INDUSTRIAL SORTING GRIPPER FOR HANDLING TISSUE GOODS: DESIGN AND DEVELOPMENT

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Abstract

Fabric and textile materials are widely used in many industrial applications and the manufacturing industry has always shown a great interest on the development of novel grippers which are able to simulate the movement and the skills of human hands. Specifically, the robotics industry has focused on repetitive, dirty and dangerous tasks. Moreover, there is an increasing need of grippers capable to perform tissue manipulation operations quickly and in a reliable way. Certainly in industry there is difficulty in handling tissues with different characteristics such as the material, shape, weight, size and texture. Textile Industry produces also delicate tissues which could be damaged during the grasping or during the manipulation. There are also very porous tissues that some types of gripper are unable to grasp and manipulate. This thesis presents the development of a novel gripper capable of grasping and manipulating tissues with different characteristics. The proposed gripper is reconfigurable and can exploit intrusive and non-intrusive grasping methods. This grasping system is composed of a parallel gripper with two wheels (rollers) on each finger. Each roller has a mechatronic system capable of extracting and retracting microspines. The gripper was mounted on an ABB robotic arm and the experiments were performed following some grasping and manipulation methodologies found in the literature; also a novel grasping and manipulation methodology, called inverse grasp, has been proposed and tested.
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CHAPTER 1

Introduction

1.1 Importance of developing new grippers for tissues manipulation

Nowadays, it is very important, for manufacturing industry, to develop automated systems that are capable of dealing with tissues. The main reason is that a large number of industries involved in manufacturing sectors like construction manufacturing, food meat processing, aerospace industries, garment manufacturing, biomedical materials etc. are interested in developing a novel system which can be exploitable for grasping and handling different kind of tissues [8]. The manufacturing industry deals, for a good percentage, with tissues such as: garments, cloths, sheets of paper, plastic sheets, leather etc. These kind of objects require strong skills in handling and, for this reason, are performed mainly by humans [13]. A large part of these industries have a great need for simple, reliable, versatile and low cost grippers for grasping and handling tissues. There are other advantages for developing these kind of systems, for instance, they reduce labor cost and another aspect not to be underestimated is the decrease in physical effort for reducing physical burden on workers [4] [28]. In robotics, grasping and handling rigid objects is now a mature field instead, the study of
deformable objects is not so extensive in the research community. Unfortunately, a deformable object has infinite degrees of freedom, which makes form closure impossible. Also, the grasp wrench space changes as the object deforms, which makes force closure analysis inapplicable [5].

1.2 Research Objectives

The aim of this research was to study a novel mechatronics system in order to develop a gripper prototype that is capable of grasping and handling tissues in a fast and reliable way. In this thesis are included theoretical concepts, CAD designs, simulation, prototyping and a proof of concept with a final test of the gripper prototype in a test rig.

The design criteria used for developing the novel gripper are listed below:

- Grasp and handling different types of tissue.
- Increase reliability of the initial grasping of different tissues.
- Grasp only one tissue at a time from layers.
- Keep grasped the tissue during the fast movement of the robotic arm.
- Minimize wrinkles and distortions after dropping of the tissue.
- Avoid damaging of the tissue.
- Grasp the tissue with different methodologies.

1.3 Thesis Outline

Chapter 2 presents a general approach overview of the argument for the thesis, the literature regarding the classification of the grippers, characteristics of tissues, the typical tissues manipulation solutions and new knowledge about robotic grippers.

Chapter 3 explains the reasons that led to the development of the robot gripper prototype and the structural characteristics of the new
gripper are explained. Part of the chapter is dedicated to the kinematics of the ABB robot.

Chapter 4 shows the best known tissue grasping methods, divided into intrusive and non-intrusive methods. In the last part of the chapter a new methodology for the grasping and manipulation of fabrics is introduced.

Chapter 5 presents the experimental activity to achieve the objectives and illustrates the characteristics of the fabrics chosen for the experimentation. The chapter is devoted to the description of the experimental tests, specifically: the manipulation of the single tissue with and without microspines; the manipulation of the tissue placed on a pile with and without microspines; the manipulation of delicate and easily damaged fabrics; experimentation of complex manipulations with inverse grasping.

Chapter 6 is the conclusion of this thesis, including the discussion of results of experimental activity, future recommendations and critical issues.
2.1 Introduction

Nowadays, for Industries, there is a need to increase productivity and constantly improve the quality of their products. This reason has led to an ever greater increase in research and development in the field of automation and industrial robotics. In the garment industry the handling and manipulation of fabric panels is estimated around at 80 percent of the total production line time \[12\]. All materials deform during grasping and manipulation. There are a variety of flexible or “non-rigid” materials where such deformations are very significant \[34\]. This is given by the nature of the materials, which react in changing their initial shape also when a very low forces are applied in them that are normally required for grasping and ordinary handling actions. Thus, it is very important for researchers designing gripper for grasping and handling tissues. A gripper is a device which is capable to hold and manipulate objects. This device must to have the capacity of grasping and releasing objects while performing an action. In Industry, grippers play an important role in grasping and handling tasks \[26\]. The first research results of grippers for handling tissues is recorded around 1980s. Since the early of 1990s a lot of gripping systems
were developed mainly on mechanical principles with elementary control and sensing capabilities. Afterwards, the researchers developed new approaches for developing gripper design and for controlling it. These approaches were taken into account the effects of the tissues proprieties and characteristics in order to have accurate accomplishment of the grasping and handling tasks. Therefore the proprieties and characteristics which must be taken into account for the effectiveness of a gripper are:

- Material Type
- Thickness
- Stiffness
- Permeability
- Elasticity
- The ability to keep an electric charge
- Weight per unit area
- Wettability
- Hairiness
- Friction
- Adhesive

An useful gripper must be able to grasp and manipulate different tissues with a variety of:

- Sizes
- Shapes
- With a wide diversity of properties
- Single ply or multiple-layer plies

The gripper must to be reliable in grasping and handling tasks therefore it must be able to perform a safe transportation of the tissues from an initial point to another one.

2.2 Classification of the Grippers

A classification of the grippers according the “Handling technique”, in conjunction with the “Gripping principle” is presented by researcher as Taylor [34], J. Stephan and G. Seliger [27]. The terms “Handling technique” and “Gripping principle” characterize the type of approaching and gripping the tissue respectively.
2.2. Classification of the Grippers

In the international literature and in the market there are a collection of many version of grippers. There are advantages and limitations, for this reason, below is explained a detailed description of the capability of each type grippers.

2.2.1 Two-sides attraction Grippers

Clamp Grippers

The clamp grippers are useful for gripping fabrics already positioned on a surface or when an edge is approachable. Some studies have tried to apply clamp grippers in the removal of tissues. An example of a commercially available Clamp Grippers is that of Walton Picker \[25\] which uses the clamp principle. Walton Picker’s device improves on Walton Pickup’s model, which used a very complex system to separate the layers, consisting of air foil, needles and suction. Paul and M. Dixon \[24\] presented a clamp gripper with two grasping points, but it was designed for a specific task. Therefore its application is limited. Another example of a clamp gripper is that of Karakerezis et al. \[7\] which is used to manipulate regular objects of flat shape. This gripper can be used to grasp a variety of objects with different sizes and shapes because the gripping system can change the distance between the two grasping points.

Pinch Grippers

Pinch grippers are designed for grasping and positioning in tasks. Two pliers are moved towards the tissue, they are closed in such a way on the tissue in order to create a fold and take it firmly an in a reliable way. This method is safe for grasping the tissue but has problems carrying it on a flat surface and positioning it without bending or wrinkling. The Clupickers gripper \[2\] \[30\] from the 1980s is bioinspired by the workings of human fingers. This gripper can grasp and lift the tissue from a stack like the movement of a human fingers. This device is outdated because it does not sufficiently take into account the properties and behavior of materials.

Taylor \[35\] has proposed an analytical model of pinch gripper that relates the friction and characteristics of the fabrics with the behavior of the gripper. Another example of a gripper inspired by the functioning of the human hand is that of Ono et al. \[19\] \[22\]
Chapter 2. State of the Art

This gripper is a complex mechanism, built with gears, belts, etc. The Ono gripper has been equipped with thickness, force and tactile sensors. A newer model of pinch gripper has two human-like fingers that can grab the tissue from a pile of materials without damaging it.

