the design framework and the gripper concepts.

3.1 Project methodology

The methodology used in this study is tailored specifically to this project, and based on two methodologies taken from design and innovation practices: The double diamond and the design research methodology.

- The design research methodology (DRM) is an iterative method that systematically investigates and develops support for the design of a solution. This methodology is based on four main stages: the research clarification stage, the descriptive study stage, the prototype synthesis stage, and a second descriptive study stage (Blessing and Chakrabart, 2009). In the research clarification stage, the project and its goal are analyzed to get an in-depth understanding of it, and its success factors; this analysis then leads to the identification of the research questions and objectives. The descriptive study stage aims at building a foundation for the rest of the project by developing a holistic understanding of the issues, and especially the influencing factors. The prototype synthesis stage involves developing a solution in a systematic way based on the results of the previous stages, and the second descriptive study stage assesses the effectiveness of the developed solution (Blessing and Chakrabart, 2009).
- In the case of this study, this methodology was merged with the double diamond methodology and its diverging and converging approach, which helps to increase the exploration and ideation of potential solutions. The double diamond is a strategic approach to design that helps designers and non-designers tackle some complex problems by breaking them down into manageable and understandable stages (Design Council, 2019). In the first diamond, the problem is analyzed, broken down, and explored to gain a deep understanding of its nature and context. In the second diamond, potential solutions are generated, tested, and refined until a suitable solution is identified (Design Council, 2019).

Overall, both methodologies have a similar goal but the design research methodology (DRM) helps to better include the study in its environment by breaking down its complexity and developing a better understanding of the success factors of the project. By combining these approaches, the methodology used in this study was a triple diamond (visible in figure 5 bellow) that aimed to provide a framework for the development of effective solutions to the problem. Indeed, the DRM provided a structured and iterative approach to problem-solving, while the double diamond methodology offered a flexible and creative approach to generating and refining solutions. This combination allowed for a holistic exploration of the problem and its environment, while also encouraging creativity and innovation in the development of solutions.

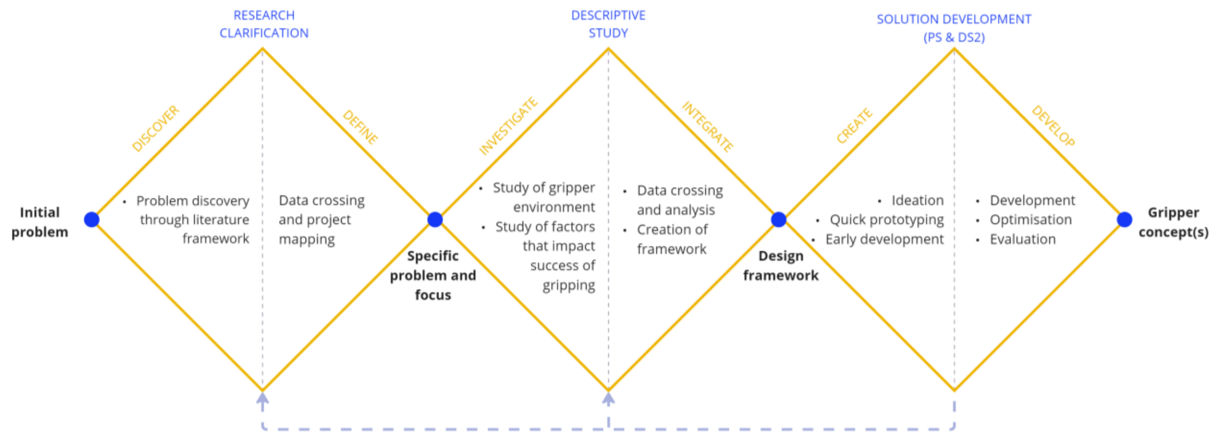


Figure 5 Visualization of the triple diamond methodology used in this project

In the research clarification stage (first diamond) the overall goal was to specify the problem and based on this understanding, define a focus for the study.

- In the discovery phase of this diamond, the main aim was to understand the situation by looking into the problem and developing a holistic understanding of it. Due to the past collaboration with the Science Park Borås, the internal problem was already familiar, therefore it was decided to go further in the understanding of the problem and its success factors by investigating the problem within the industry as it is an important stakeholder in this project (the concept developed aims to be used in the industry). Due to the diverging nature of this phase, many aspects of the clothe automation industry were looked into, from the handling of fabric by robots to the production of clothing itself and the evolution of research on the topic. This step was essential to develop a holistic vision instead of assuming the situation based on the problem the company has, or even on the previous collaboration with them. Furthermore, researching the problem also allowed to confirm the existence of this problem in the industry and the need for a solution.
- In the defining phase of this diamond, all the data gathered was crossed and used to map the project (process detailed in section 3.2), which broke down the complexity of the project. Since the goal of the defining phase is to define the purpose of this study, this mapping was mainly focused on the links between the different stakeholders' needs and will with this study, which allowed to fit the study, its purpose and focus according to its environment. Based on the result of this mapping, the key research questions and objectives were then identified, and a research plan was developed.

In the descriptive study stage, and building upon the results of the research clarification stage, the aim was to build a foundation for the rest of the project by developing an understanding of the issues and especially the influencing factors.

- Therefore, in the investigation phase of this diamond, a throughout literature review (presented in section 3.3) was conducted. Due to the diverging nature of this phase, the focus was initially on the typical gripper environment, and then, based on the DRM approach, the different factors that impact the performances of a gripper were investigated. Simultaneously, semi-structured interviews were conducted with the same focus, but also the will to confirm the findings of the literature review. During this phase, patterns of factors impacting the gripping of fabric were uncovered across the different data gathered, which sparked the idea of creating a design framework that gather this data.

- In the integration phase, the goal was to find a way to make the collected data usable, therefore based on the data collected and the different themes that appeared during data collection, a meticulous thematic analysis (described in section 3.4) was conducted. The results of this analysis were then included in a design framework.

Finally, in the solution development stage, different ideas were generated based on the results of the previous stages, then they were developed and tested. As the prototype synthesis stage and a second descriptive study stage were conducted within the company and over a month only, the stages were merged and conducted simultaneously to make the process more efficient and effective, which allowed to quickly develop and test potential solutions.

- In the creation phase, different ideas were generated based on the goal set with the company and the industry's need, in this case, the focus was on picking up two different pieces of fabric from the cutting machine and placing them precisely over one another.
- In the development phase, those ideas were 3D modeled, prototyped, optimized, and tested, narrowing down the options to a final concept.

The iterative aspect of the triple diamond methodology was a key aspect that was taken from the DRM; indeed, it allowed the methodology of this study to be different from linear problem-solving approaches. Since the process of discovering, investigating, and ideating/developing is not a linear sequence of actions, but rather a circular process of improvement and refinement, such an approach was really useful, especially during the solution development stage (as ideas were constantly iterated after some quick prototypes and testing), some ideas would even spark ideas of different concepts. Another type of iteration also took place in the development stage, those were due to new ideas that required investigation on a specific topic.

Iterations also took place in the first stages of the project, those types of iterations were usually due to the discovery of new elements when collecting or analyzing data, which lead to an adjustment of the project's focus or aim. This was the case when getting the idea of a design framework, which was not part of the initial project scope.

Overall, the triple diamond methodology was a flexible and dynamic process that allowed for continuous improvement and iteration, which ensured that the final solution was effective and met the desired requirements.

3.2 Method for project mapping

The first step in the project mapping was a brainstorming of the project's stakeholders and their goals/impact on the study. 10 main stakeholders that have different impacts on the project were identified through this initial brainstorming. This process was based on 2 interviews with one of the company's managers (Jonas Larsson) for previous courses (project methodology and innovation and creativity management), which also allowed to undercover the individual goals of the stakeholder regarding this specific study.

As seen in figure 1 presented in the introduction, stakeholders and their goals were then categorized into three categories; definitive, expectant, and latent stakeholders. This categorization is the result of the salience model which categorizes stakeholders into seven classes based on three key attributes (Mitchell, Agle, and Wood, 1997):

- Power: Stakeholder with the ability to impose its will
- Legitimacy: Stakeholder with a right to make requests (generally stakeholders that are involved and have knowledge about what is going on)
- Urgency: Stakeholder that needs quick action (because of the urgent nature of the situation or the importance of the issue)

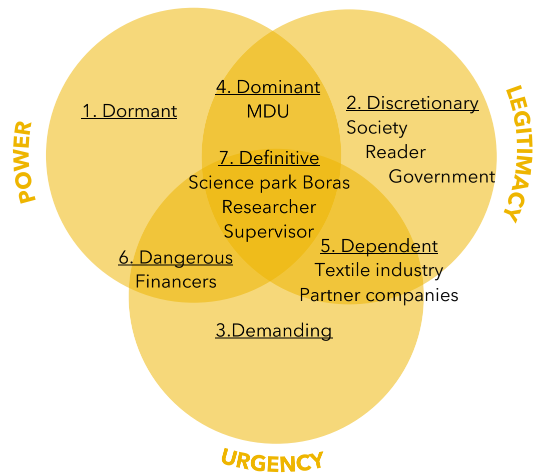


Figure 6 Salience model of the stakeholder classification adapted from Mitchell, Agle and Wood (1997)

By analyzing the nature of the stakeholder's goal, it was possible to identify whether they had power, legitimacy, urgency, or a combination of these attributes and therefore categorize them.

Once the goal of the stakeholders and their importance was getting explicit, the purpose of this study was getting clearer, but to define it further, it was decided to create a value flow model of the project that would offer an understanding of the interactions between the stakeholders, but also the nature of these interactions and the values they bring to every stakeholder (Den Ouden, 2013). Developing this understanding of the relations and links between stakeholders showed how and which elements must be integrated to create a coherent value proposition; in other words, "the aim in this phase is to get the core value proposition right and to address valuable complementary offers as well" (Den Ouden, 2013). Booth et al. (2016) also support this idea by saying that "to matter, a study must address a problem that others also want to solve". Using the value flow model allowed to better fit the thesis in its environment, but also, find additional ways to enrich the project and to better frame it so that it delivers the right outcomes to the different stakeholders and especially the important ones.

The first step in the creation of the value flow framework was to think about the obvious link between stakeholders such as the one between financers and the Science Park Borås, who fund the company's projects. Once these links were drawn, the stakeholders' individual goals were used to find additional connections and value exchanges between them. Doing so highlighted the links and the nature of the relationship between the stakeholders, which was great to understand how they are related and what they expect from each other but also to understand what they expect from this project and therefore, what should be the goal of this project.

