

# Underactuated 3-finger robotic gripper for grasping fabrics.

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**Abstract**— In apparel industries, the handling of fabrics still remains a manual work and its automation is a real challenge. In this paper, a three finger gripper is developed for grasping (pinching and clamping) fabrics under different ways. It is inspired by the human fingers movements in order to grasp a piece of fabric that is laid on a table. The conceptualization, the design and the prototype of the gripper are presented, along with the kinematic and static analysis of its mechanism. The proposed versatile gripper is based on a simple mechanism, where the two of the three fingers (pointer and middle) are underactuated by a tendon. Also, the plan for the sequence and the synchronization of the movements of the fingers is defined according to the grasping task. A prototype of the gripper is produced using 3D printing technique, which keeps the total cost very low. The prototype has been tested experimentally under several grasping tasks, where its agility is demonstrated.

**Keywords**— *robotic gripper; fabric cloth handling; grasping; underactuation*

## I. INTRODUCTION

The automation of the apparel industry faced a significant problem, which is mostly caused by the difficulties to handle the raw materials. The garments, fabrics and cloths are composed by quite soft materials and require very skilful handling, performed mainly by humans. Thus, the cloths assembly is partially automated and still the cloth production is high labor demanding. On the other side, domestic robots in household chores should deal with everyday objects that are very flexible and extremely deformable (sheets, towels, tablecloths, clothes etc.). For the successful application of robots in these attractive cases, the research should focus on the design of gripping systems among other challenges. Therefore, there is great need in designing simple, reliable, versatile and low cost grippers for handling intractable objects such as fabrics.

Last decades, a lot of robotic grippers have been studied and developed, but the vast majority of them are dedicated for rigid or semi-rigid objects. A lot of them are human hand like grippers with mostly three fingers. A comprehensive review for underactuated hands was presented by L. Birglen et.al. [1], while a collection of state of the art papers for underactuated robotic hands can be found in [2]. The research on robotic grippers for handling fabrics and cloths is limited to a few cases.

A broad review about grippers developed for handling fabrics was presented by P. Koustoumpardis et al. [3]. The most common gripping principles as well as the gripping techniques, sensors and control strategies are categorized and presented. The most widespread grasping principles, the “clamp” when the fabric is grasped by both of its surfaces, and the “pinch” when the fabric is grasped only by the upper of its surface are analyzed extensively. A lot of grippers based on gripping techniques, such as needles, vacuum, air-flow, glue, electrostatic, velcro etc. have been developed in the past with more or less success. On the other hand, there are very few gripper cases with two or three fingers or human inspired grippers for grasping and handling cloths, fabrics, garments etc.

A long-standing research carried out in Japan by Eiicho Ono et al. [5][6]. In their first paper [5], which was one of the first applications in this field, the presented gripper consists of two moving fingers and a palm. The gripper avoids any bending on the fabric which means that the “clamp” principle is followed. The gripper was quite complex, since it has 2 DoF in the first finger and 3 DoF in the second. At their latest approach [6], a gripper with 3 human like fingers and a palm was presented. The gripper was designed to grasp and pick up a piece of fabric from stacks of fabrics. They focused mainly on how the fabric behaves when the upper layer should be separated from the lower ones, while with their approach only the “pinch” principle was feasible.

A specially designed sensors-equipped gripper with a roller mechanism at the fingertips was presented in [4]. The basic problem, that was studied and coped, is how to retrieve the fabric when there is a change of slipping away from the gripper.

A two finger gripper for pinching sensitive wool cloths, furs etc., was presented in [7]. The gripper was constructed based on two passively turning fingers and a simple on off pneumatic drive mechanism. It combines the pinching separation principle with the clamping for secure and effective grasp of cloths out of a bundle. But, this technique faced some issues with the thickness of the fabric and the accurate grasping location.

A gripper with a human-like fingertip and a quite complex mechanism was presented in [8]. The novel fingertip was equipped with a hard nail in combination with a soft elastic skin in order to handle cloths. It is designed to be capable to use two or more fingers to manipulate thin cloths and paper.

They are also focused on how to detect the change of contact type with the object and sense the surface structure using the nail.