2.2.2 Intrusive Grippers

The first grippers with integrated pins were initially developed by Durham [29]. In this type of grippers, the pins have been positioned around the circumference of a cylinder. These pins are used to capture the fabric as the cylinder rotates. This model has been improved because it has been equipped with optical sensors that allow the gripper to position the tissue on a stack precisely and accurately.

<table>
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Figure 2.1: Classification of mechanical grippers.

2.2.3 Surface attraction

Pneumatic grippers

There are two types of gripper with the pneumatic method: those that use suction cups and those that use airflow or air jet. The first to apply airflow to grippers was Ozcelik [23], but only a year later his
2.2. Classification of the Grippers

own research group studied grippers capable of handling rigid and semi-rigid tissues. Kemp et al. [9] instead combined the principles of the air jet with the clamp. The air jet, positioned on the gripper, is used to lift the fabric by a clamp which will then be captured by two jaws. The gripper was equipped with two sensors, one to detect the tissue on the stack and another to confirm the capture. However, grippers that use the air jet have some critical points: tissues can have characteristics of different materials, such as porosity. If the tissue is too porous, the gripper is unable to manipulate it. This type of gripper can only separate the tissue from a stack. To make the vacuum gripper more functional, the porosity and weight properties of the tissues must be taken into account. Kolluru with his research group [11] developed a gripper on the vacuum principle. This gripper captures a pre-separated tissue or an entire stack at a time, and then repositioned it accurately. A number of revisions have been made to improve the initial model. The same research group, after five years, has come up with a reconfigurable gripper system capable of manipulating tissues of different shapes and sizes [10].

Adhesive grippers

Adhesive grippers are tapes or rollers coated with glue. Certainly these grippers have disadvantages: you need to find an adhesive material that works with different types of tissue. Furthermore, the glue could damage the tissues or create problems during the manipulation. Stephan and Seliger [27] have developed a gripper that uses the principle of freezing. However, the same researchers tried to solve the problem of damage to manipulated tissues. Grippers work with frozen water which allows the grasp of the tissue; the frozen water is liquefied, by compressed air, therefore the object is released.

Electrostatic grippers

These grippers use the attraction of electrostatic forces to grasp the tissues. These grippers can handle tissues with a low density and large molecular weight properties, such as cotton, silk and nylon [18] [36]. The advantages of these grippers are: the tissue treated is not damaged and wrinkles are not created when the object is
placed. It may happen that due to the electrostatics, several tissues are grabbed at the same time. Also, a potential greater than 4000V must be applied and this can cause malfunction to electronic parts.

**Brush and Velcro grippers**

This type of gripper uses the principle of the scrubbing-brush [15]. This principle is possible characterized as an intrusive method because it can be compromise the integrity of the material. This type of gripper can only be used with very thick or very porous materials. Lundstrom [15] used the velcro principle, creating a gripper that uses two strips of material with fibrous hooks or loops. The velcro gripper can grip a limited number of tissue and also there is the problem of removing, from the gripper, the tissue without damaging it.
2.3 Characteristics of tissues

Many materials processed by the manufacturing industry can be studied as flexible and deformable flat sheets. These tissues have different types of structure. Most are fabrics made from textile fibers produced by interlocking raw fiber materials.

There can be several properties that can be used to describe the behavior of tissues. These properties can be mass like uniaxial, biaxial tension and compression traction, compression and shear, bending behavior, torsional response, under a stress concentration, dimensional stability and fatigue resistance, etc. We can also identify surface properties which are contact behavior, roughness, resis-
tance to friction, friction and resistance to stress concentrations, etc. We can also have transfer properties which are air permeability, water permeability, filtration efficiency, resistance to penetration and heat transfer, etc. When handling activities take place through grippers, we have to take into account the properties of tissues such as structure, roughness, area weight and stiffness. In addition to the material properties, geometric properties such as size, thickness, also the shape.

### 2.4 Contemporary grippers for grasping and manipulating tissues

The manipulation of objects through robots that simulate the functioning of the human hand still remains an interesting and evolving field of research. This type of study would allow us to develop robots that are increasingly capable of performing more difficult tasks such as positioning an object after having grasped it. In this section we will describe some recent prototypes of grippers which are interesting from the point of view of the manipulation of tissues.

#### 2.4.1 Rollers gripper

Shenli Yuan et al. [40] have developed, in 2020, a gripper prototype with articulated active rollers at the fingertips as shown in Figure 2.3. These rollers are rotatable and allow infinite rotations of the gripped object, without moving the fingers. The gripper is made up of three kinematically similar fingers, each made up of DoF. Neoprene strips are placed on the rollers to increase grip. The fingertip roller is capable of rotating continuously and Neoprene was used to increase finger grip. The gripper just described weighs 800 g and each finger can provides 20 N of normal force at the roller center.
2.4. Contemporary grippers for grasping and manipulating tissues

![Image of a roller gripper prototype](image1)

*Figure 2.3: The roller gripper prototype taken from [40].*

2.4.2 Needles gripper

Subyeong Ku et al. [14] have developed, in 2020, a gripper prototype capable of manipulating objects in a delicate way, for applications in the clothing industry. The inspiration comes from the observation of a parasite (as shown in Figure 2.4 (a)), called Lamprey, famous for its strength of adhesion to the surface to which it adheres.

![Image of oral disc, top view of microneedle-embedded soft gripper, and enlarged image of embedded microneedle](image2)

*Figure 2.4: (a) Oral disc with sharp teeth of Pacific lamprey (Lampetratridentata). (b) Top view of microneedle-embedded soft gripper. (c) Enlarged image of embedded microneedle. Picture taken from [14].*

The gripper can grasp a fabric from a pile and hold it without damaging it. The gripper consists of two different silicone elastomers with embedded microneedles inspired by the lamprey’s mouth. This gripper can easily grasp tissue with porous structure with microneedles and then the vacuum allows a more stable and secure grip (as shown in Figure 2.5 (c)). Two forces are used to hold the fabric: friction and suction. It is important to know that the microneedles on the tip of the gripper are only used to pinch the
fabric but not to hold it. The frictional force is proportional to the coefficient of friction and the normal force applied to the contact surfaces of the gripper as shown in Figure 2.5 (a).

![Figure 2.5: (a) Schematic of the proposed gripping mechanism. (b) Simple free-body diagram with forces applied to the fabric. (c) Schematics (top) and actual photos (bottom) of gripper operation. The pressure inside the gripper, P, is lower than the atmospheric pressure. (d) Gripper base with embedded needles (left), deformable end-effector (middle), and assembled gripper (right). Picture taken from [14].](image)

### 2.4.3 Magnetic gripper

Mag grippers exploit the principle of electromagnetism to manipulate the object. The mag gripper proposed in [16] is lightweight, modular and with a limited encumbrance. This particular Mag-gripper is similar to a jaw gripper but in its central part there is an electromagnet which is mounted on the top of a linear actuator (as shown in Figure 2.6b). When the electromagnet is active, a magnetic field is generated which causes a magnetic force attracting the metal part attached to the cloth. This electromagnet is used in combination with the jaws: the former allows to lift up the cloth while
2.4. Contemporary grippers for grasping and manipulating tissues

![Mag-Gripper prototype and Mag-Gripper CAD](image)

**Figure 2.6:** Mag-Gripper taken from [16].

The jaws allow a safe grasp during the cloth manipulation. Therefore this gripper takes the advantages of both the electromagnet and the jaw gripper. The advantages of this gripper are:

- Very simple and low-cost.
- Under-actuated (only one actuator).
- Reliable grasping.

Unfortunately this gripper needs a metal plate embeded in the object to be manipulated otherwise the electromagnet is not capable of grasping and manipulate objects.
Description of the proposed gripper

3.1 Motivation for the proposed gripper

A first inspiration, for developing the new gripper, starts from some papers which deal with manipulation of tissues using a parallel gripper that has placed two rotational wheels on the top of each fingertips [6] and exploits some ideas used to pick up textile fabrics from layers described in [20] and [21]. The choice of using microspines in the gripper is given by the fact that the study in [7] provided very reliable results for grasping and handling flat and deformable materials such as tissues. Another strong inspiration comes from an interesting work [3] where, in the Jet Propulsion Laboratory (JPL), has been developed a lightweight robot which is able to climb rough surface using wheels with microspines (as shown in Figure 3.1). The interactions between microspines and asperities of the rough surface generate the relative movement of the robot. Therefore, the idea is to exploit the same principle of the previous robot described but using it to grasp the porous surface of textile fabrics or other similar tissues structure.