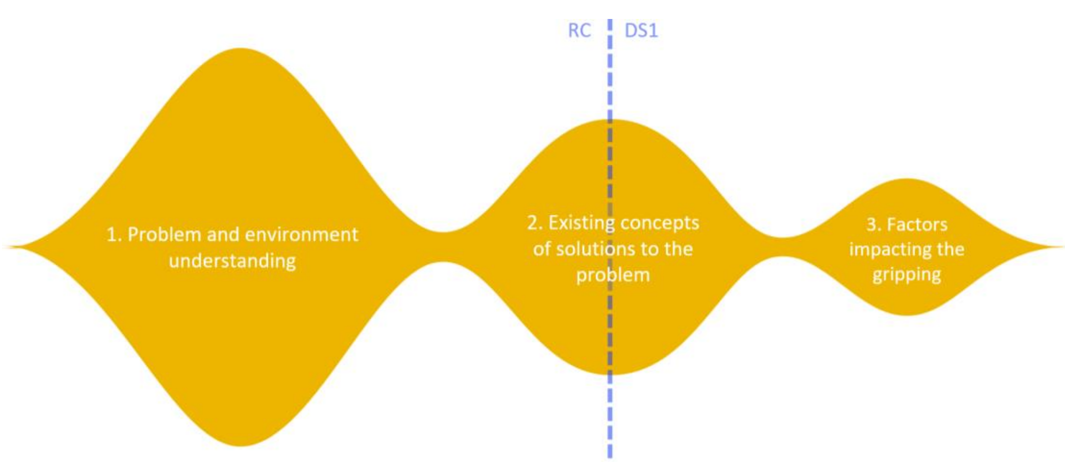
3.3 Method for data collection

3.3.1 Iterative literature review

The main method of data collection in this study was an iterative literature review. This literature review was an essential and central piece of this study as it contributed in many ways. Indeed, with this literature review being part of the first and second divergent phase of the study's triple diamond method, its first goal was to explore a wide range of topics related to the project, without excluding any information as they could be relevant later on. This approach allowed to "build upon the work that has already been researched" (Fisher, Buglear, and Al, 2004) but also helped collect diverse and relevant data that participated in the development of this study. As the data collected through this literature review was also going to be used in the converging phase to specify the problem and develop a research framework, it had a secondary goal, which was to collect in-depth data that would support the development of the problem and the design framework.

To achieve these goals, a comprehensive search of relevant literature from multiple sources, including academic journals, books, and conference proceedings was conducted. In total 20 papers were collected, covering a wide range of topics related to the project. These papers have been published over the last 30 years but the vast majority of them are from the last 10 years.

The literature review was conducted in three stages (visible in Figure 7 below) that have different focuses. With the focus of each stage narrowing down based on the insights and findings of the previous stage, this iterative approach allowed to specify the problem and the focus of the study. Indeed, each stage involved conducting a comprehensive literature review using about the same set of papers, which made the process longer but allowed to develop a more in-depth and coherent understanding of the topic, as well as to extract different perspectives and insights from the existing literature, leading to a more nuanced understanding of the topic and the problem.



▼ Figure 7 Focuses and process of the literature review

- The first focus was to get an overall understanding of textile manufacturing and its automation, as well as robotic fabric handling. This was especially important as the author of this thesis did not have a background in textile and textile manufacturing; furthermore, when researching the complexity of automating textile manufacturing, it was clear that one of the most challenging problems is the handling of flexible fabric. Even though it accounts for 80% of the total production line time (Koustoumpardis, P. and Aspragathos, N. 2004), still the vast majority of industrial automation solutions only cover the sewing aspect of textile manufacturing (Sun and Zhang, 2019). Therefore, it felt natural to first look into the gripping and handling of fabric to develop a better and more precise understanding of the problem.

- Based on this initial understanding, the second focus of the literature review was to examine how the problem of textile manufacturing automation and robotic fabric gripping has been addressed in previous research. This second focus was especially useful to do what Fisher, Buglear, and al (2004) describe as "removing the need to rediscover knowledge that has already been reported"; furthermore it allowed to identify different approaches and factors that need to be considered when addressing the fabric gripping and handling problem, indeed according to Ragunathan and Karunamoorthy (2008) such an understanding requires the integration of fabric features and behavior with analyses of gripping, and handling tasks (manipulation, transportation tasks, etc.)

- Building on the findings of the previous focus, the third focus of the literature review was to investigate the different factors that impact the gripping of fabric in the context of textile manufacturing automation. These findings are the foundation of the design framework.

3.3.2 Semi-structured interviews

The secondary method of data collection in this study was semi-structured interviews, the goal of those interviews was to improve the design framework by benefiting from experts' experience. Since this framework is based on the findings of the literature review, the idea behind interviewing experts that already worked on fabric gripping development but also robotics and automation of clothing-making was to validate the data that was going to be used to create the design framework, but also undercover deeper insights on the factors that impact the design of grippers. They were then implemented in the framework, making it more comprehensive and accurate.

Questions were therefore designed around this goal, exploring the individuals' experiences with clothing-making automation and gripper design (if they have experience in gripper design) to understand the factors they would consider when working with clothing-making automation and/or gripper design. Participants were also asked to reflect on their overall experience in clothing-making automation, what they learned, and the advice they would give to others working in this field.

Three interviews were conducted online between march and april, the interviewees were two researchers that previously worked on the design of a gripper and a researcher that worked with clothing-making automation. Interesting insights that confirm what was already uncovered in this study were collected but no groundbreaking conclusions were drawn; for example, the importance of considering fabric and handling actions was confirmed, furthermore, the importance of those two factors especially was made very clear. Interviewees also suggested that a great way to consider those factors in a design was to do it through engineering requirements or design principles (as in principles that are always kept in mind when designing and referred to when taking design decisions).

It was chosen to conduct semi-structured interviews to first discuss desired topics that are important for the development and validation of the design framework, but also to allow "the respondent to have as much latitude to respond to the questions in the ways that seem sensible to them" (Fisher, Buglear and Al, 2004) which can uncover unexpected outputs, notably useful to further develop the design framework.

3.4 Method for data analysis

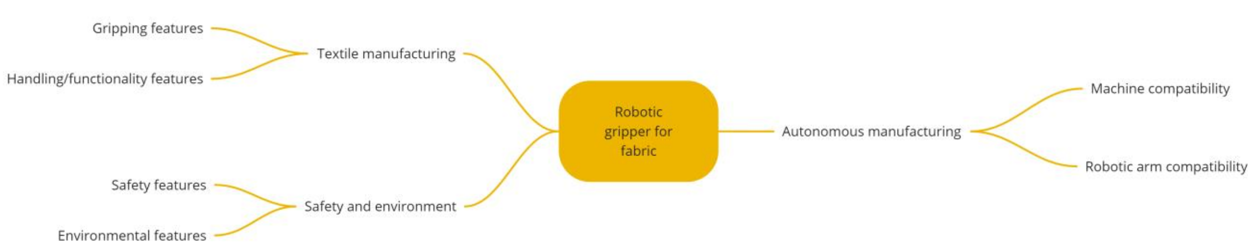
Once the data was collected and because of its qualitative nature, it was decided to carry out a thematic analysis of the data. Indeed, during the literature review, it quickly appeared that fabric gripping was a very complex process influenced by different elements and that those elements were usually the same from one paper to another. However, to conduct a proper thematic analysis and not be biased by the obvious themes identified when collecting data, the thematic analysis took place in three steps.

- The first step was an immersion phase during which the data was consulted again and again to gain a deep understanding of it and its nuances. Furthermore, interesting sections and facts were highlighted and isolated to facilitate their treatment. Once again to avoid a biased analysis this immersion was done with an open mind and without any preconceptions.
- The second step of this process was to look for patterns or connections within the data, to later identify the main themes. To identify accurate and not preconceived themes, inductive coding was used and similarities and differences were identified within the data collected, allowing to identify the main themes: Textile manufacturing, Autonomous manufacturing, Safety, and Environment.
- Finally, once these themes were identified, the data was broken down into smaller chunks before being placed into the appropriate theme based on its content.

Even though this process seems very straightforward, in the case of this study it was an iterative process that involved going back and forth between the different stages of the analysis. Thanks to this iterative process, the understanding of the data was sharpened and the themes identified reflect the content of the data collected.

3.5 Method for design framework development

As said earlier, the idea behind this design framework comes from the crossing of data and the observation of patterns within the data analyzed. The goal of this framework was to gather those data into a useful tool to efficiently design a gripping solution that can be used by the designer as a redline to ensure the success of a gripper's design, both in terms of its functionality and its ability to integrate into its environment. The mind map (figure 8 below) was an essential element in the creation of the framework, it was used as a brainstorming tool that allowed to break down the complexity of the gripper's system into smaller and more manageable parts. Doing so confirmed the importance of certain factors such as the material characteristics but also undercovered other factors that were not considered initially like the machine compatibility or the sustainable aspects.



▼ Figure 8 Mind map of the factors to consider in a gripper design

The mind map (figure 8 visible above) is centered around the gripper and served as the framework for identifying three broad categories that are crucial to consider in the design of a gripper: textile manufacturing, autonomous manufacturing, and safety and environment. These categories serve as the main factors that need to be considered in the design of a gripper. Within each category, subcategories were developed down into more specific factors.

Once these precise subcategories were identified, each of them was developed by looking at how they should be considered for a successful design. For example, to write down requirements for the handling/functionality features sub-category of the textile manufacturing category, the assembly process and each of the main operations, fabric cutting, sewing, processing, and stacking were broken down into individual steps and all of the already automated steps and non-handling steps were eliminated, resulting in the handling steps that need to be automatized visible in figure 9 bellow. From those steps, it was then easier to come up with individual requirements.

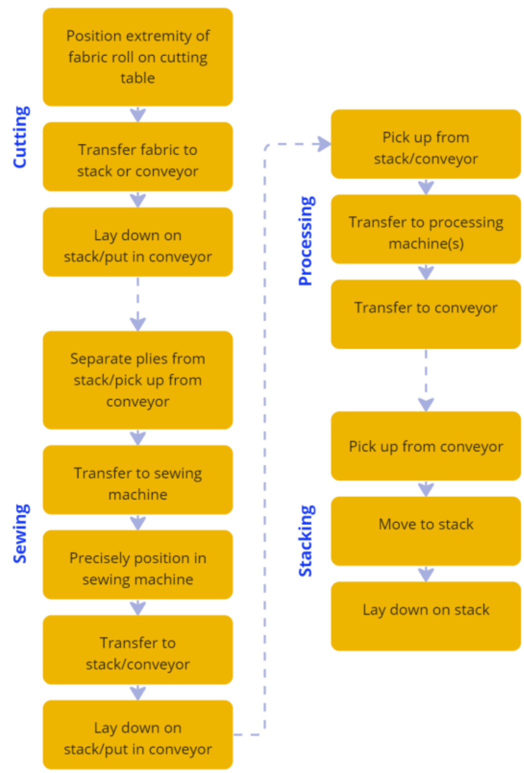


Figure 9 Visualization of all the actions the gripper must realize

3.6 Method for concept development

3.6.1 Ideation

In the ideation phase, the goal was to generate different ideas of concepts that would then be evaluated to select the most promising ones for further development. This phase was especially important as it was a creative phase that allowed for a lot of exploration, which lead to innovative solutions. Moreover, the results of this ideation are the foundation of the following phases.

To generate concepts, the focus of this ideation phase was on achieving the specific action set with the partner company: the reliable pickup and precise alignment of fabric pieces from a cutting table. To accomplish this, the end action was broken into smaller steps that are picking up fabric, translation of fabric, and placement of fabric; then different broad requirements for the gripper concepts were established based on the action (precision, reliability, control, and consistency). Then, using the design framework, those requirements were developed into more precise ones that could be easily considered in the ideation process and acted as a guideline. However, complex requirements and limitations such as universal compatibility with fabric were not considered in this phase to not restrict the creative process.