In the present paper, the conceptualization, the design, the prototype and experiments of a gripper with three fingers for “clamping” and “pinching” is presented. It is inspired by the human fingers and the way they move in order to grasp a piece of fabric that is laid on a table. The gripper consists of one finger with one compliant passive joint and two underactuated fingers, that moved by a tendon. Each finger consists by three joints-phalanges and one degree of freedom, which is driven by a servo motor actuator. The gripper is capable to grasp a fabric from a corner (clamp), from the edge (clamp) and from above (pinch) and it is equipped with a simple sensing system for identifying the successful grasping or not of the fabrics. In the following Sections II and III, the grasping and handling difficulties, the human way to grasp fabrics and the requirements of the gripper are presented. The kinematic and static analysis of the fingers mechanism and the mechanical and electrical details of the gripper prototype are presented in Section IV. Finally, the experimental results and the gripper's efficiency in grasping fabrics under several test cases and different ways are presented in Section V.

## II. PROBLEM DEFINITION

The utilization of dexterous and versatile grippers is one of the main factors for the successful automation of the fabric handling tasks in the apparel industry. Unlike rigid objects, the grasping and handling of fabrics is highly unpredictable due to their very low bending rigidity and due to their non-linear and complex static and dynamic behavior. Therefore, conventional grippers, for handling rigid objects, are inadequate. There are several grasping and handling tasks that should be managed by a gripper, including: fabric separation, folding, unfolding, positioning, feeding in a sewing machine, packaging etc. Due to these demanding and diversiform tasks, for the design of such a gripper, the human performance should be taken into account. Additionally, it should be based on a mechatronic design approach so as to lead to a versatile gripper with integrated simple control and capable to manipulate intelligently the fabrics in several handling tasks.

In the apparel industry, workers are using tables as an auxiliary tool, for helping them, because a table can reduce the possible states that a fabric can take when it is manipulated. Thus, the problem caused by the very low bending rigidity of fabrics can be reduced considerably using a table.

The initial requirements that were set to be met by the gripper were based on the above mentioned features. In addition, the gripper should be capable to grasp a fabric that is laid on a table following four different grasping types, as shown in Fig. 1,:

- 1) *from a corner* of the fabric, as shown in Fig. 1a.
- 2) *from an edge* of the fabric(Fig. 1b).
- 3) *from the top* of the fabric (pinch) and inside its area (Fig. 1c).
- 4) *from a corner of the upper layer of a folded fabric* (Fig. 1d) in order to unfold it.

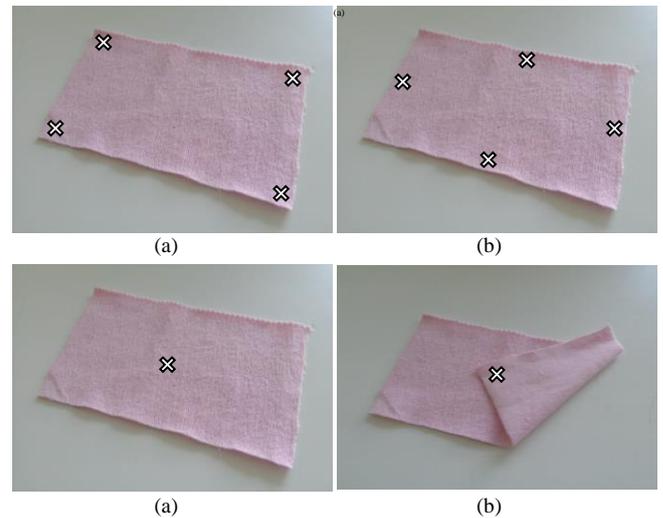


Fig. 1. Different ways-locations for grasping a fabric with a gripper.

The definition of the initial grasping points should be determined by a higher control level and it is not considered in the present paper.

## III. HUMAN GRASPING ANALYSIS OF FABRICS AND PROPOSED GRIPPER'S CONCEPT.

The aim, of the presented concept, is to design a gripper inspired by the human grasping technique and the anatomy of its hand and used fingers. Therefore, the requirements and the specifications, for the design of the gripper, are defined by a detailed study of the actual humans' fingers movements when they handle and grasp the fabrics that are laid on a table. The target of this analysis is to decide about:

- the number of the required fingers of the gripper.
- the type of the fingers.
- the appropriate grasping position on the fabrics according to the case of grasping type.
- the sequence of the fingers motion that should be followed according to the handling task.

A number of humans (females and males) is observed, while they have been asked to take a fabric from the table. Their technique is recorded and analyzed and the results of this study are used to form the concept of the gripper as well as to quantify its design. The several ways that a human used to approach and grasp a fabric are shown in Fig. 2, while its fingers' movements are shown step by step in Fig. 3. The human-inspired grasping of the fabric is achieved as a combination of mixed movements of the pointer and the middle fingers, while the thumb finger is used as an auxiliary barrier mechanical stop for the clamping of the fabric. Specifically, the two fingertips (of pointer and middle) are following a complex trajectory with this sequence:

- at the beginning of their movement the fingertips delineate a curve in order to approach the table.
- when they are in contact with the table a linear trajectory is followed in order to pinch the fabric

between the thumb and the other finger (pointer or middle).