The literature has helped in the decision-making choice of the type of gripper to be developed. In this paper [8], is illustrated a survey focused on industrial grippers used for tissues handling.
Chapter 3. Description of the proposed gripper

Figure 3.1: An inspiration for developing the novel rotary needle gripper. Image taken from [3].

Figure 3.2 shows the percentage of the gripping principles most used, to manipulate fabrics, in manufacturing Industry. As shown in Figure 3.2, 42% of the most used grippers are either pinches or needle-pins.

Figure 3.2: Percentage of use gripping principles. Image taken from [8].

In this book [17] has been described various types of grippers
3.1. Motivation for the proposed gripper

and in Figure 3.3 shows a comparison of different gripping principles used for handling tissues. The choice to develop the novel gripper described in the next chapter was essentially made from the experience provided by the literature. Although the Figure 3.3 shows the convenience of using grippers with contiguous (thermal and chemical) gripping principles, these have some problems. These problems are essentially related to ruining the handled fabrics, gripper reliability and grip velocity. Therefore, it was decided to develop a new gripper which exploit the principles of impactive, intrusive and ingressive gripping. In this way it was possible to exploit the advantages of the three principles.

Figure 3.3: Comparison of several prehension principles with respect to their suitability with textile objects. Image taken from [17].
Chapter 3. Description of the proposed gripper

3.2 Reconfigurable Rollers-Needles gripper prototype design

In this section the new gripper solution, for grasping and handling tissues, will be explained. A different approach used in this research exploits an intrusive method using microspines, but also a non-intrusive method exploiting the friction of the wheels; it is also possible to combine their effects in order to use friction and microspines at the same time.

The gripper proposed in this thesis is a combination of the advantages of a parallel gripper with the wheels placed on the fingertips and it is also called rollers-needles gripper. A parallel gripper was chosen for its wide use in the manufacturing industry which is simple to build, but very reliable and useful for pinching objects to be grasped and manipulated. This gripper was mounted on the end-effector of a robotic arm in order to exploit its additional degrees of freedom for movement in space. The Figure 3.4 illustrates the CAD model of the gripper prototype created with Creo Parametric 4.0 software. As can be seen in Figure 3.4 the gripper is composed of a various mechanical, electrical and electronics components. Starting the description of the gripper from the top, the first mechanical component is a coupling flange which is used to connect the gripper to a robotic arm. The coupling flange is screwed up to a Bosch profile which, the latter, holds a linear rail. Two guide carriages allow each finger to slide along the linear rail. Each finger is independently moved by a servo linear actuator which allows their opening and closure. Each finger can also be rotated on their own axis independently due to the servo rotary actuators mounted in the structure as illustrated in Figure 3.4.

For a better understanding of the gripper components, Figure 3.5 shows a front view of a single finger. In this view it is possible to observe other components hidden in the previous Figure. Therefore, continuing the above discussion, in Figure 3.5 it is possible to notice a further rotary actuator. The actuator is connected directly to a worm drive which allows to reduce its speed by a ratio of 1:10 and therefore increase its torque. This type of transmission allows the irreversible motion of the wheels which avoid the electric mo-
3.2. Reconfigurable Rollers-Needles gripper prototype design

**Figure 3.4:** CAD design of the gripper prototype.

Motors to keep constantly their torques active. This mechanical system allows also the continuous and independently rotation in clockwise and anticlockwise direction of each wheel on its axis.

**Figure 3.5:** CAD of the front view of the single gripper’s finger.

Figure 3.5 shows the section of the cylindrical wheel which represents all components of a complex mechanism to extract or retract the microspines. The mechanism consists of two main components, the internal cylinder and the external cylinder. The sliding shaft is moved, by a linear actuator (as illustrated in Figure 3.5), along the axis of the internal cylinder dragging the sliding pin along a helicoidal slot located inside the external cylinder (as shown in Figure...
Due to this relative movement between the two cylinders, it is possible to change the length of the microspines. The four internal modules (colored green in Figure 3.8) are used to insert, inside the wheel, the rows of microspines and for constraining them to the internal cylinder. The external modules (colored gray in Figure 3.8) allow easier insertion of the microspines and have inside holes with a spiral path that facilitate the winding of the microspines onto the internal cylinder. The microspines follow the path of the holes present on the external modules therefore by changing them, the angle of inclination of the output microspines can be changed. Due to the use of these modules, it is also possible to change the wire’s diameter of the microspines. The external surface of the external cylinders is covered with 10 rubber bands (as shown in Figure 3.8) in order to cover as much of them as possible. The rubber bands are placed so as not to interfere with the exit of the microspines and they are used to increase the friction surface for a better tissues gripping and handling.
3.2. Reconfigurable Rollers-Needles gripper prototype design

Figure 3.6: CAD wheel section of the mechanism to extract or retract the microspines.

Figure 3.7: CAD External cylinder of the mechanism to extract or retract the microspines.

The real gripper prototype, shown in Figure 3.11, was created using the FDM 3D printing technique. In fact, most of the components have been made of PLA which is a plastic material, quite resistant from a mechanical point of view. The material used to make the microspines is C85 harmonic steel in wires with a diameter of 0.15 mm. The wire of each microspine follows a logarith-
mic spiral path, inside a spiral hole of the wheel showed in Figure 3.6, which has the Cartesian coordinates expressed in the following parametric form [4]:

\[
\begin{align*}
x(\theta) &= r(\theta)\cos(\theta) \\
y(\theta) &= r(\theta)\sin(\theta)
\end{align*}
\]

where $\theta$ is the angle expressed in radians and $r(\theta) = r_0 e^{b\theta}$ is its polar equation. The terms of the polar equation are: $r_0$ which is the radius where the logarithmic curve starts and $b$ is a parameter for determining the rate of increase of the spiral. The parameter $b$ is expressed in radians because $b = \cot(\psi)$, where $\psi$ is the angle between $r(\theta)$ and the respective tangent of the curve. Figure 3.9 shows an example when $\psi = 70^\circ$ and the interesting aspect is that this angle remains constant so it means that it does not depend on the values of $\theta$ and $r_0$. Figure 3.10 shows different paths as the $\psi$ angle changes. The variable $\theta$ is very useful in order to compute the total length of the spiral.

Figure 3.12a shows the gripper with microspines retracted instead the Figure 3.12b shows the gripper with microspines extracted.
3.2. Reconfigurable Rollers-Needles gripper prototype design

Figure 3.9: Equiangular spiral path. Image taken from [4]

Figure 3.10: Example of different logarithmic spiral path as the $\psi$ angle changes. Image taken from [4]
Chapter 3. Description of the proposed gripper

Figure 3.11: Real gripper prototype.

Figure 3.12: Figure 3.12a shows the gripper with microspines retracted instead of the Figure 3.12b shows the gripper with microspines extracted.
3.3 Kinematics of the ABB robot

3.3.1 Theory of forward kinematics analysis

A robot manipulator is a composed of a set of links connected together by joints and they can be a revolute joint or a prismatic joint. Each joint can be considered with a single degree of freedom and therefore the action of each joint can be described by a single real number. In the case of revolute joint can be described with an angle, instead, a prismatic joint can be represented with a displacement. The aim of forward kinematic analysis is to determine the position and orientation of the end-effector given the values of joint variables [32]. A robot manipulator with \( n \) joints will have \( n + 1 \) links, since each joint connects two links. The joints and the links are numbered from 1 to \( n \) starting from the base. By this convention, joint \( i \) connects link \( i - 1 \) to link \( i \). The location of the joint \( i \) is considered fixed with respect to link \( i - 1 \). Link \( i \) moves when joint \( i \) is actuated but link 0 (the first link) is fixed, and does not move when the joints are actuated. The robot manipulator could itself be mobile, for example, it could be mounted on a mobile platform or on an autonomous vehicle but this aspect will not be dealt with in this thesis. With the \( i^{th} \) joint is associate a joint variable and it is denoted by \( q_i \). The variable \( q_i \) for a revolute joint is the angle of rotation, and in the case of a prismatic joint, \( q_i \) is the joint displacement:

\[
q_i = \begin{cases} 
\theta_i & \text{if joint } i \text{ is revolute} \\
 d_i & \text{if joint } i \text{ is prismatic}
\end{cases} \tag{3.1}
\]