As a result, new solutions with innovative concepts were imagined, but improvements of existing principles were also imagined based on the requirements of the design framework. Moreover, to generate as many ideas as possible, different approaches were explored within each step, for example, for the fabric pickup, ideas were generated for grabbing the fabric from its edge or its surface. By breaking down the process into requirements instead of a broad action, more solutions were imagined, which enhanced the likelihood of coming up with innovative concepts. This creative process and flow of ideas are detailed further in the gripper concept section of the result chapter (page 32).

3.6.2 Development

Following the ideation phase, the next step was to develop the selected concepts. The development was carried out in different stages. To start, the different ideas were iterated based on different focuses, from precision to reliability, including performance and innovation, and on the requirements of the design framework that allowed to fulfill those focuses. This approach allowed to create different versions of each concept, but it also allowed to generate new ideas.

Then, based on the quick sketches or notes describing the ideas and their different versions, the concepts were developed to be prototyped. To do so, each concept was 3D modeled using Solidworks, during this step, the goal was also to refine and improve the ideas by taking into account the initial goal and the requirements of the design framework. Once again, this whole process is detailed for every concept in the gripper concept section of the result chapter (page 32).

By iterating on the initial concepts, the development process facilitated the creation of more refined and viable solutions. The use of Solidworks allowed for the visualization and testing of each concept, resulting in a more efficient development process.

3.6.3 Prototyping, testing, and optimization

Finally, the third phase of the development process is prototyping and testing, where the selected designs were physically made and tested based on the requirements set in the design framework. The goal of this phase was to validate the performance and functionality of the gripper concepts and make any necessary adjustments to improve them. By physically building and testing the concepts in the real world, it was possible to evaluate their capabilities and refine their design into advanced and more optimized concepts. For better efficiency, the prototyping and testing happened in two stages, indeed simple and quick prototypes were first created using a 3D printer, those prototypes were then tested by hand, which enabled a quick evaluation of the concepts' performances and the elimination of the less effective solutions. Then the final concepts (two of them) were developed and optimized further according to the result of the initial test before being prototyped into more advanced and finished pieces that could be tested on a robotic arm.

- During the hand testing phase, the goal was to quickly evaluate the effectiveness of the gripper concepts by conducting basic physical tests on a specific type of fabric, the main focus then was on assessing the gripping performance and feeling of the different concepts. To do so, each concept was tested on its grip on fabric (strong grip and non-slip requirements) and its lifting capabilities, with light and heavy fabric (gripper customization requirement).

- The robotic testing was more advanced, indeed the goal was on validating the necessary requirements of the action aimed, such as the control offered over the fabric, as well as the consistency in the handling, the precision, and reliability in gripping and positioning the fabric. Furthermore, testing of the grip on different types of fabric was also conducted. Precision, control, and consistency were first tested by picking up, translating, and placing a single piece of fabric. This simple test allowed to first assess the control of the gripper on the fabric by looking at how well can the grippers move the fabric and whether the fabric reacted as expected or whether there was a lack of control on the fabric that would cause unwanted wrinkles or movement of the fabric. Repeating this action also allowed to evaluate the precision of the grippers and if the fabric would lay down in the same zone every time, which also allowed to evaluate the consistency and reliability of each gripper by making sure the fabric was grasped and released properly every time.

  Then the targeted action was tested, by picking two pieces one by one and trying to align them precisely on top of one another, it was possible to further asses the precision, control, and consistency of the grippers. Moreover, this test allowed to validate the concepts regarding the goal set with the company, still results of this test have to be interpreted carefully as they depend heavily on the robotic arm programming.

Those tests were conducted 20 times in a row for each solution and assessment of performances was only done visually. Although precise measurement would have been great to quantitate those factors, time constraints in the company prevented it from happening. However, with the differences in performance between the selected concepts being so apparent, and one of the concepts performing significantly better, it was not necessary to carry out precise measurements to compare the concepts. Therefore, this simple testing still allowed to make informed decisions despite the lack of precise data.

By testing and prototyping in different stages, the development process also facilitated the identification and elimination of potential issues, resulting in a more robust final concept that allowed for the optimization of the design and the validation of its real-world capabilities, resulting in a more robust final concept.

4. Results

This chapter is in three parts, in the first part, results from the data analysis are presented in the form of a design framework for the design of grippers. Then in the second part result of the ideation process and quick testing of the gripper concepts are presented, finally, in the last part the most promising concepts are further developed and tested on a robotic arm.

4.1 Design Framework

This section presents a design framework that provides a systematic description of all the elements that need to be taken into account when designing a robotic gripper for fabric handling. It first focuses on general requirements that result from the development of a mind map based on the data collected, and then focuses on fabric specifications and their impact on the choice of gripping principle. Indeed, it has been found through the analysis of data that fabric specifications generate requirements for the choice of gripping principle whereas other factors generate requirements for the overall design of the gripper.

4.1.1 General requirements

The requirements presented in the tables are for the most part results of the mind map development presented in the methodology section or either the direct results of the literature review or the result of the deconstruction of the clothing manufacturing process and handling actions. The requirements are categorized according to the different factors and subcategories of factors identified earlier.

Gripping requirements: These are requirements related to how the robotic gripper must interact with the object being manipulated.

Gripping requirements	
Precise gripping: A gripper should be able to precisely grasp the extremity of a piece of fabric.	Non-slip grip: A gripper should be able to grip fabric without it slipping, even when the fabric is slippery or has a smooth surface.
Gentle grip: A gripper should be able to grip fabric without damaging it, this is especially important for weak fabrics (Kolluru et al., 1995).	Gripper customization: A gripper should be customizable to accommodate specific needs and fabric types (Koustoumpardis and Aspragathos, 2004)
Strong grip: A gripper should be able to securely hold the fabric to prevent it from falling during transport and handling (Ragunathan and Karunamoorthy, 2008).	Separation capabilities: A gripper should be able to separate plies of fabric from a stack without damaging them or grabbing numerous of them at the same time.

▼ Figure 10 Table of the gripping requirements to consider in the design of a gripper

Functionality requirements: These are requirements related to the overall functions and capabilities the gripper must achieve.

Functionality requirements	
Versatile movement: A gripper should be able to move the fabric in every way to facilitate handling. (Donaire et al., 2020)	Quick release: A gripper should have a quick-release mechanism to allow for easy release and quick performance.
Gripper flexibility: A gripper should have a flexible head to allow it to grip fabric from different angles and positions.	Vision system integration: A gripper should be able to integrate with a vision system to accurately detect the position of the fabric and ensure precise gripping and positioning (Paraskevi, 2012).
Accurate positioning: A gripper should be able to position fabric precisely to accommodate certain steps.	

▼ Figure 11 Table of the functionality requirements to consider in the design of a gripper

Manufacturing compatibility requirements: These are requirements related to how the robotic arm will be integrated into the manufacturing process.

Manufacturing compatibility requirements	
Easy integration: A gripper should be easy to integrate into the cutting and sewing process and work seamlessly with the other equipment.	Durable: A gripper should be durable enough to withstand industrial use and require minimal maintenance.
End-effector compatibility: A gripper should be compatible with different end-effectors, such as cutting tools or sewing machines, to enable a seamless workflow.	Automatic calibration: A gripper should have an automatic calibration feature to ensure consistent gripping and positioning accuracy.

▼ Figure 12 Table of the manufacturing compatibility requirements to consider in the design of a gripper

Robotic arm compatibility requirements: These are requirements related to how the gripper will be mounted and interact with the robotic arm it's mounted on.

Robotic arm compatibility requirements
Compatibility with different robot arms: A gripper should be compatible with different robot arm types and models to enable its use in various manufacturing environments.
Lightweight design: A gripper should have a lightweight design to minimize the load on the robot arm and reduce energy consumption.
Control compatibility: A gripper if electronic should preferably be compatible with the control system of the robotic arm to enable seamless integration and operation.

▼ Figure 13 Table of the robotic arm compatibility requirements to consider in the design of a gripper

Safety requirements: These are requirements related to the safety of the gripper within the manufacturing process, both for workers if there are some, for the rest of the equipment, and for the products being manufactured.

Safety requirements
Safety features: A gripper should have safety features, such as emergency stop buttons and collision detection sensors, to prevent accidents during operation.
Sturdy design: A gripper should support a specific weight without breaking
Overload protection: A gripper should have an overload protection feature to prevent it from overloading and causing damage or injury.

▼ Figure 14 Table of the safety requirements to consider in the design of a gripper

Environmental requirements: These are requirements related to the environmental impact of the gripper.

Environmental requirements	
Environmentally friendly: A gripper should be environmentally friendly, with minimal energy consumption and minimal waste generation.	Compatible with environmentally friendly fabrics: A gripper should be compatible with environmentally friendly fabrics, to promote sustainable manufacturing practices.

▼ Figure 15 Table of the environmental requirements to consider in the design of a gripper

The requirements presented above provide a valuable tool to efficiently design a gripping solution that meets the specific needs of a project. While requirements may vary a lot from one project to another, meaning that all requirements may not apply to a specific situation, they offer a comprehensive framework that can guide a designer in making informed decisions.

For example, if a gripper is intended to interact with other autonomous machines, a key requirement for it would be that 'it should be easy to integrate into the process and work seamlessly with the other equipment'. This can mean creating a compact design that allows for easy manipulation between other machines, as well as sensors on the gripper to avoid collisions or potential damage to the equipment. Similarly, if a lot of transport is involved, the gripper needs to fulfill the requirement of a 'strong grip', to do so the designer knows that he needs to create a secure hold of the fabric, which can be achieved through the use of strong motors or a contact surface with a lot of friction.

By following these requirements, a designer can be sure that he is taking into account all the relevant factors and making informed decisions that are based on the specific needs of a project and the complexity of the environment. Ultimately, the goal of these requirements is to provide a redline or guide that can help ensure the success of a gripper's design, both in terms of its functionality and its ability to integrate into its environment.

An important aspect to consider with this design framework is the clear differentiation between the gripper and the robotic arm, indeed more requirements are to consider to handle fabric but those requirements depend on the robotic arm and must not be mixed with the gripper, this is, for example, the case for the quick and efficient transportation of fabric, and compatibility with different fabric size that may require multiple robot arms, … Moreover, some gripping requirements also apply to the robotic arm as they work in hand, this is the case for the seamless integration of the system in the manufacturing environment.

4.1.2 Choice of gripping technology based on fabric specification

Based on the analysis of previous gripper development projects as well as the information presented in the literature framework, it has been found that fabric specifications mostly generate requirements for the choice of gripping principle, whereas other factors generate requirements for the overall design of the gripper. Therefore, this second part of the design framework is about the impact of fabric specification on the design of a gripper, especially on the choice of gripping principle. This part is especially important as the global design first depends on the gripping principle chosen.

This part originated from the observation that gripping principles work better with materials that have specific characteristics, for instance, Kolluru et al. (1995) indicates that material with low density and weight are most subject to electro-adhesion. Another example is the vacuum principle, which does not perform well with a permeable fabric as air goes through the fibers of the fabric (Ebraheem, Drean, and Adolphe, 2020), whereas an intrusive/puncturing technology only works with permeable fabrics as the needles can go in and out of the fabric without damaging it (Koustoumpardis, Zacharia and Aspragathos, 2006; and Ebraheem, Drean and Adolphe, 2020). From this observation, the idea was to develop a way to find the most adequate gripping principle based on the fabric used.