- another type of curve is followed when the fingertips living the table in order to come in contact with the thumb and cage the fabric.
- finally, an almost linear trajectory is followed on the surface of the thumb finger, while they are trying to rub the fabric between the thumb and one of the other two fingers in order to unfold the pinched part of the fabric.

Besides the above finger movements, the fingers are synchronized each other with different sequences according to the gripping type.

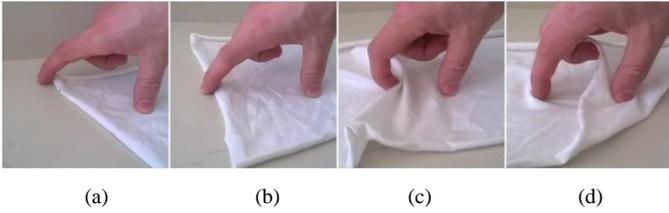


Fig. 2. Human grasping a fabric from a) a corner, b) an edge, c) the top and d) a corner of the upper layer of a folded fabric.

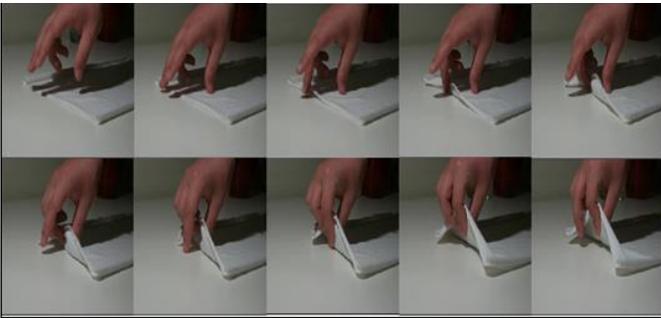


Fig. 3. Human hand grasping the fabric

Finally, taking into account the above human actions, the proposed concept of the gripper consists of the following:

- three fingers having a topological morphology similar to the thumb, the pointer and the middle-finger of the human.
- the thumb finger should have only one passive compliant joint.
- each one of the fingers (pointer and middle) should have one actuated degree of freedom and three compliant passive joints.
- all fingertips should have the appropriate surface form, so as to facilitate the relative motion: 1) between each other, 2) between the finger and the table and 3) between the finger and the fabrics.

From the human fingers movements the critical conclusion about the sequence of the gripper fingers' motion as well as the intervals of the fingers' motion is observed, recorded and calculated and it is used to define the respective sequences of

the gripper's motion. All the four grasping types in combination to the sequence of the fingers' motion are presented in TABLE I. , while it is assumed that the thumb finger has been placed on the fabric, as it is shown in Fig. 5.

TABLE I. SEQUENCES OF THE FINGERS' MOTION ACCORDING TO THE GRASPING TYPES.

Grasping type	Sequences of the fingers' relative motions		
	Finger	Elapsed time	
from a corner	Pointer		C <sup>a</sup>
	Middle	C	
from an edge	Pointer		C
	Middle	C	O <sup>b</sup> C
from the top	Pointer	C	
	Middle	C	
from a folded corner	Pointer	C	O
	Middle		C

a. C: closing motion of the finger  
b. O: opening motion of the finger

It is obvious that, for each grasping type, a different sequence of the fingers' movements should be followed according to the observation of the human movements. For example, in the second case (grasping the fabric from an edge) the following sequence should be performed as it is shown in the second row of TABLE I. , which is also illustrated in Fig. 3 (human fingers motion) and in Fig. 5 (gripper finger motion):

*The gripper should start closing the middle finger (C) and at the beginning of the D-part of the trajectory (shown in Fig. 5) the second finger (pointer) is starting its closing motion (C). Immediately after, the middle is moving back (O) and opens again. Finally, and while the pointer continuous its closing motion and just before its ending location, the middle is closed (C) again. At the end, both of the fingers should grasp the fabric, by a clamp manner, and overcome the crumple caused by the initial pinching process.*

Specifically, it came out that the human moves his first finger (middle) for about 0.21sec and when reaches the first 0.17 sec then the second finger starts its movement. The second finger (pointer), now moves for about 0.16 sec and while the first releases the folded between the fingers fabric. Identical procedure is followed for the other grasping types. It is obvious that those intervals are quite small and require electric motors with significant accelerations to reach them. Thus, those intervals will be scaled proportionally with lower accelerations.