In order to perform the kinematic analysis a coordinate frame rigidly \( i \) attached to each link. In particular the coordinate frame \( o_i x_i y_i z_i \) is attached to the link \( i \). In this way when the robot moves the coordinates of each point on link \( i \) are constant when expressed in the \( i^{th} \) coordinate frame. The frame \( o_0 x_0 y_0 z_0 \) is attached to the robot base and it is referred to as the inertial frame. Depending on the manner the frames are rigidly attached to the corresponding links, the position of the end-effector, when expressed in frame \( n \), is constant independent of the configuration of the robot. Equation 3.2 represents the homogeneous transformation matrix and it denotes the position and orientation of the end-effector with respect to
the inertial or base frame. The term $o_n^0$ is a three-vector and defines the position of the end-effector while the orientation is expressed by the 3x3 rotation matrix $R_n^0$.

$$H = \begin{bmatrix} R_n^0 & o_n^0 \\ 0 & 1 \end{bmatrix}$$

(3.2)

There is another more compact form defines $H$ matrix for computing the position and orientation of the end-effector in the inertial frame. This is achieved by multiplying all the transformation matrices with each other as:

$$H = T_n^0 = A_1(q_1) \ldots A_n(q_n)$$

(3.3)

Each homogeneous transformation $A_i$ is of the form:

$$A_i = \begin{bmatrix} R_{i-1}^i & o_{i-1}^i \\ 0 & 1 \end{bmatrix}$$

(3.4)

Hence

$$T_j^i = A_{i+1} \ldots A_j = \begin{bmatrix} R_n^0 & o_n^0 \\ 0 & 1 \end{bmatrix}$$

(3.5)

The matrix $R_j^i$ expresses the orientation of $o_j x_j y_j z_j$ relative to $o_i x_i y_i z_i$ and is given by the rotational parts of the A-matrices as:

$$R_j^i = R_{i+1}^i \ldots R_{j-1}^i$$

(3.6)

The coordinate vectors $o_j^i$ are given recursively by the formula:

$$o_j^i = o_{j-1}^i + R_{j-1}^i o_j^{i-1}$$

(3.7)

### 3.3.2 Denavit-Hartenberg convention

The kinematic analysis of an $n$-link manipulator can be extremely complex and the conventions introduced below simplify the analysis considerably. A commonly used convention for selecting frames of reference in robotic applications is the Denavit-Hartenberg, or called also DH convention \[32\]. In this convention, each homogeneous transformation $A_i$ is represented as a product of four basic
3.3. Kinematics of the ABB robot

transformations:

\[
A_i = \text{Rot}_{z, \theta_i} \cdot \text{Trans}_{z, d_i} \cdot \text{Trans}_{x, a_i} \cdot \text{Rot}_{x, \alpha_i}
\]

\[
= \begin{bmatrix}
  c_{\theta_i} & -s_{\theta_i} & 0 & 0 \\
  s_{\theta_i} & c_{\theta_i} & 0 & 0 \\
  0 & 0 & 1 & 0 \\
  0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
  1 & 0 & 0 & a_i \\
  0 & 1 & 0 & 0 \\
  0 & 0 & 1 & d_i \\
  0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
  1 & 0 & 0 & 0 \\
  0 & c_{\alpha_i} & -s_{\alpha_i} & 0 \\
  0 & s_{\alpha_i} & c_{\alpha_i} & 0 \\
  0 & 0 & 0 & 1
\end{bmatrix}
\]

\[(3.8)\]

In Equation (3.8) the term \(\text{Rot}_{z, \theta_i}\) represents a rotation about z-axis with an angle \(\theta_i\) between frame \(i - 1\) and \(i\) while \(\text{Rot}_{x, \alpha_i}\) represents a rotation between frame \(i - 1\) and \(i\). The term \(\text{Trans}_{*, *}\) represents a translation along either the z-axis or the x-axis by either \(d_i\) or \(a_i\) between frame \(i - 1\) and \(i\). The four parameters \(a_i, \alpha_i, d_i\) and \(\theta_i\) are called respectively as link length, link twist, link offset and joint angle.

![Figure 3.13: The four parameters, shown in red, of classic Denavit-Hartenberg convention are \(\theta_i, d_i, a_i, \alpha_i\). Courtesy of [39].](image)

- **Link length** \(a_i\) is the distance between \(z_{i-1}\) and \(z_i\) axes along the \(x_i\)-axis. \(a_i\) is the kinematic length of link (i).

- **Link twist** \(\alpha_i\) is the required rotation of the \(z_{i-1}\) axis about the \(x_i\) axis to become parallel to the \(z_i\)-axis.
Chapter 3. Description of the proposed gripper

- **Joint distance** $d_i$ is the distance between $x_{i-1}$ and $x_i$ axes along the $z_{i-1}$ axis. Joint distance is also called **link offset**.

- **Joint angle** $\theta_i$ is the required rotation of $x_{i-1}$ axis about the $z_{i-1}$ axis to become parallel to the $x_i$ axis.

### 3.3.3 Denavit-Hartenberg parameters of ABB IRB1600-10/1.2

The reference frames, for the ABB IRB1600-10/1.2 robotic arm according to the Denavit-Hartenberg convention, are assigned as shown in Figure 3.15. The robot dimension values given in the product specification [1] are also shown in Figure 3.14. Through this data, in Table 3.1 are reported the Denavit-Hartenberg parameters. Putting these values into the transformation matrices from Equation 3.8, $A_i$ matrices are reported in Equation 3.9.

![Figure 3.14: Dimensions of the robotic arm ABB IRB1600-10/1.2 expressed in mm. Taken from [1].](image)
3.3. Kinematics of the ABB robot

Figure 3.15: Denavit-Hartenberg frame assignment for ABB IRB1600-10/1.2 robotic arm.

Table 3.1: Denavit-Hartenberg parameters of ABB IRB1600-10/1.2 robotic arm.

<table>
<thead>
<tr>
<th>Link</th>
<th>( \theta_i )</th>
<th>( d_i ) (mm)</th>
<th>( a_i ) (mm)</th>
<th>( \alpha_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( q_1 )</td>
<td>486.5</td>
<td>150</td>
<td>(-90^\circ)</td>
</tr>
<tr>
<td>2</td>
<td>( q_2 - 90^\circ )</td>
<td>0</td>
<td>475</td>
<td>0(^\circ)</td>
</tr>
<tr>
<td>3</td>
<td>( q_3 )</td>
<td>0</td>
<td>0</td>
<td>(-90^\circ)</td>
</tr>
<tr>
<td>4</td>
<td>( q_4 )</td>
<td>600</td>
<td>0</td>
<td>90(^\circ)</td>
</tr>
<tr>
<td>5</td>
<td>( q_5 + 180^\circ )</td>
<td>0</td>
<td>0</td>
<td>90(^\circ)</td>
</tr>
<tr>
<td>6</td>
<td>( q_6 )</td>
<td>65</td>
<td>0</td>
<td>0(^\circ)</td>
</tr>
</tbody>
</table>
### 3.4 Inverse kinematics

In this section is discussed the inverse problem of finding the joint variables in terms of the end-effector position and orientation. The problem of inverse kinematics, in general, it is more difficult than the forward kinematics problem. The robot used in this thesis has six joints and the last three joints intersect at a point. In this case it is possible to split the inverse kinematics problem into two simpler problems known respectively, as inverse position kinematics, and inverse orientation kinematics \[32\]. This procedure is called kinematic decoupling and that is one problem is considered at the first three joint configurations and the second one is considered at the last three joints. For first it is necessary to find the position of
the intersection of the wrist axes, hereafter called the wrist center, and then finding the orientation of the wrist. In the Figure 3.15 shows the axes $z_3, z_4$ and $z_5$ which all intersect at a point. Therefore this last three joint axes intersect at a point represented with $o_c = [x_c, y_c, z_c]^T$. This point represents the center of the robot wrist. The origins $o_4$ and $o_5$ assigned by the DH-convention will always be at the wrist center $o_c$. The important point of this assumption for the inverse kinematics is that motion of the final three links about these axes will not change the position of $o_c$. Thus, the position of the wrist center is a function of only the first three joint variables $q_1, q_2$ and $q_3$. The position of the end-effector $o$ is achieved by a translation of distance $d_6$ along $z_5$ from $o_c$. The axis $z_5$ and $z_6$ are the same (as shown in Figure 3.15) and the third column of $R$ expresses the direction of $z_6$ with respect to the base frame. Therefore $o$ is expressed as:

$$o = o_c^0 + d_6 R \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$  \hspace{1cm} (3.10)