A similar concept has already been developed by Ebraheem, Drean, and Adolphe, (2020) in which the researchers compared gripping principles according to different fabric types (permeable, waterproof, thick, thin, release, …) however with every material even within those fabric types having different specifications, it seemed more precise and advanced to compare gripping principles based on fabric specifications. Therefore, by crossing the material specifications data and the pros, cons, and limitations of each gripping technology requirements, as well as data generated in Ebraheem, Drean, and Adolphe's framework (2020) it was possible as seen in Figure 16 below to theoretically categorize every gripping according to fabric specifications. In this figure, gripping principles are individually compared to fabric specifications, this comparison is made on three levels, '+' for very compatible, '≈' for moderately compatible, and '-' for non-compatible.

	Grip	Intrusion	Adhesion	Suction	Electrostatic
Heavy	+	≈	≈	≈	-
Light	+	+	+	+	+
Elastic	+	≈	-	≈	+
Non-elastic	+	+	+	+	+
Strong	+	≈	+	+	+
Weak	-	≈	-	+	+
Rough	+	≈	+	≈	-
Smooth	+	+	≈	+	+
Permeable	+	+	+	-	-
Non-permeable	+	-	+	+	+

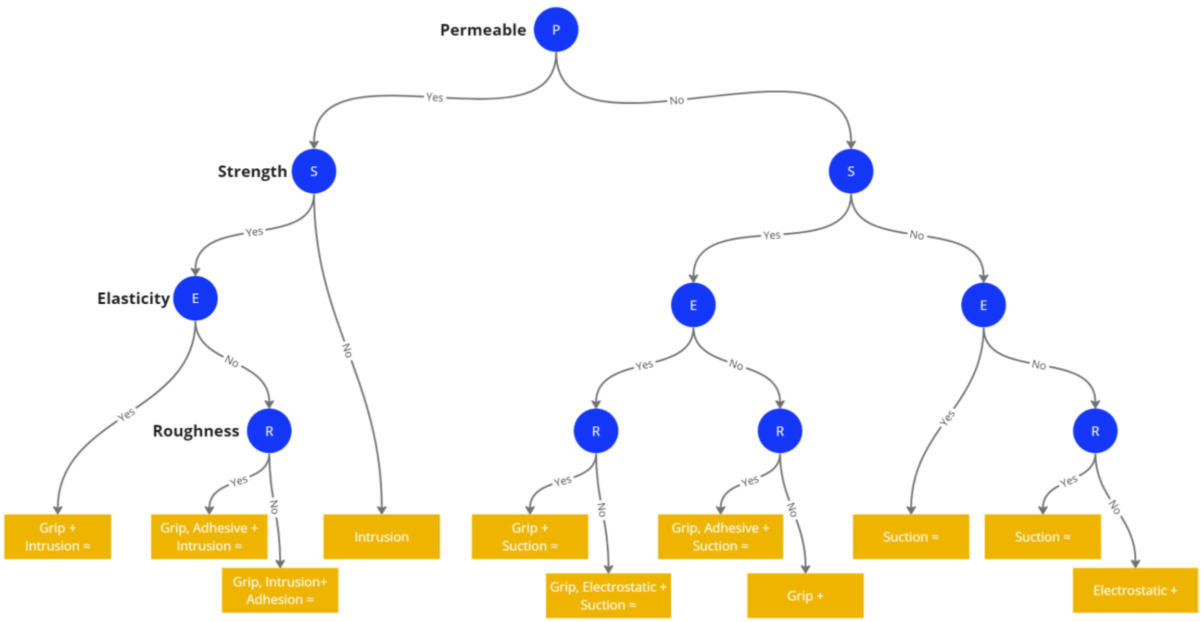
▼ Figure 16 Classification of the gripping principles according to fabric specifications (adapted and improved from Ebraheem, Drean, and Adolphe, 2020)

Using the specifications of some materials, it was possible to cross data using the results of Figure 16 above and classify the gripping principles according to the material as shown in Figure 17 visible below.

	Grip	Intrusion	Adhesion	Suction/pneumatic	Electrostatic
Canva	++	≈	++	+	-
Cotton	++	≈	-	≈	++
Denim	++	≈	+	+	-
Leather	+	-	+	-	--
Linen	+	+	+	+	+
Silk	-	≈	-	+	+
Wool	++	≈	+	≈	--

▼ Figure 17 Classification of the gripping principles according to materials

However, this process is time-consuming and not intuitive as it involves narrowing down gripping principles based on a set of attributes. To streamline and simplify this process, a decision tree was created (fig. 18 visible below) with the same objective in mind. It provides a faster, more visual, and intuitive approach to selecting the appropriate gripping principle based on material characteristics. With the decision tree, relevant gripping principles can easily be identified by following the decision path. (Weight of the fabric has not been considered in the decision as it does barely affect the final result and is more of a characteristic that needs to be considered in the overall design of the gripper).



▼ Figure 18 Decision tree for choice of gripping principle according to material specifications

4.2 Gripper concept ideation, quick prototyping, and early development

In this section, the different ideas of gripper concepts generated are presented as well as their prototype and their performance.

4.2.1 Principle combination

Based on the results of the design framework (figure 16), the mechanical gripping principle is the most universal one out of the existing principles. This principle is however bad with weaker materials as excessive force can damage them, therefore to bypass this issue, one idea was to combine mechanical grip with another gripping principle that works with weaker materials. Two options were then available within the existing principles: electrostatic and suction. Due to the complexity, danger, and equipment needed for electrostatic, it was decided to use suction instead. A similar solution already exists and is already being commercialized by Robotextile (see Figure 19 below). Still, based on the philosophy of the science park, this existing solution was looked at in more detail with the idea to improve it based on its weaknesses.

▼ Figure 19 Picture of the gripping principle combination solution of Robotextile (source Robotextile.de)

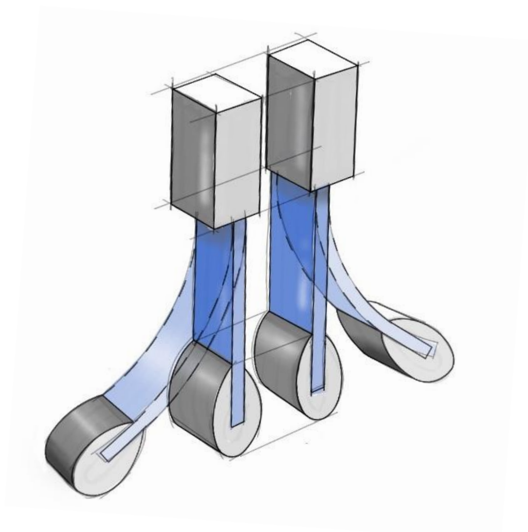
The main weakness identified in this solution is the fact that the mechanical gripping is relying on suction first, meaning that if trying to grab a very permeable fabric, the suction system won't work properly and the fabric won't be lifted, as a result, it won't be possible to grab the fabric with the clamp. This then led to the idea of a gripper where both principles can work independently from one another, but also together, meaning that they do not have to rely on each other, making the solution more universal.

However, such a system is very complex to develop over a limited time, moreover, the goal set with the company was more on achieving a specific action than on universality and complex solutions. Still, more on this concept can be read in the further research section.

4.2.2 Flexible clamping

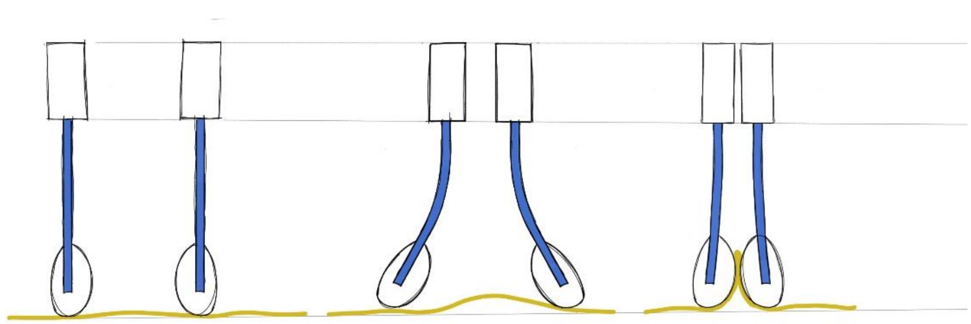
As said earlier, the mechanical grip principle is effective for most materials, but it can cause damage to weaker fabrics if excessive force is applied. To address this issue, this concept was designed with a focus on two requirements of the design framework; 'Gentle grip' and 'Compatibility with different fabrics', while still including other basic requirements such as 'Strong grip' to allow for the translation of the fabric, 'Non-slip grip', and others. Based on those requirements, variations of a classic clamping grip were imagined, including an adaptive grip to create a variable force that can adapt to any type of fabric to not damage them.

From using force control sensors to vision cameras, there are many ways to create an adaptable grip. However, to create a rapid prototype to try out the idea, a simpler version was designed using flexible and elastic materials on the gripper arms themselves (see Figure 20 below).



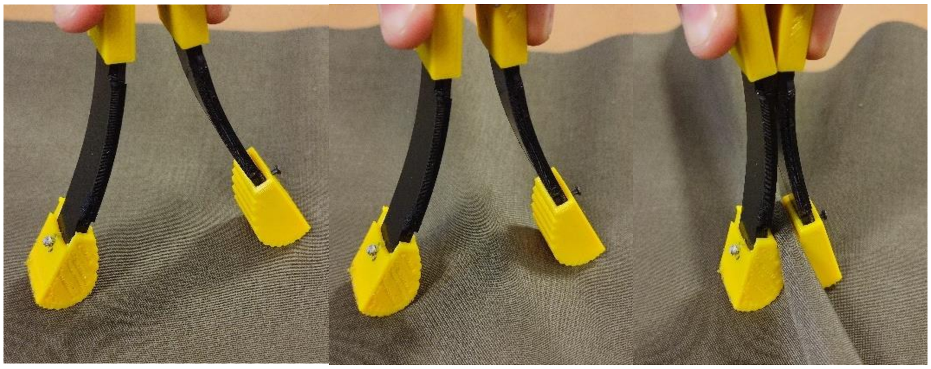
▼ Figure 20 Sketch of the flexible clamping concept

The natural elasticity of this material acts as a spring and pinches the fabric. (see Figure 21 below).



▼ Figure 21 Step-by-step sketch of the flexible clamping concept grabbing fabric

During the hand testing of the prototype, the arms had difficulty bending due to their natural perpendicular position, so an angle was added to facilitate bending (see Figure 22 below).