#### IV. GRIPPER DESIGN.

##### A. The prototype of the gripper

The final 3D-model of the gripper and the constructed, with a 3D-printer, prototype are shown in Fig. 4. Since the thumb should play the role of a barrier it is designed to has only one elastic rotational joint, i.e. a passive compliance using a torsional spring, in order to reach the table safety. For making

the gripper as simple as possible we use underactuated fingers for the cases of the pointer and the middle fingers. This was achieved by designing the fingers with three passive joints and three phalanges, as the human finger has, and driving them with a tendon attached on a pulley rotated by a motor for each finger.

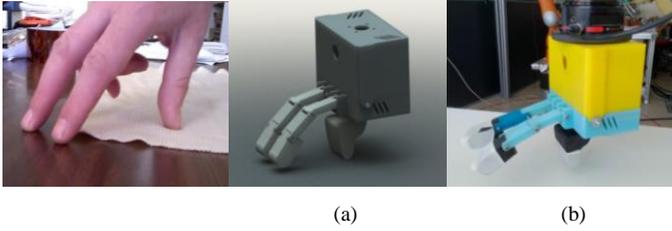


Fig. 4. The three fingers gripper a) 3D model and b) 3D-printed prototype.

The fingers' joints 2 and 3, shown in Fig. 5, are equipped with a torsional spring, which resist in the phalanges movement and bring them back, when the tendon is relaxed, to their mechanical limits. On the other hand, only for the first joint, the torsional spring works on the opposite direction compared to the other two springs. That, provides the mechanism with an extra passive compliance. This feature is of primary importance for safe touch with the fabric/table. Also, there is a critical need for high compliance of the finger in order to be capable to follow a linear trajectory on the table as described in the following paragraph. In other words, this feature makes the fingers quite flexible on the environmental constraints (table or thumb finger).

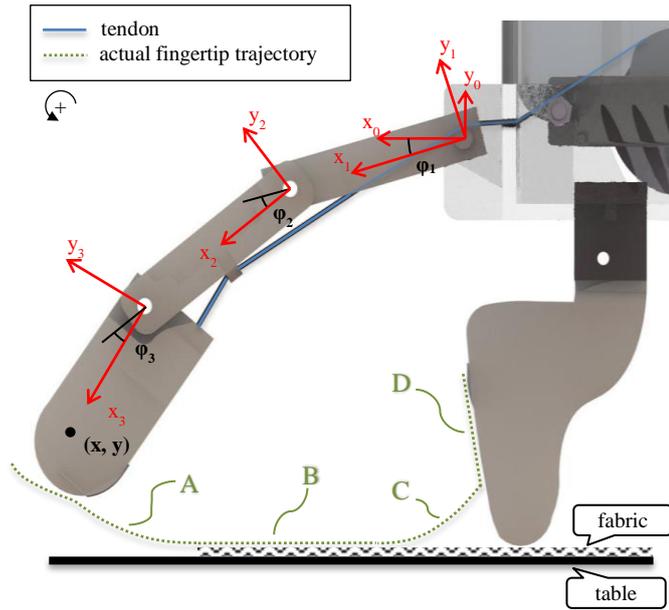


Fig. 5. The kinematic problem

When the gripper works without the fingers to contact with the table, then only the phalanx 2 and 3 could be moved by the tendon. When the fingers come in contact with the thumb or contact to the table then their first joints are rotated if the

applied torque is higher than the torsional spring resistance of this joint. Actually, the fingertips of the two fingers follow a complex trajectory, as shown in Fig. 5 with a green dotted line. This trajectory is crucial for successful grasping (pinching) of the fabric. Actually, the fabric is wrinkled during the B-phase of the trajectory, it is scrubbed and partially unwrapped during the D-phase as it is rubbed on the thumb finger and finally pinched (or clamped) at the end of D-phase. Therefore, the whole morphology and the shapes of the 3-fingers are designed in order to serve towards these special requirements for the desirable trajectory.

### B. Kinematic analysis of the fingers.

In the following the kinematic analysis of the proposed finger's model, as a 3-link mechanism, is presented.

The exact position of the fingertip is given by the following equations:

$$x = L_1 \cos \varphi_1 + L_2 \cos(\varphi_1 + \varphi_2) + L_3 \cos(\varphi_1 + \varphi_2 + \varphi_3) \quad (1)$$

$$y = L_1 \sin \varphi_1 + L_2 \sin(\varphi_1 + \varphi_2) + L_3 \sin(\varphi_1 + \varphi_2 + \varphi_3) \quad (2)$$

where,  $L_1, L_2, L_3$  are the lengths of the phalanges and  $\varphi_1, \varphi_2, \varphi_3$  are the joint angles.