Therefore the end-effector of the robot can be moved at the point with coordinates given by $o$ and the orientation given by $R = (r_{ij})$ but it is necessary that the wrist center $o_c$ have coordinates given by:

$$o_c^0 = o - d_6 R \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$  \hspace{1cm} (3.11)

If the position of the end-effector $o$ is represented with components $o_x, o_y, o_z$ and the components of the wrist center $o_c^0$ are denoted $x_c, y_c, z_c$ the 3.11 becomes:

$$\begin{bmatrix} x_c \\ y_c \\ z_c \end{bmatrix} = \begin{bmatrix} o_x - d_6 r_{13} \\ o_y - d_6 r_{23} \\ o_z - d_6 r_{33} \end{bmatrix}$$  \hspace{1cm} (3.12)
Chapter 3. Description of the proposed gripper

3.4.1 A geometric approach to compute the inverse position kinematics

The inverse position kinematics can use a geometric approach to find the variables \( q_1, q_2 \) and \( q_3 \). For the first \( q_1 \) is found using \( x_c \) and \( y_c \) projection which are the first two components of \( o_c \) (see the equation [3.11]) and using the two-argument arctangent becomes [32]:

\[
q_1 = \text{atan}_2(x_c, y_c)
\]  

(3.13)

Figure 3.16: Projection of the wrist center onto \( x_0 - y_0 \) plane.

Now it can be possible to find \( q_2 \) and \( q_3 \) but for the first, it is necessary to build a new plane \( x^* - z^* \) which is parallel to the \( z_0 - x_0 \) plane (as shown in Figure 3.17).

Figure 3.17: Joint angles \( q_2 \) and \( q_3 \) in \( x^* - z^* \) plane.
3.4. Inverse kinematics

After that it is necessary to compute the distance $r$ along $x^*$ from the center of joint 2 to $x_c$ and the distance $s$ along $z^*$ in the same way that is from the center of joint 2 to $z_c$

\[
 r = \sqrt{(x_c - a_1 \cos q_1)^2 + (z_c - a_1 \sin q_1)^2} \quad (3.14)
\]

\[
 s = z_c - d_1 \quad (3.15)
\]

Therefore $\theta_3$ is computed with the law of cosines as:

\[
 \cos \theta_3 = \frac{r^2 + s^2 - a_3^2 - d_3^2}{2a_2d_4} = \frac{(x_c - a_1 \cos q_1)^2 + (y_c - a_1 \sin q_1)^2 + (z_c - a_1 \sin q_1)^2 - a_2^2 - d_4^2}{2a_2d_4} := D \quad (3.16)
\]

\[
 \sin \theta_3 = \pm \sqrt{1 - D^2} \quad (3.17)
\]

\[
 \theta_3 = \arctan(\pm \sqrt{1 - D^2}, D) \quad (3.18)
\]

At the end $q_3$ is computed as:

\[
 q_3 = -\theta_3 - \frac{\pi}{2} \quad (3.19)
\]
Chapter 3. Description of the proposed gripper

Equation 3.19 is compensating for the zero position of the third joint, which is rotated $\frac{\pi}{2}$ rad from the zero position used to calculate $\theta_3$. $q_3$ is also defined negative relative to $\theta_3$. Because of the ± sign in Equation 3.18 there are two different solutions of $q_3$ corresponding to either elbow up or elbow down. The joint $q_2$ is computed as in Equation 3.22 through $\theta_2$ (Eq. 3.21). $\theta_2$ is the difference between the angle between the $x^*$-axis and the stapled line from joint 2 to $o_c$, and the angle $\beta$, shown in Figure 3.17. The resulting equations becomes:

\[
\theta_2 = \arctan_2(s, r) - \arctan_2(a_2 + d_4 \cos \theta_3, a_2 + d_4 \sin \theta_3) \tag{3.20}
\]

\[
\theta_2 = \arctan_2(z_c - d_1, \sqrt{(x_c - a_1 \cos q_1)^2 + (y_c - a_1 \sin q_1)^2}) - \arctan_2(a_2 + d_4 \cos \theta_3, d_4 \sin \theta_3) \tag{3.21}
\]

\[
q_2 = \frac{\pi}{2} - \theta_2 \tag{3.22}
\]

3.4.2 The inverse orientation kinematics

The inverse orientation problem is now one of finding the values of the final three joint variables. \[32\]. The first three joint angles are known as well as $R = R_6^0(q)$ which is the orientation of the end-effector relative to the frame $o_3x_3y_3z_3$. Investigating the equation 3.23 the orientation angles can be found. Starting from the DH matrices the matrices mentioned before are computed in Equation 3.24:

\[
R_6^3(q) = (R_3^0(q))^T R_6^0(q) \tag{3.23}
\]
3.4. Inverse kinematics

\[
\begin{bmatrix}
  s_4 q_6 - c_4 c_5 c_6 & s_4 q_6 + c_4 c_5 s_6 & -c_4 q_5 \\
  -c_4 q_6 - s_4 c_5 c_6 & -c_4 q_6 + s_4 c_5 s_6 & s_4 q_5 \\
  -s_5 c_6 & s_5 s_6 & c_5 
\end{bmatrix}
= 
\begin{bmatrix}
  c_1 s_2 c_3 + c_1 c_2 s_3 & s_1 s_2 c_3 + s_1 c_2 s_3 & c_2 s_3 - s_2 s_3 \\
  -c_1 s_2 s_3 + c_1 c_2 c_3 & -s_1 s_2 s_3 + s_1 c_2 c_3 & -c_2 s_3 - s_2 c_3 \\
  r_{11} & r_{12} & r_{13} \\
  r_{21} & r_{22} & r_{23} \\
  r_{31} & r_{32} & r_{33} 
\end{bmatrix}
\tag{3.24}
\]

Checking the matrices above, the cosine of \( q_5 \) is found in the lower right corner, and it is calculated through matrix multiplication as following:

\[
\begin{align*}
  c_{q_5} &= r_{13}(-c_{q_1}s_{q_2}s_{q_3} + c_{q_1}c_{q_2}c_{q_3}) \\
  &\quad + r_{23}(-s_{q_1}s_{q_2}s_{q_3} + s_{q_1}c_{q_2}c_{q_3}) \\
  &\quad + r_{33}(-c_{q_2}s_{q_3} - s_{q_2}c_{q_3})
\end{align*}
\tag{3.25}
\]

The sine of \( q_5 \) is taken from the other two elements on column three, and it is computed as:

\[
\begin{align*}
  \pm s_{q_5} &= \sqrt{(-c_{q_4}s_{q_5})^2 + (-s_{q_4}s_{q_5})^2} \\
  &= \sqrt{(r_{13}(c_{q_1}s_{q_2}c_{q_3} + c_{q_1}c_{q_2}s_{q_3}) + r_{23}(s_{q_1}s_{q_2}c_{q_3} + s_{q_1}c_{q_2}s_{q_3})} \\
  &\quad + r_{33}(c_{q_2}s_{q_3} - s_{q_2}c_{q_3})^2 + (r_{13}s_{q_1} - r_{23}c_{q_1})^2
\end{align*}
\tag{3.26}
\]

Now, the joint angle \( q_5 \) can then be computed using these following expression:

\[
q_5 = \arctan_2(\pm s_{q_5}, c_{q_5})
\tag{3.27}
\]

With \( q_5 \) can be computed the last two orientation angles. Checking the third row and column of Equation \[3.24\] these angles can be computed, depending on if \( s_{q_5} \) is positive or negative respectively, with the following equations:

\[
q_4 = \arctan_2(\pm(s_{q_4}s_{q_5}), \pm(-c_{q_4}s_{q_5}))
\tag{3.28}
\]

\[
q_6 = \arctan_2(\pm(s_{q_5}s_{q_6}), \pm(s_{q_5}c_{q_6}))
\tag{3.29}
\]
Methodologies for grasping tissues

4.1 Introduction

This chapter explains the different approaches used by the novel gripper prototype, described in the section 3.2 for tissues grasping and manipulating. The new proposed gripper prototype is capable of using the intrusive method, extracting the microspines from the wheels, through the complex mechanism described in section 3.2. The length of the microspine can be changed in order to manipulate tissues of different thickness. Instead, retracting the microspines, into the wheels, the gripper is capable to use a non-intrusive method in order to exploit the surface friction of the rubber bands placed around to the external cylinders (as shown in the previous Figure 3.6). For a stronger grip it is possible to use the two combined effects, namely that of the microspines and the rubber bands together.