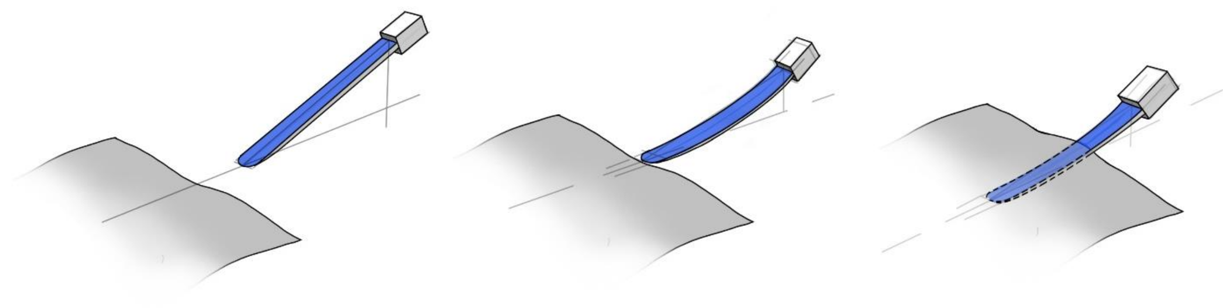
▼ Figure 22 Step-by-step picture of the flexible clamping prototype in action

The prototype of this first concept reminded of the way humans grab fabric with their hands, and after observation of the human motion when grabbing fabric, the thumb is stiff and only the other fingers are flexible. This inspired a variation of the previous solution, where only one of the robotic fingers is made flexible. However, during the testing of the prototype, it was clear that dealing with only one flexible finger was very complex. To adapt to this stiff part, the gripper required a complex system, and while the solution could probably have been developed further into a working one, it was decided not to because of the complexity, and the fact that its performance would probably not be better than the previous idea.

Moreover, testing of both solutions revealed that the gripper's bend-based principle reduces the control over the fabric. Indeed, if the fabric is bent within the gripper, it becomes difficult to predict its behavior when being released from the gripper. Despite this, the idea of using elastic materials for an adaptive grip remains a great solution due to its simplicity, and simplicity is often the best approach in engineering.

4.2.3 Flexible slider

When considering how to have the best control over the fabric and fulfill the 'Accurate positioning' requirement that was not fulfilled by the previous solution, one idea was to use a linear gripper that could grasp the fabric along its entire length, such as a long and thin slider that could slide beneath the fabric before grasping it. The goal with this idea was to constrain the fabric along one controllable line but to create a flexible solution (based on the 'Gripper flexibility' requirement of the framework), one idea of improvement was to use a long slider made of thin and flexible metal, as it would allow adapting to the angle of the robotic arm and slide flat under the fabric, even if the placement of the slider is not precise, avoiding the need to fill the 'Automatic calibration' requirement, moreover, this flexibility would also allow for a 'Gentle grip' (requirement taken from the framework) and durability.

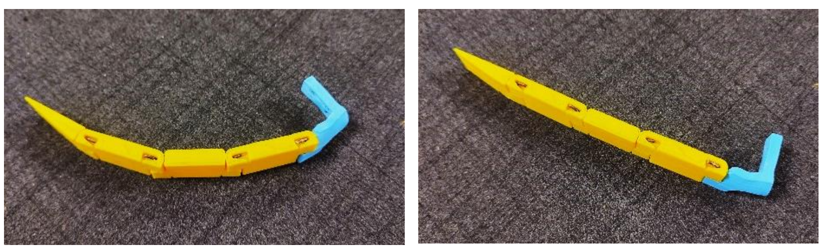


▼ Figure 23 Step-by-step drawing of the flexible slider in action

Still, this idea presented a challenge as such a slider can bend in two directions, the one wanted to slide under the fabric, but also the opposite one, unwanted in this case as it would go against the intended goal of controlling and stiffening the fabric.

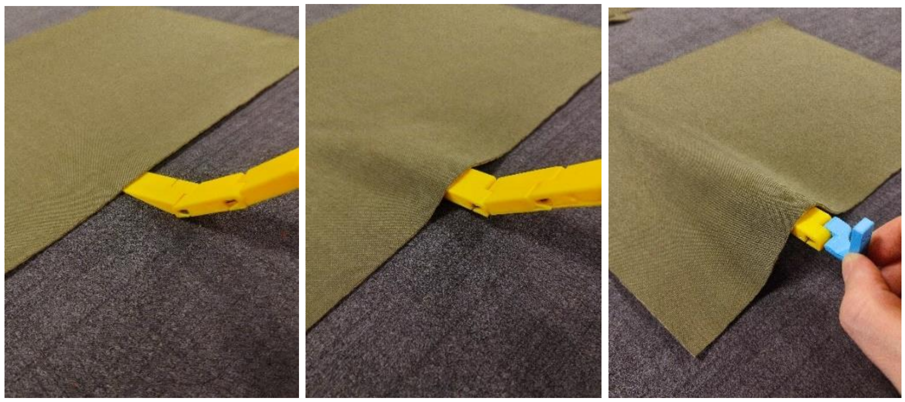
One way to solve the problem is to have a second part as long as the slider and equipped with electromagnets that could attract the slider on a straight surface while grabbing the fabric between the two parts. However, such a system is very complex to design but also to prototype as it requires specific components and an electrical system.

Therefore, to simplify this concept and test it, an articulated system was developed. This system has a one-way flexibility, which means that it is flexible in one direction to allow the slider to easily slide underneath the fabric, but stays rigid in the other direction to securely grasp the fabric.



▼ Figure 24 Pictures of the articulated flexible slider prototype (moving freely on the left and being constrained on the right)

This variant was initially made as a quick and easy-to-make prototype but it proved to be highly efficient.



▼ Figure 25 Step-by-step picture of the flexible slider prototype in action

Indeed, the gripper's flexibility allows the slider to lay flat and easily slide beneath the fabric by adapting on its own, regardless of the gap size between the robotic arm and the fabric surface or the angle of the arm with the surface. Making this solution great for picking up a single piece of fabric laid down on a flat surface. Moreover, as this concept grabs the fabric from below, it does not create any bend on the fabric, which offer more control as it avoids unwanted folds.

Based on those positive results, it was decided to proceed with the development of this solution, further development is visible in the next section (4.2.2 Robotic testing and optimization).

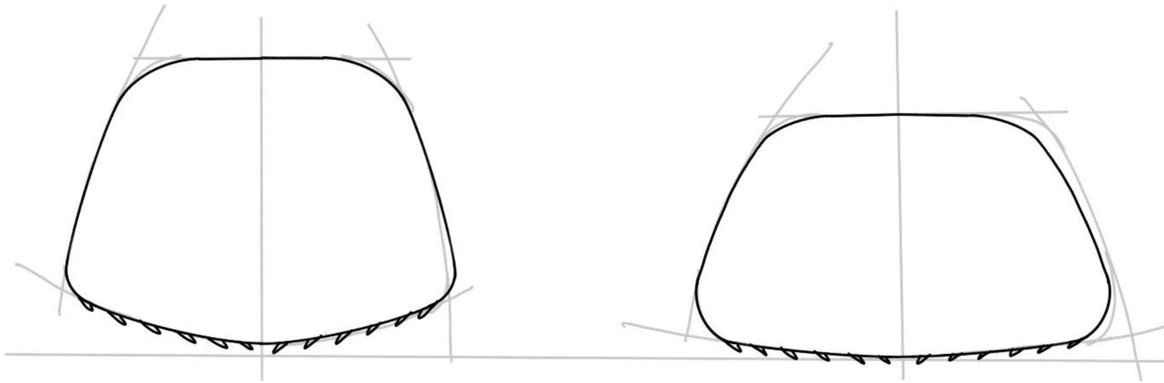
4.2.4 Soft gripper

When focusing on generating solutions that are adaptable to fulfill the 'Gripper customization' requirement, another track of exploration was soft solutions as they can adapt to any shape or surface curvature. This idea of adapting to any shape reminded of pad printings which is an inking method that uses flexible pads to transfer ink onto products (see Figure 26 attached).

▼ Figure 26 Picture of pad printing (source aola.lt)

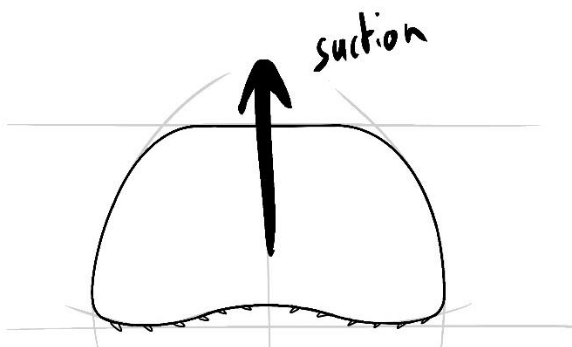
Moreover, to grasp the fabric, inspiration was drawn from the griping principles of animals and insects especially, which often involve using small/microscopic hooks to grip onto surfaces.

The overall idea is that the soft plastic material would conform to the shape of the fabric, and while doing so, the angle of the microneedles (fixed on the soft plastic) would naturally adapt and penetrate the fabric, creating a grip on the fabric (see figure 27 below).



▼ Figure 27 Drawing of the soft adaptable micro teeth concept in rest position and adapting to the fabric

However, once the gripper lifts off the fabric, its softness would make it go back to its original shape, risking that the fabric would unhook from the microneedles. To address this issue, one idea of improvement was to incorporate suction in the soft plastic part, which would make it maintain its shape and keep the needles in place, even when the fabric is lifted ensuring a secure grip on the fabric.

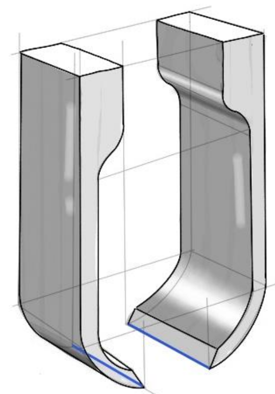


▼ Figure 28 Drawing of the soft adaptable micro teeth concept with suction

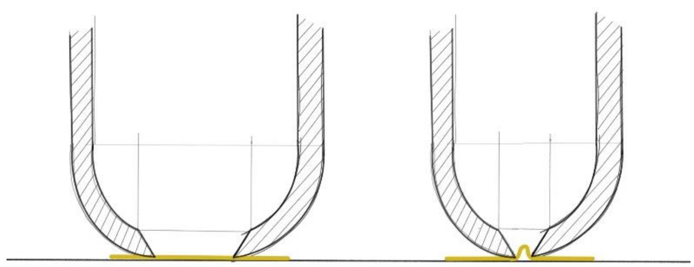
4.2.5 Micro pinching

When first trying to generate ideas, human ways of picking up fabric were looked into as a source of inspiration. After some personal experimentation, one method that can be used is to pinch the fabric with our nails. Indeed, the sharpness and concentration of force of nails offer a tight grip on the fabric, even without applying much pressure (fulfilling the 'Strong grip' and 'Lightweight design' requirements).

Based on this observation, a concept of micro pinching was developed (Figures 29 and 30) using a similar approach and using the humans' assets that allow us to grab fabric with our nails. Therefore, the micro pinching solution was designed with two sharp edges that align and meet precisely with each other to provide a linear grip on a focused zone, which would be especially useful for tasks that require precision and accuracy (fulfilling the 'Precise gripping' requirement).