4.2 Intrusive methodologies

Before starting any operation, the thickness of the tissue should be known to be able to manipulate it in order to regulate the right length of the microspines which have to penetrate into the material, as shown in Figure 4.1 [4]. This gripper is studied also to pick up
a tissue from layers. The disadvantage of using this mode is that, if the tissue to be treated is delicate, there is a risk of damaging it. This risk will be investigated in the chapter 5 with the grasping and manipulation of many tissues through various experiments. However, to avoid completely this problem, the microspines can be retracted and non-intrusive method can be used.

Figure 4.1: Detail of the interaction between wheels and tissue. Image taken from my paper [4].

4.2.1 First intrusive method

This first strategy adopted to take a tissue can be summarized in the following points:

- Gripper approaching
- Grasping action
- Manipulation
- Releasing

In this first method the gripper is placed to the center and above the fabric, the two fingers are closed at an appropriate distance. At this point the microspines are extracted to a specific length that corresponds to the thickness of the tissue. After that, the wheels are moved until they gently touch the tissue and, in this case, a very large contact force is not required. The grasping action is performed by rotating the wheels at the same speed so that the microspines penetrate between the warps and wefts of the fabric texture. The torque generated by the wheels causes the bend and lift up
4.2. Intrusive methodologies

of the tissue, as in Figure 4.2. At this point, to have a more stable and reliable grip, the two parallel fingers are strongly closed and the tissue is lifted up and moved quickly to a predefined point or it can be manipulated furthermore. At the end of the manipulation, the tissue is released by retracting the microspines and opening the fingers.

![Figure 4.2: First intrusive method in order to Buckle and lift up the tissue. Image taken from my paper [4].](image)

4.2.2 Second intrusive method

This second strategy adopted to take a tissue is similar to the first but can be used when the gripper cannot access the central or internal part of the tissue. It can be summarized in the same points:

- Gripper approaching
- Grasping action
- Manipulation
- Releasing

In this second method, however, the gripper is positioned at the edge and above the tissue, the two fingers are opened at an appropriate distance. At this point the microspines are extracted to a specific length that corresponds to the thickness of the tissue. After that the wheels are moved until they gently touch the tissue and, in this case, a very large contact force is not required. The grasping action is performed by rotating the wheels at the same speed so, in this way, the microspines penetrate between the wefts and warp of the fabric texture. The torque generated by the wheels causes a lifting up and capturing of the corner of the tissue, as in Figure 4.3.
Chapter 4. Methodologies for grasping tissues

At this point, always to have a more stable and reliable grip, the two parallel fingers are strongly closed and the tissue is lifted up and moved quickly to a predefined point or it can be manipulated furthermore. At the end of the manipulation, the tissue is released by retracting the microspines and also opening the fingers.

![Image](image.png)

Figure 4.3: Second intrusive method in order to Buckle and lift up the tissue near to the boundary. Image taken from my paper [4].

4.3 Non-intrusive methodologies

The non-intrusive methodology is that which exploits the friction of the contact surfaces between rubber band and fabric. In this way it is possible to exploit the frictional force generated by the contact between the two surfaces, simulating the movement that occurs when the fingers of one hand grasp an object.

4.3.1 First non-intrusive method

First non-intrusive method. This first non-intrusive strategy is used when the material to be handled is very delicate and risks being damaged by the penetration of microspines. It can always be summarized in the following points:

- Gripper approaching
- Grasping action
- Manipulation
- Releasing

In this first non-intrusive method the gripper is placed to the center and above the fabric and the two fingers are closed at an appropriate
4.3. Non-intrusive methodologies

distance. After this first procedure, the wheels are moved until they touch the fabric and in this case a certain contact force is required, so as to generate a sufficient friction force between the wheels and the fabric. The grasping action is performed by turning the wheels at the same speed in order to be able to buckle and lift up the fabric. The torque generated by the wheels causes the fabric to bend and lift up, as in Figure 4.4. At this point, always to have a more stable and reliable grip, the two parallel fingers are strongly closed and the fabric is lifted up and moved away to a predefined point or it can be manipulated furthermore. At the end of the manipulation, the tissue is released by only opening the fingers.

![Figure 4.4](image)

**Figure 4.4:** *First non-intrusive method in order to Buckle and lift up the tissue.*

4.3.2 Second non-intrusive method

This second non-intrusive strategy is always used when the material to be handled is very delicate and risks being damaged by the penetration of microspines. It is also used when only, for example, the boundary is approachable. It can always be summarized in the following points:

- Gripper approaching
- Grasping action
- Manipulation
- Releasing

In this second non-intrusive method the gripper is placed at the above the edge of the fabric, the two fingers are closed at an appropriate distance. After this, the wheels are moved until they touch
Chapter 4. Methodologies for grasping tissues

the fabric and in this case a certain contact force is required in order to generate a sufficient friction force between the wheels and the fabric. The grasping action is performed by turning the wheels at the same speed in order to be able to buckle and lift up the edge of the fabric. The torque generated by the wheels causes a lifting up of the edge of the fabric, as represented in Figure 4.5. At this point, to have a more stable and reliable grip, the two parallel fingers are closed and the fabric is lifted and moved to a predefined point or it can be manipulated further. At the end of the manipulation, the tissue is released by simply opening the fingers.

Figure 4.5: Second non-intrusive method in order to Buckle and lift up the tissue near to the boundary.

4.4 A Novel methodology for Grasping and Manipulating tissues

4.4.1 Introduction

There are grippers in the literature that are capable of grasping the tissues from the corners or from the two extreme edges in order to perform more complex tasks. An example of this mechatronic system is a parallel gripper with an adjustable clamp on each finger. These tipology of grippers are usually mounted on a single arm. These kind of grippers are capable to grasp a tissue from the opposite corners. Two examples of these kind of grippers are shown in Figure 4.6a and 4.6b. Another typology found in the literature is a system composed of two robotic arms where is mounted, on each wrist, a clamp gripper. Each clamp gripper is capable to grasp the tissue from the corners in a way to perform the various manipulation tasks of sorting, holding, stretching, folding, unfolding,
4.4. A Novel methodology for Grasping and Manipulating tissues

This system is called the CloPeMa robot (Clothes Perception and Manipulation) which consists of two seven degrees of freedom YASKAWA arms and a custom made YASKAWA turn-table [33]. An example of this system is shown in Figure 4.7. The idea of the research for the novel gripper is to develop a new mechatronic system, as versatile as possible, capable of tackling even more complex tasks in order to perform the operations of the robots described above.

**Figure 4.6:** Two clamps gripper mounted on a single-arm that holds the tissue from opposite edges. The gripper in Figure (a) taken from [31] and (b) taken from [8].

**Figure 4.7:** Two clamps gripper mounted each on arm of a dual-arm. The system is able to grasp and hold the tissue from opposite edges. Picture taken from [38].
4.4.2 Description of the Novel methodology for grasping and manipulation tissues

This innovative strategy can only be used with the intrusive method because it involves the use of microspines. By being able to rotate the fingers, of the gripper prototype, on their own axis, it is possible to take advantage of the new features, such as the inverse grasp and it also capable of stretching of the tissues. This type of grasping is also faster than the previously described and has advantages with regard to some complex tasks such as grasping the tissues placed in a mess way in order to be able to move them in an ordered manner on layers of fabrics. Another task that can be tackled which turns out to be quite difficult to accomplish is to grasp the tissue and fold it back on itself. Specifically, in the inverse grasp, each finger of the gripper must be rotated of $180^\circ$, as shown in Figure [4.3b], in order to reverse the direction of the microspines. When we want to grasp the messy fabric on a table plane, the fingers of the gripper, which must be opened in order to place each of them above to the two corners of the tissue. After that, the microspines are extracted and then the fingers are approached closer to the corners of the fabric in order to touch it. At this point, the wheels are rotated in order to penetrate the tissue with the microspines. In this way the fabric is grasped but also stretched.
4.4. A Novel methodology for Grasping and Manipulating tissues

The fabric can be lifted up by the robotic arm and moved until it is completely stretched, in an orderly manner, on the table. This operation can be repeated several times in order to create an orderly pile of fabrics. Another useful task in the manufacturing industry is that of stretching the fabric that can present folds. It can also be applied to keep the fabric stretched on in order to perform operations such as cutting, sewing, steam ironing, etc. Another important task is to be able to fold the fabric on itself. Thanks to the robotic arm, the fingers of the novel gripper must be positioned over the two opposite edges of the fabric, lifted up and folded onto a surface. The tissue release operation is performed through the retraction of the microspines.