▼ Figure 29 Drawing of the micro pinch concept



▼ Figure 30 Step-by-step Drawing of the micro pinch concept in action

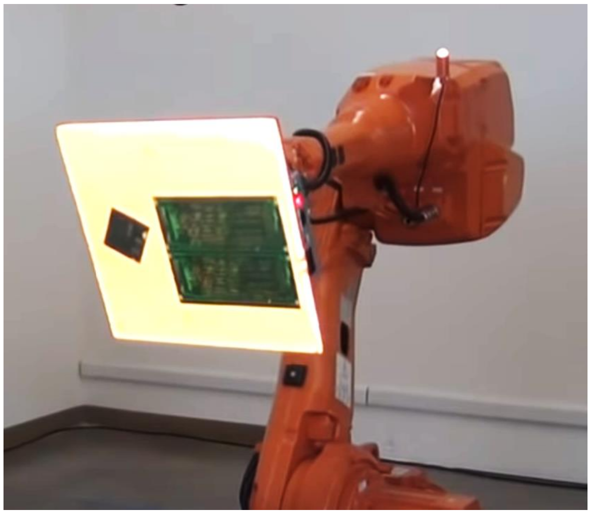

▼ Figure 31 Pictures of the micro pinching prototype in action

To test the micro pinching solution, a prototype (visible in Figure 31 above) was built and tested by hand. The initial results were promising as they confirmed that a focused application of force on fabric could allow to grab it. However, the solution's limitation quickly appeared as it was tested with different materials, indeed the concept was effective at gripping a variety of fabrics but struggled with thick fabrics and rigid materials. Another drawback of the solution concerns the linear and focused grip which limits the lifting force of the solution.

Because of these drawbacks, the gripping capabilities of this concept are not sufficient for further development.

4.2.6 Micro intrusion

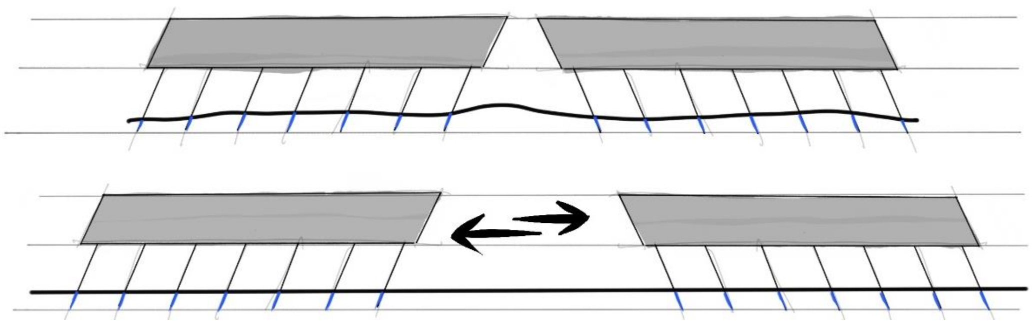
With a focus on control and especially the 'Precise gripping' and 'Accurate positioning' requirements, the idea with this concept was to find a way to replicate the lifting capabilities of electrostatic solutions. Indeed, electrostatic solutions allow the lifting of panels of materials (from fabric to glass or electronic boards) while keeping them flat during the translation (see an example below in Figure 32), which is great for fabric applications. Still, electrostatic solutions function with high voltage, making their development but also their installation very dangerous and complex.



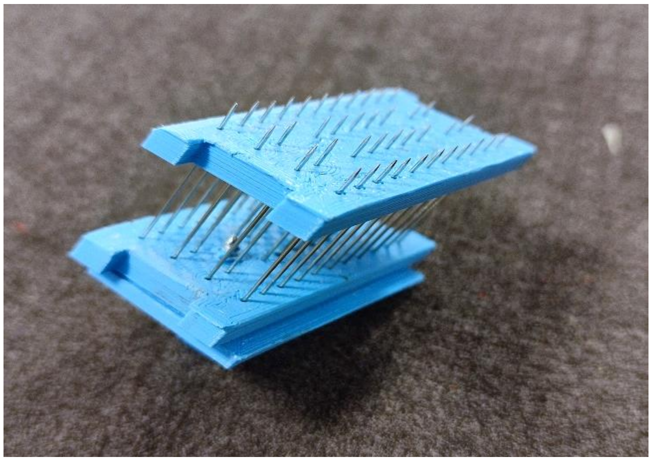
▼ Figure 32 Picture of an electrostatic gripper (source Grabit Inc)

The goal with this concept was therefore to find a way to generate a large control or even a surface control over the fabric. The first idea was to use suction in large panels and grab fabric this way, however, similar solutions already exist (from brands such as TAWI), and due to their use of suction, they present limitations when working with permeable materials.

One idea to achieve this large control was to use two pads that would grasp into the fabric and push toward different directions to create tension on the fabric and therefore have control over it (see Figure 33 below). To create a grasp on the fabric, the idea was to use needles that can only penetrate the fabric at a small depth to avoid damaging it.



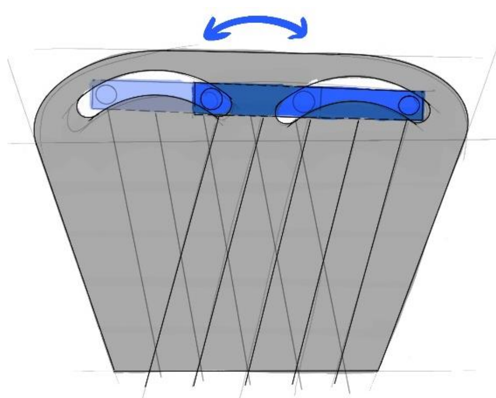
▼ Figure 33 Step-by-step drawing of the needle pad concept in action



▼ Figure 34 Picture of one of the needle pads' prototypes

The prototype of this idea (visible in Figure 34 above) showed that it was hard for every row to grasp onto the fabric and that only the first one would grab, however, even with a single row grasping on the fabric and with a tension between the two pads, the prototype was offering a good grip on the fabric.

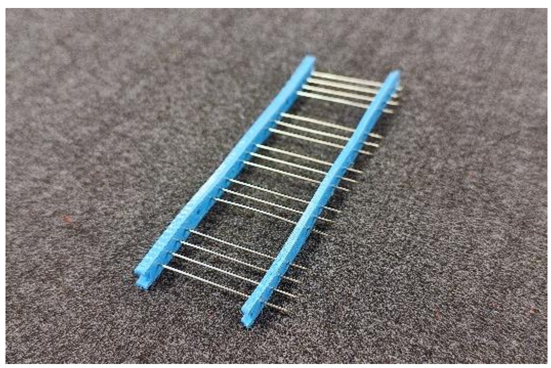
To try to explore this idea more, and come back to the requirement of adaptability, as well as the idea of creating it through flexibility. A similar concept was created where the angle of the needles could change (see Figure 35 below) indeed, based on the results of the prototype (figure 36 below), the angle of the needle seemed to be what generates the grip on the fabric. The idea behind this new version was to first lay the gripper flat on the fabric with the needles perpendicular to it and then change their angle before applying tension, the goal with this adaptive angle was to make sure that all needles are grasped and not only the first row.



▼ Figure 35 Drawing of the micro pinch concept

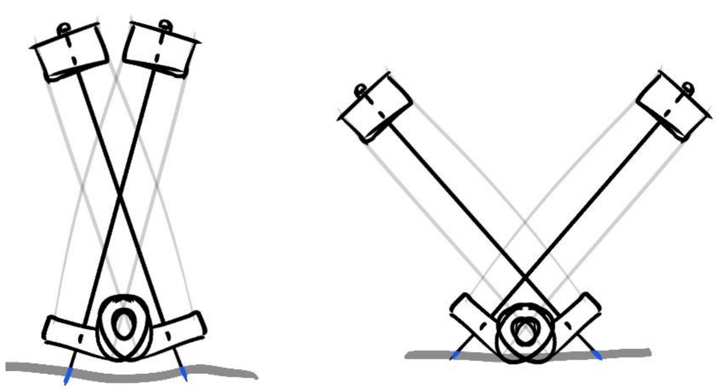
▼ Figure 36 Picture of the adaptive angle needle pad prototype

However, the prototype (visible in Figure 37) of this concept once again showed that even with an adaptable angle, only the first row was gripping the fabric, therefore it was decided to explore the potential of using single rows of needle stretching on the fabric.

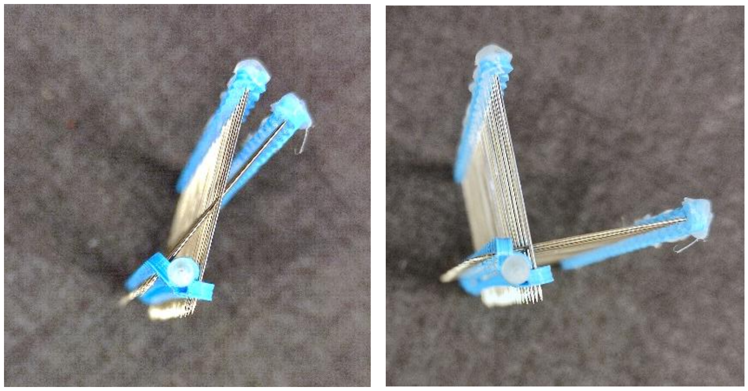


▼ Figure 37 Picture of the single row of needle prototype

The performances of this prototype were similar to the previous one, but it sparked the idea of crossing the two rows of needles so that they go in opposite directions. By adding a pivot, it was possible to adapt the angle between the needles and create the necessary tension to grasp and hold onto the fabric as visible in Figure 38 below.

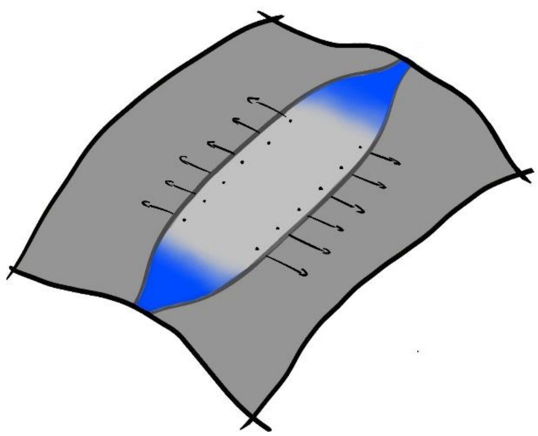


▼ Figure 38 Step-by-step drawing of the needle cross concept grabbing fabric



▼ Figure 39 Pictures of the crossed needle row prototype closed (left) and opened (right)

This prototype worked surprisingly well and with different materials as well, even if it uses needles and intrusion. The grasp of this concept is created by the difference of angles of the needles creates tension on the fabric between the rows of needles, but also on the sides of the gripper as tension spreads within the fabric, which allows for great control of the fabric (see figure 40 below).



▼ Figure 40 Drawing of the tension naturally spreading into the fabric (blue zone)

Moreover, similarly to the flexible finger concept, another great advantage of this solution is that it grabs the fabric flat without creating folds within the fabric, and as folds add a degree of randomness to the comportment of fabric, especially when it unfolds, avoiding them offers better control over the fabric behavior. Based on those positive results, it was decided to proceed with the development of this solution.

4.3 Gripper development, robotic testing, and optimization

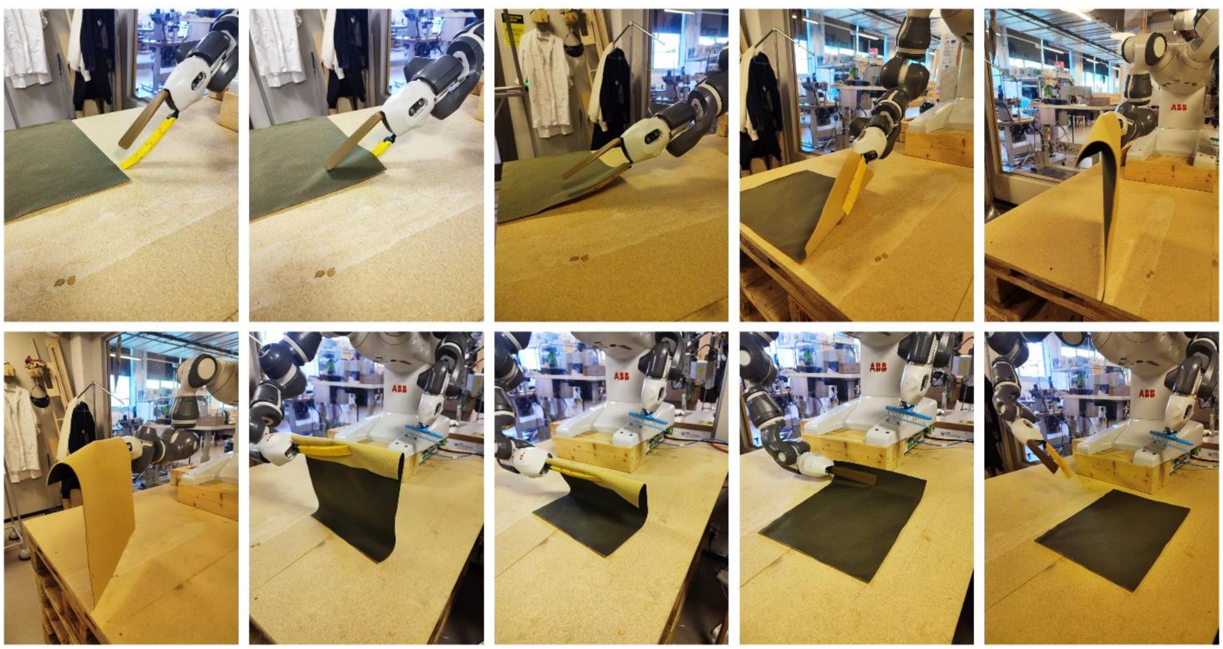
Based on the results of the hand testing, two concepts were kept for further development and robotic testing, the results of this development and testing are presented in this section.

4.3.1 Flexible slider

Once developed further by adding fixations to mount the solution on the robot, this concept did not need further improvement to be tested, indeed its initial hand testing revealed great performances and no need for specific optimization.

- Testing:

On the single piece pick up, translation, and placement test, this concept presented a level of precision of 70% as the fabric was laid down in the targeted place 14 times out of the 20 tests (results of one of the tests are visible in Figure 41 below).



▼ Figure 41 Step-by-step pictures of a successful single piece pick up, translation, and placement test

This low precision is the consequence of bad control over the fabric; indeed, the fabric tended to fold in different ways from one test to another. Those folds would then create unwanted movements or unwanted folds once the fabric was laid down, meaning that the fabric would either lay down in a different zone or in a different position as folds were created.

However, this lack of precision does not mean that this concept is bad, indeed it offers great consistency as the fabric was grasped and released as intended 19 times out of 20 (95%). During this only fail, the slider went over the fabric instead of under it, meaning that the reliability of the solution is really good as the fabric was transported properly and without falling off the gripper 19 times out of 19.

On the test of the targeted action, where two pieces are picked up individually before being laid down on top of each other, the lack of precision and control of this concept generated bad results as the two pieces of fabric would sometimes move differently or even fold, resulting on the two pieces being aligned only 5% of the time (1 test out of 20).

Regarding the material testing, this solution worked with all the types of materials tested (from thick to thin, heavy to light, elastic or not, rough or smooth, permeable or not, strong and even weak), such results were expected as the mechanical grip is indicated as the most universal principle in the design framework, however, the flexibility and flat grip of this solution also allows it to handle weak materials without damaging them.

Because of the operating mode of this concept, which picks up fabric from its edge, one specific test had to be conducted. Since the goal of the concepts developed is to pick up fabric from a cutting table, it is important to consider a specific aspect of the cutting machine, indeed this machine precisely cuts down the fabric into smaller pieces using a micro rotary knife, which results in the edges of the fabric pieces being nearly flush as visible in figure 42 below.

However, due to the natural flexibility of the concept, the slider bends over this gap as shown in Figure 42, meaning that it cannot grab fabric from the cutting table (at least not if two pieces are flush together). Because of this major disadvantage, which would require a complex system to solve the issue, this solution was not developed further as it cannot achieve the desired action. Still, the flexibility of the concept allows it to adapt to different fabrics and situations, making this solution great for simple use such as the translation of fabric pieces that can be picked from their edge and do not require much precision. Moreover, this concept's simplicity is a strength as it makes it reliable and consistent.

▼ Figure 42 Picture of the solution sliding over the fabric gap

4.3.2 Crossed needle intrusion

To allow testing of this concept on the robot, it had to be further developed to be mounted on the robot. One aspect that was essential to the proper functioning of the gripper on the robotic arm was to add crossed arms to have a constant height between the base of the gripper and the extremity of the gripper, however adding crossed arms to the gripper added freedom of movement to the gripper that needed to be constrained to guarantee the proper opening and closing, therefore a system of springs to guarantee the come back to the position of the gripper (visible in figure 43 attached) was added.

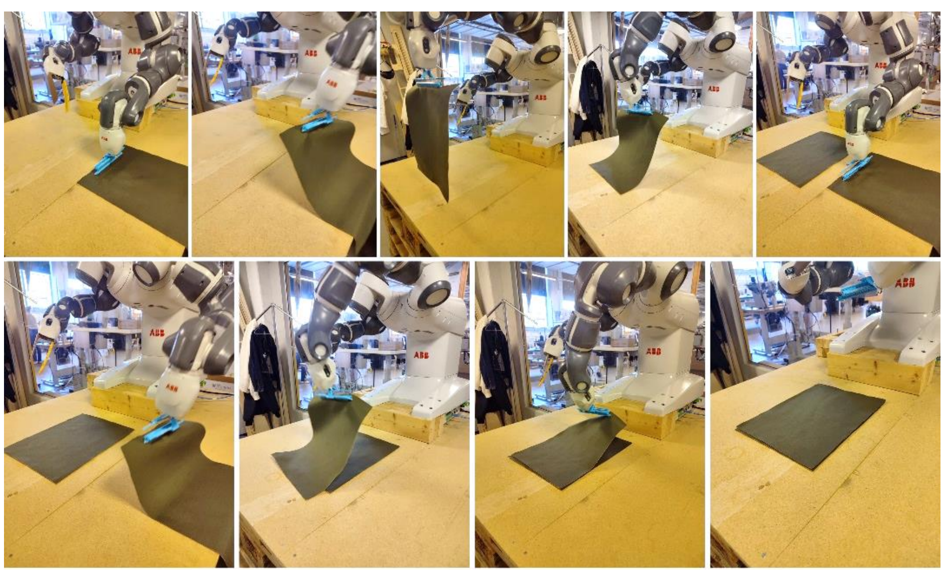
▼ Figure 43 Picture of the crossed needle solution mounted on the robot

- Testing:

On the single piece pick up, translation, and placement test, this concept presented a level of precision of 95% as the fabric was laid down in the targeted place 19 times out of the 20 tests. The one test that failed was due to the fabric being stuck on the gripper when it opened, and not releasing instead of laying in the targeted spot. Apart from this exception, the solution's consistency is great as the fabric was grasped and released as intended for those 19 times out of 20.

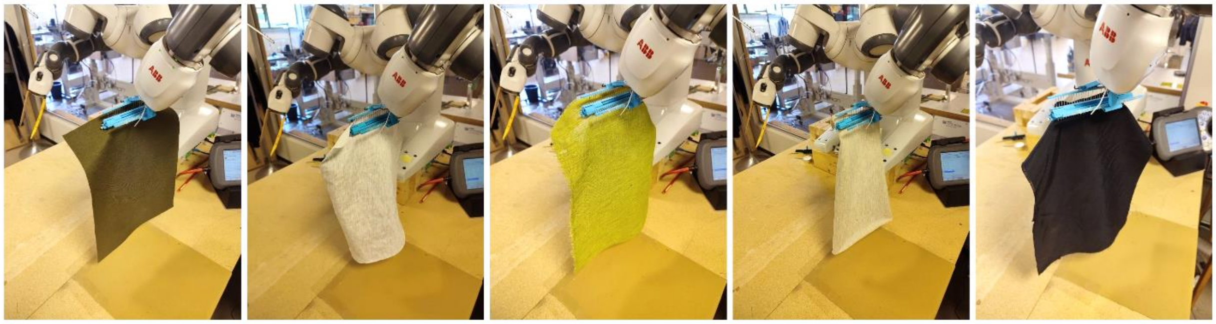
This first series of tests revealed one strength of this solution which is its control over the fabric, indeed when spreading the rows of needles from each other, tension is applied in the fabric, between the rows of needles. And as tension naturally spreads in the fabric (see Figure 40 page 45), it also spreads the control over the fabric.

On the test of the targeted action, where two pieces are picked up individually before being laid down on top of each other, this control offered by the solution allowed for reliable and precise alignment of the two pieces 90% of the time (18 out of 20), see a successful test in Figure 44 below, which fulfills the goal set with the company.



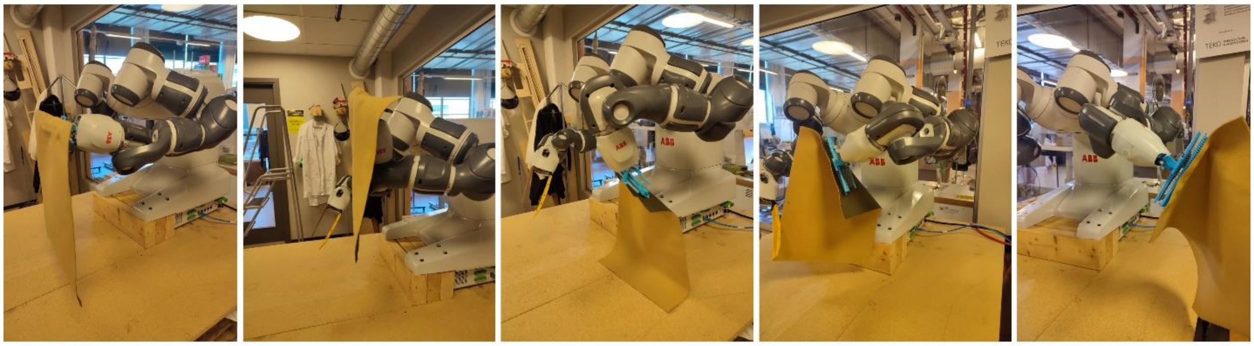
▼ Figure 44 Step-by-step pictures of a successful targeted action test with crossed needle gripper

Results of the different tests and especially the material testing (visible below in Figure 45) showed an unexpected advantage offered by the spring-loaded system, indeed, it allows the angle of the needles to slightly adapt to the elasticity of the fabric, and therefore not damage them (apart from very rigid ones). For example, if a material is slightly rigid, the needles' angle won't open entirely because the spring will stop it from happening, however, if a fabric is elastic, then the needles can open widely to compensate for the fabric elasticity and still have a grip on it. Making the solution spring-loaded allowed to grasp weak fabrics that are initially not compatible with intrusive gripping.