Figure 4.8: Reconfiguration of the gripper for grasping and manipulating the tissue with an new inverse grasp.
CHAPTER 5

Experimental test and results

5.1 Experimental Set-up

In all experiments, the gripper is mounted onto an industrial arm robot **ABB IRB 1600-10/1.2** which has a weight of 250 kg and reach of 1.2 meters. In industry there are other bigger ABB robot and the model used in this thesis can be considered a small articulated industrial robot. The robotic arm used has a payload of 10 kg and with a position repeatability of 0.02 mm and a path repeatability of 0.06 mm. Therefore, it is ideal for tasks such as Arc Welding, Machine Tending, Material Handling, Gluing, Deburring and Grinding applications [37]. Another important aspect for the robot is the working range and, for this reason, in Figure 5.2 is illustrated the working range of the ABB robotic arm. Figure 5.1 shows the main components of the set-up used for the experiments which are essentially: the robotic arm, a laboratory table and the gripper prototype.
Chapter 5. Experimental test and results

Figure 5.1: Experimental Set-up.

Figure 5.2: Working range ABB IRB 1600-10/1.2. Picture taken from [37].

The gripper is mounted on a wrist of an ABB robotic arm which is described above. The gripper proposed, as previously mentioned in this thesis, is composed of two fingers each moved by a linear servo actuator Actuonix model P16-50-64-12P. The fingers can be rotated on their own axis, each by a rotary servomotor Hitec model HS422. The wheels described in Section 3.2 are each driven by a DC Maxon motor which can be reversed using an H-Bridge board. These motors are equipped each of a rotary encoder model
5.1. Experimental Set-up

<table>
<thead>
<tr>
<th>Controller</th>
<th>ARDUINO DUE based on a 32-bit ARM core microcontroller. It has 54 digital input/output pins (of which 12 can be used as PWM outputs), 12 analog inputs, a 84 MHz clock.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opening/Closure fingers and extration/retraction microspines</td>
<td>4x linear servo actuator with LAC Actuonix P16 12V, stroke 50 mm, gear ratio 64:1, F=90N v=18mm/s, Potentiometer feedback.</td>
</tr>
<tr>
<td>Rotation wheels (DC Motors)</td>
<td>2 x Maxon DCX14L EB KL 9V - Planetary gear GPX14HP 83:1 - Encoder ENX10 EASY 256IMP Tnom=525 mNm, Tstall=1627 mNm, Vnom=63 rpm</td>
</tr>
<tr>
<td>Rotation fingers</td>
<td>2x HS-422 Std servo motor 5V Tmax=50 oz/in Speed(Second @ 60°) = 0.2</td>
</tr>
<tr>
<td>DC motors reverse</td>
<td>L298 Dual H_Bridge</td>
</tr>
</tbody>
</table>

Table 5.1: Electronic components used in the proposed gripper.

ENX10 EASY 256IMP and a planetary gear model GPX14HP with a gear ratio of 83:1. Each motor is controlled in position with a PID controller using an arduino PID library. In this way, it is possible to know where are located the microspine and it is possible to count the number of revolutions to turn correctly the wheels in order to grasp successfully the tissue. The microspines are extracted with the same linear servo actuator used to move the fingers. Every servo linear actuator has a potentiometer feedback therefore its elongation is known. In order to manage the control of all 8 motors has been used an Arduino DUE which is a 32-bit microcontroller which is capable to control the the movement of each motor. The main characteristics of the electronics used to develop the gripper prototype are summarized in table 5.1. Figure 5.3 shows the box which contains the control system where the main components are: in the left side the dual H-Bridge and in the right side the Arduino DUE.
Chapter 5. Experimental test and results

Figure 5.3: Control system with Arduino Due and H-Bridge.

5.2 Tissues chosen for experimentation

In the manufacturing industry are handled tissues of common use with different shapes and characteristics. These type of tissues are quite different from each other, therefore the difference in difficulty to manipulate them, depends on their shape, size and types of the material which are composed, etc. In Table 5.2 are reported different tissues of common use, treated in all experiments, with the main characteristics of: weight, materials, size and the thickness.
5.3. Gripper prototype evaluation

5.3.1 First Tests on a single tissue with microspines retracted

The first tests carried out have the purpose of evaluating the preliminary performance of the gripper in manipulation of different types of tissue. The aim of these experiments is to evaluate the performance of the gripper proposed in elementary operations such as grasping, holding and releasing for each individual tissue. These operations are performed exploiting the first and second non-intrusive method described in Section 4.3 without the use of microspines, that is, using only the rubber bands. In the Table 5.3 are illustrated the results of the experiments with the various operations described above. It is possible to notice that all the tissues has been successfully grasped, holded and released when the microspines were retracted. Therefore, the gripper has been exploited only using friction and applying the right contact force between the wheels and the single tissue. In this way it was possible to perform correctly all these sequences of operations, for each single tissue, in a success way. It is important to know that the surface on which the tissue is placed must to be slippery otherwise the operation cannot be carried out. In Figure 5.4 are illustrated the operations of grasping,
holding, releasing of a surgical mask applied at the center on a surgical mask using the first non-intrusive method. Figure 5.5 shows the same operations on socks but applying the second method.

(a) Grasping.  (b) Holding.  (c) Releasing.

**Figure 5.4:** Steps to deal with the gripper for operations of grasping, holding, releasing of a surgical mask using rubber bands with the first non-intrusive method (at the center).

(a) Grasping.  (b) Holding.  (c) Releasing.

**Figure 5.5:** Steps to deal with the gripper for operations of grasping, holding, releasing of socks using rubber bands with the second non-intrusive method (at the boundary).

<table>
<thead>
<tr>
<th>Microspines retracted</th>
<th>Tissues</th>
<th>grasping</th>
<th>holding</th>
<th>releasing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Socks</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>T-shirts</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Potholders</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Towels</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Kitchen towels</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Microfiber cloths</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Surgical masks</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Gloves</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>

**Table 5.3:** Grasping, holding, releasing operation successes for single tissue using only rubber bands.
5.3. Gripper prototype evaluation

5.3.2 Second Test on a single tissue with microspines extracted

The second tests carried out have the purpose of evaluating the preliminary performance of the gripper in manipulation for the same tissues used in the first tests. The aim of these experiments is always to evaluate the performance of the gripper proposed in elementary operations such as grasping, holding and releasing for each individual tissue. These operations are performed sequentially exploiting the first and second intrusive method described in Section 4.2 and therefore using the microspines. Table 5.4 shows the results for each single operation. It is possible to notice how all the tissues has been successfully grasped, holded and released also this time. The advantage of using the microspines is that it is not necessary to apply a great contact force between the wheels and the tissue treated. It is only necessary to get closer enough with the gripper to the tissue in order to penetrate with microspine between the warp and weft texture of the tissue and, after that, activate the movement of the wheels. In this way it is possible to buckle and lift up the tissue in a very easy way. For holding the tissue in a strong way it is necessary to close the fingers of the gripper. In this way, the robotic arm can be move, the grasped tissue, very quickly. For releasing the object it is not only necessary to open the fingers of the gripper but the it needs to retract the microspines inside the wheels. This is because, otherwise, the tissue is stucked by the microspines.

Figure 5.6: Steps to deal with the gripper for operations of grasping, holding, releasing of gloves using rubber bands with the first intrusive method (at the center).
Chapter 5. Experimental test and results

Figure 5.7: Steps to deal with the gripper for operations of grasping, holding, releasing of gloves using rubber bands with the second intrusive method (at the boundary).

Table 5.4: Grasping, holding, releasing operation successes for single tissue using microspines.

<table>
<thead>
<tr>
<th>Microspines extracted</th>
<th>Tissues</th>
<th>grasping</th>
<th>holding</th>
<th>releasing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Socks</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>T-shirts</td>
<td>✓</td>
<td>✓</td>
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<td></td>
<td>Potholders</td>
<td>✓</td>
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<td>Towels</td>
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<td>Kitchen towels</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<td></td>
<td>Microfiber cloths</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Surgical masks</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Gloves</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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</table>

5.3.3 Success test on repetitive task

The aim of these further experiments is to evaluate the gripper’s potential in manipulating tissues when they are arranged in a stack. The robot has been programmed to always follow the same paths to repetitively pick up each tissue positioned on top of the stack. A stack made up of 10 tissues of the same type was created and the robot was programmed in order that the gripper takes each tissue in sequence, starting from the first on top of the stack to the last. In total, 10 consecutive cycles were performed without microspines and with microspines; each cycle consists of the following operations: approaching, reaching, grasping, holding, releasing and placing. This sequence of operations, repeated 10 times, were carried out to calculate the success rate of the gripper. In table 5.5 it is possible to notice the success rates following the operation described above with the gripper using microspines retracted (only using rub-
ber bands). For each tissue used in the experiment, the success rate is 0%, this because the gripper was unable to individually grasp the tissue from the stack but, instead, it grasps several tissue at the same time. In Figure 5.8 are shown some examples of multiple tissues grasped by the gripper and this is clearly an unwanted behavior for this type of test. Instead in Table 5.6 can be observed the success rates of the tests with microspines extracted. In this case, it is possible to notice that for each tested tissue, the success rates is 100% because the gripper at each cycle was able to take the first tissue individually from the stack and complete the manipulation cycle in a reliable way. In Figure 5.9 are shown some examples of single tissue tested successfully, from a top of the layers, by the gripper and this is clearly a wanted behavior for this type of test.

<table>
<thead>
<tr>
<th>Tissues</th>
<th>Number of trials</th>
<th>Success rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Socks</td>
<td>10</td>
<td>0%</td>
</tr>
<tr>
<td>T-shirts</td>
<td>10</td>
<td>0%</td>
</tr>
<tr>
<td>Potholders</td>
<td>10</td>
<td>0%</td>
</tr>
<tr>
<td>Towels</td>
<td>10</td>
<td>0%</td>
</tr>
<tr>
<td>Kitchen towels</td>
<td>10</td>
<td>0%</td>
</tr>
<tr>
<td>Microfiber cloths</td>
<td>10</td>
<td>0%</td>
</tr>
<tr>
<td>Surgical masks</td>
<td>10</td>
<td>0%</td>
</tr>
</tbody>
</table>

Table 5.5: Computation of the success rate using the gripper only rubber bands.
Chapter 5. Experimental test and results

Figure 5.9: Multiple tissues grasped using the gripper with rubber bands.

<table>
<thead>
<tr>
<th>Microspines extracted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tissues</td>
</tr>
<tr>
<td>Socks</td>
</tr>
<tr>
<td>T-shirts</td>
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<tr>
<td>Potholders</td>
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<tr>
<td>Towels</td>
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<td>Kitchen towels</td>
</tr>
<tr>
<td>Microfiber cloths</td>
</tr>
<tr>
<td>Surgical masks</td>
</tr>
</tbody>
</table>

Table 5.6: Computation of the success rate using the gripper with microspines.

5.3.4 Experimental Test for evaluating damage on delicate tissues

In this experiment the risk of damaging some very delicate tissues, during the manipulation, was evaluated. The two tissues examined were nylon tights and a type of light polyester scarf. At first, the grasping test of the two tissues found on the market was carried out, using only the rubber bands, that is, without extracting the microspines. As can be seen in Figure 5.10b, the rubber bands has been able to grasp the single tissue without creating any damage to it. The second part of the experiment showed some small damage to the texture of the tissue and this is happened when the microspines is used to grasp the delicate tissue. The small damage to the nylon tights can be seen in Figure 5.10b. As regards the light polyester scarf, no damage was found on it after the tests.
5.3. Gripper prototype evaluation

(a) Nylon tights not damaged.
(b) Nylon tights slightly damaged

Figure 5.10: Figure 5.10a shows the nylon tights not damaged by using rubber bands instead the Figure 5.10b shows the zoom-in of the small damage in the Nylon tights by using microspines
5.3.5 Experimental Test for complex task with inverse grasping

The proposed gripper prototype has also been tested with the inverse grasping described in 4.4.2 and in the experiments it was used to perform tasks more complex compared to the previously. These gripper are capable to grasp the tissue from the corners in a way to perform the various manipulation tasks of sorting, holding, stretching, folding, unfolding, placing, etc. Usually for these complex task are performed with a single parallel gripper which has mounted an adjustable clamps on each finger as described in 4.4.1. This kind of gripper is mounted on a single arm. Another system, to perform the task mentioned above, is composed with two robotic arms each one equipped, on the end-effector, with a dedicated clamp gripper (described in 4.4.1). In the case of the gripper proposed it was necessary to change the normal configuration (as shown in Figure 5.11a) by rotating the fingers each by $180^\circ$ as shown in Figure 5.11b. The gripper has been moved in order to approach the tissue, then the fingers are opened correctly in order to align the wheels near to the opposite corners of the tissue. After that, the microspines has been extracted of the same length as the tissue. The wheels of the gripper have been brought closer until they touched, in a proper way, the tissue. Therefore, the wheels are rotated in order to let the microspines penetrate between the warp and the weft of the tissue. The rotation of the wheels permit the grasping action and, this rotation, continues until the tissue is hooked well to the gripper as shown in Figure 5.11c. At this point, it has been possible to lift up the stretched tissue (as shown in Figure 5.11d) and move it until the tissue is placed in an orderly manner on the table. Figure 5.11 summarizes all the operations to be carried out to grasp a messy sock and place it in an orderly way on a table.
5.3. Gripper prototype evaluation

Figure 5.11: Steps to deal with the gripper for handling a sock.
Chapter 5. Experimental test and results

Similar operations were carried out to manipulate a microfibre cloth. In this case, the tissue was picked up in a messy way but was repositioned neatly on top of another microfibre cloth (as shown in 5.12d). In this way, it was possible to create a stack of tissues as shown in Figure 5.12d.

Figure 5.12: Gripper’s procedures for manipulating a microfibre cloth.

(a) Approaching and extraction microspines.
(b) Grasping.
(c) Lifting up.
(d) Placing, retraction microspines and Releasing.
Conclusion and future works

As explained in the Chapter 1.1, textile Industry, is very interested in the development of new grippers especially to reduce labor costs and increase productivity. In the Chapter 2.1 are illustrated different types of grippers, present in literature, which have been developed for the manipulation of tissues with different methodologies of grasping, holding and releasing. Unfortunately, one of the biggest problems, for the manufacturing Industry, is to develop a gripper capable of handling different types of tissues, with different characteristics, quickly and in a reliable way. This thesis work involved in the design, construction and testing of a reconfigurable gripper which can exploit intrusive and non-intrusive grasping methods. It has been studied the effectiveness of the gripper prototype and the versatility of application with different types of tissues. The gripper has been tested to understand the performance of grasping and even more complex manipulations which required the inverse grasp method.

6.0.1 Results

From Chapter 5, dedicated to the experimental phase, it is clear that the gripper prototype is satisfactory when its task is to grasp
single objects on a plane. These good results can be observed both in tests without microspines, that is using rubber bands, and with microspines. The problem occurs when the gripper has to grasp a single tissue from the top of a stack. The gripper works great using microspines while using the rubber bands it picks up many tissues at the same time. This is due to the high contact force that the gripper has to apply to the tissue. This contact force is transferred to the other tissues generating a frictional forces among them. The gripper has presented critical issues when it was used to grasp, using microspines, an extremely delicate tissue such as nylon tights. In fact, as can be seen from the tests, the tissue has suffered light damage. On the other hand, by retracting the microspines and using only the rubber bands, the tissue, was not damaged during the grasp. In the latest experiments, the gripper was tested with the novel inverse grasp method proposed. The results of these latest experiments have been satisfactory with the tissues tested.

6.0.2 Future works

The study can be continued in some different perspectives:

- Development of a more reliable gripper made of metal.

- Integration, on the gripping system, of other sensors (such as force sensors, proximity sensors etc.) in order to perform all the tasks autonomously.

- Carry out other tests to perform more complex and specific tasks in Industry. For example, the novel gripper, can be used to keep stretched the tissue while a sewing machine puts stitches to sew it.

- Carry out tests with other flat and deformable objects such as sheets of paper, plastic, and so on.
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<td>The four parameters, shown in red, of classic Denavit-Hartenberg convention are ( \theta_i, d_i, a_i, \alpha_i ). Courtesy of [39].</td>
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<td>4.3</td>
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<td>4.4</td>
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<td>4.5</td>
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</table>


[28] Jose Sanchez, Juan-Antonio Corrales, Belhassen-Chedli Bouzgarrou, and Youcef Mezouar. Robotic manipulation and


[38] CLOPEMA URL. Clopema unige. URL http://www.pmar. robotics.unige.it/clopema.