▼ Figure 45 Pictures of crossed needle gripper picking different materials

Furthermore, to assess the reliability of this concept further and validate it, it was subject to a stress test where the fabric was grasped and moved around in unnatural positions (pictures of the test visible in Figure 46 below). The results of this test were very positive as the fabric never grasped off the gripper, fulfilling the 'Gripper flexibility' requirement.



▼ Figure 46 Step-by-step pictures of the stress test

5. Discussion

5.1 Innovation of the final concept

The final concept developed is new and innovative on different levels. Firstly, it demonstrates that with an adaptive force, intrusion, and especially needles can be used to grab different types of fabric without damaging them (with a few exceptions). Moreover, unlikely most existing grippers, which grab fabrics from their edge except for electrostatic, this concept allows to pick up fabric from its surface, creating more control and precision on the fabric, which opens the possibilities of fabric manipulations. Finally, one of the key innovations of this concept is its utilization of the tension within the fabric itself to have control over it, this tension not only offers a secure grip on the fabric, but it also offers great control over the fabric as it slightly stiffens it.

5.2 Project methodology

By using a triple diamond methodology tailored specifically to this project, it was possible to successfully integrate design methodologies in an engineering project, and come up with innovative solutions. Indeed, engineering methods traditionally focus on technical aspects, often overlooking the importance of a holistic vision of the problem, therefore by incorporating approaches taken from the double diamond methodology, and the DRM, the complexities of the project and the problem itself could be explored on multiple levels. This holistic and deep understanding provided valuable insights that allowed to frame the scope of this thesis and ensured its alignment with the project's environment. Moreover, it allowed for an in-depth analysis of the influencing factors on fabric gripping/handling.

Moreover, with the diverging and converging approach taken from the double diamond, it was possible to combine divergent thinking to explore a wide range of concepts and gather a comprehensive understanding of the problem, but also convergent thinking to focus on refining the study and identifying/developing potential solutions.

Another interesting aspect of the methodology used in this project was the use of prototyping and experimentation, which played a crucial role in the project's success. Indeed, with the use of quick prototyping techniques such as 3d printing, it was possible to rapidly explore and test different design ideas. This iterative process not only allowed to discover valuable insights, but it also facilitated the generation of ideas; a great example is the crossed needle gripper, which initially started as a completely different concept but evolved into the final solution through different iterations. The prototyping phase led to more robust and innovative concepts, moreover, it provided a mean of experimentation and validation, that also bridged the gaps between theory and practice, a great example once again related to the crossed needle concept, is the use of needle on weak fabric, which is usually described as not possible.

5.3 Gripper design framework

The design framework developed in this thesis was a valuable tool in the development and generation of ideas for grippers for fabric manipulation. Indeed, by highlighting the different requirements to consider based on the gripper's environment, the framework offered a holistic approach to address the complexity of fabric gripping.

Throughout this project, and especially during the development phase, the framework was used as a guideline, the final solution developed demonstrates its effectiveness as the final concept developed achieves the targeted action.

The requirement part of the framework covers a wide range of factors that need to be considered in the design of a gripper, from gripping requirements to functionality ones, or even manufacturing compatibility. By using this framework, it was possible to identify and address the key factors necessary to handle fabrics for the targeted action, and it helped make sure that key requirements were not overlooked, maintaining a holistic approach throughout the design process. In addition, an unexpected use of the design framework was to compare and validate the concepts developed, for example; by evaluating how each concept met the framework’s requirements, it was clear that the cross-needle concept met more requirements than other concepts, and the testing of the solution proves it to be better. This result highlights the framework's capacity to not only facilitate the development of solutions but also to compare and validate them.

However, it is important to note that the framework is based on existing and previous knowledge and experience in the field, therefore, some recommendations such as the limitations and choice of gripping principles may not apply to new and innovative solutions. For instance, the framework describes mechanical grippers as ineffective for weak fabrics, but the mechanical grippers developed in this project (while taking into account the limitation of this principle) showed the opposite. Similarly, the framework describes needle gripping as problematic for gripping fabric, but in reality, this is more complex as it can depend on the type of intrusion performed.

So, while the framework highlights certain limitations of existing gripping principles, it should not discourage designers from exploring and using alternative principles that may go against the framework's recommendations.

5.4 Multidisciplinary nature of the problem-solving process

The development of a robotic gripper for material handling turned out to be an interdisciplinary process that requires expertise in various fields including mechanical engineering, material science, programming, and robotics. Working on such a project alone was therefore difficult as it required time-consuming learning in unfamiliar domains. This difficulty emphasizes the importance of multidisciplinary teams in solving complex problems, indeed working with experts from different disciplines not only allows for more effective problem-solving by using collective knowledge and skills, but it also gives a more comprehensive and holistic approach to a problem, for example; in this project, the individual holistic understanding process took several weeks.

5.5 Ethics and Sustainability

The concepts developed in this study have the potential to accelerate the clothing-making automation revolution by solving one of its biggest challenges; the gripping and handling of fabric. Such an acceleration brings us closer to clothing-making automation and therefore, local production in expensive labor regions, through projects like the Science Park Boras’ micro factory project. This has the potential to create a shift towards local production, which would directly impact the carbon footprint of the fashion industry, as clothes would not have to be transported across the world and from countries that still use fossil energies to produce their electricity, resulting in significant savings in terms of energy consumption and greenhouse gas emissions. Such a shift would not only reduce the environmental impact of clothing production, but it would also promote sustainable manufacturing practices, even for complex manufacturing processes like clothing making. This shift towards local production would also impact the current state of the clothing industry, indeed fashion and especially fast fashion rely heavily on outsourcing labor to countries where unethical working conditions, low income for workers, and child labor are common. By making local production possible through automated clothing making, we can potentially end those practices, moreover, the shift towards local production would also have a positive impact on the local economy, as new job opportunities could be created in the textile and clothing industries. Additionally, enabling local production would also support small and medium-sized businesses, which are essential elements of local economies. Combined, these shifts would create a sustainable economy with long-term growth and prosperity.

On an ethical aspect, the principal concern is about replacing human labor with robots. While such a change would be beneficial against regions with unethical labor conditions, there are many regions where workers are protected by labor laws, and where working conditions are good. In those regions, automation would result in job loss and displacement of skilled workers, which could potentially lead to economic and social disruptions. However, it is important to note that the benefits of automation may outweigh this potential cost, moreover, as said earlier, the shift towards local production would also create new educated job opportunities in the textile and clothing industries to manage factories, program them or even maintain robots.

6. Conclusion

In conclusion, this study addressed the research questions that were: •What parameters need to be considered in the design of a robotic fabric gripper, and how to integrate them into a design framework? And, •How to design a concept of fabric gripping device to handle non-stiffened fabric?

Those questions were answered by exploring the factors to consider for the design of a gripper through a holistic exploration of the problem and its environment, developing a design framework that can guide the design of a gripper based on these parameters, and finally developing a concept of gripper that achieves the targeted action and can handle a variety of materials.

By using a triple diamond methodology tailored to this project, incorporating design methodologies such as the double diamond and the DRM in an engineering project was made possible. The triple diamond allowed for a deep understanding of the problem, and the exploration of factors and parameters that go beyond traditional engineering constraints. Moreover, this methodology allowed to diverge, converge, and iterate, and therefore, come up with multiple new innovative concepts that were then prototyped and further developed. This iterative approach not only facilitated the generation of innovative ideas and the discovery of valuable insights, but it also bridged the gap between theory and practice.

One significant learning from this study is the importance of flexibility (as in adaptative) in the design of a gripper, indeed every solution that has been designed this way presented significantly better performances than non-flexible solutions. This difference in performance allows flexible solutions to grab different types of material with different characteristics without damaging them, but it also allows for more complex handling operations or manipulations.

As a result, this thesis has investigated the fabric gripper key factors, developed a design framework, and created a gripper concept for gripping non-stiffened fabric. Results highlight the importance of flexibility and control in a gripper design, furthermore, they contribute to the advancement of fabric manipulation in robotics and generated insights for ethical and sustainable manufacturing practices in the fashion industry. With more research and development in this area, the handling of fabric may be revolutionized.

7. Future work

7.1 Further development of crossed needle gripper

Due to the limited period spent in the company developing and testing the different concepts, the final solution still is at a very conceptual stage. A working prototype was developed and shows that the concept works and is efficient, but many aspects of the solution still need to be investigated and experimented with. One aspect that needs to be studied further is the impact of the needles' length, diameter, and depth on the fabric regarding the grip generated on the fabric and the potential damage to it. Furthermore, the idea of creating tension within the fabric to have better control over it also needs to be studied to validate that it has an impact, but also to find ways to improve it and have the best control over the fabric possible.

Finally, this solution still needs to be simplified and made more reliable, indeed as of today the solution is not very stiff and fragile for industrial use. Talking about industrial use, this concept needs to be developed into a proper first version that could sustain industrial use ('Durable requirement' of the design framework), moreover, the solution needs to be developed into an all-integrated and working solution that could be mounted on any robotic arm, this means motorizing the concept and making it adaptable to any robotic arms. With those tasks achieved, the solution could then be further developed and optimized into a second, third, or fourth version before being finalized and commercialized for example.

7.2 Gripping principle combination concept

Due to the limited time for solution development, an interesting concept has not been explored: The principles combination solution. This solution combines mechanical grip and suction to benefit from both methods, which could give the solution the potential to perform greatly. Indeed, the main advantage of this solution is its universality when it comes to material handling. As seen in the design framework, each principle works with a limited range of materials, therefore, by combining the two principles, every material could be handled regardless of its characteristics or specifications. If designed with the ability to work independently or simultaneously, the solution would be even more versatile as mechanical gripping could be used to lift or transport fabric for example, and then suction could be used to hold them in place for more precise manipulation. Alternatively, both principles could be used simultaneously to create a stable and secure grip on the textile, increasing the efficiency of the solution and reducing the need for multiple handling devices or manual intervention.

7.3 Manufacturing

Another track of future research regarding clothing-making automation is on the process itself, indeed the current approaches to automatic clothing production often replicate the human manual process. This is done by breaking down the process into individual steps that are usually carried by humans, such as cutting, sewing, and finishing touches, and then replacing the human doing that specific step with a machine or robot.

However, the results of this approach will never be the most efficient, since the human process was designed around human capabilities, who usually have a set of skills in one specific area (including cutting, sewing, or finishing touches). As a result, current solutions are machines that focus on single steps only; automatic cutting, and automatic sewing machines, … Then, solutions like the one designed in this study have to be created to link those machines together.

Therefore, future research should focus on rethinking the entire process based on the unique capabilities of robots. To achieve this, the manufacturing process may need to be redesigned, by being more continuous and less centered on individual steps, or by carrying multiple steps of the process at once. Such a redesign has already been done by a diaper maker, whose process was reinvented and its entire assembly process is now performed on a single piece of fabric, which is then cut into individual diapers once they are fully assembled. Closer to the process used in sheet metal automation than human manufacturing of diapers, the diaper manufacturer was able to streamline its production process and improve efficiency and consistency in product quality. By leveraging the strengths of robotic technology, the diaper manufacturer managed to revolutionize its process and stay ahead of the competition.

Such a change would revolutionize the way we make clothing, improving the process by making it more efficient and potentially creating other benefits.

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