Subsequently, the most significant part of this study concerned the calculation of required tendon's displacement in order to move the fingertip as it is needed. This is approached by using the polygon of vectors as described in the followings and shown in Fig. 6.

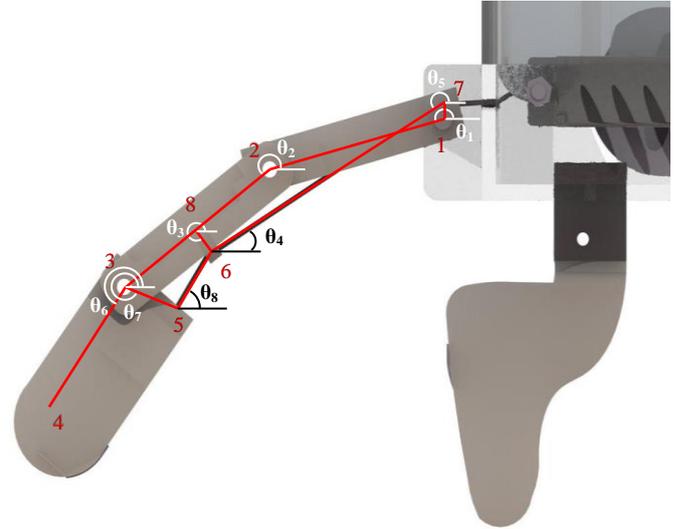


Fig. 6. Polygon of vectors

$$\theta_1 = \varphi_1 + \pi$$

$$\theta_2 = \varphi_2 + \theta_1$$

$$\theta_3 = \frac{\pi}{2} + \theta_2 \quad (3)$$

$$\theta_5 = 1.14 \text{ rad (from geometry)}$$

$$\theta_6 = \theta_2 + \varphi_3$$

$$\theta_7 = \theta_6 + 1.64 \text{ rad}$$

The equations from the closed chain vectors, shown in Fig. 6, analyzed in the  $x$  and  $y$  axes are:

$$L_{12}\cos\theta_1 + L_{28}\cos\theta_2 + L_{86}\cos\theta_3 + L_{67}\cos\theta_4 + L_{71}\cos\theta_5 = 0 \quad (4)$$

$$L_{12}\sin\theta_1 + L_{28}\sin\theta_2 + L_{86}\sin\theta_3 + L_{67}\sin\theta_4 + L_{71}\sin\theta_5 = 0$$

$$L_{83}\cos\theta_2 + L_{35}\cos\theta_7 + L_{56}\cos\theta_8 + L_{68}\cos(\theta_3 - 180) = 0 \quad (5)$$

$$L_{83}\sin\theta_2 + L_{35}\sin\theta_7 + L_{56}\sin\theta_8 + L_{68}\sin(\theta_3 - 180) = 0$$

where,  $L_{ij}$  are the lengths between points  $i, j$  shown in Fig. 6 and

$i, j = 1, 2, \dots, 8$  points.

The unknown  $\theta_4$  and  $\theta_8$  angles, from (4) and (5), can be calculated as:

$$\theta_4 = \tan^{-1}\left(\frac{L_{12}\sin\theta_1 + L_{28}\sin\theta_2 + L_{86}\sin\theta_3 + L_{71}\sin\theta_5}{L_{12}\cos\theta_1 + L_{28}\cos\theta_2 + L_{86}\cos\theta_3 + L_{71}\cos\theta_5}\right) \quad (6)$$

$$\theta_8 = \tan^{-1}\left(\frac{L_{83}\sin\theta_2 + L_{35}\sin\theta_7 + L_{68}\sin(\theta_3 - 180)}{L_{83}\cos\theta_2 + L_{35}\cos\theta_7 + L_{68}\cos(\theta_3 - 180)}\right) \quad (7)$$

And consequently, the displacements of the tendon between points 6 and 7 ( $\Delta l_1$ ) and between points 5 and 6 ( $\Delta l_2$ ) are:

$$\Delta l_1 = \frac{L_{12}\cos\theta_1 + L_{28}\cos\theta_2 + L_{86}\cos\theta_3 + L_{71}\cos(\pi + \theta_5)}{\cos\theta_4} + C_1 \quad (8)$$

$$\Delta l_2 = \frac{L_{83}\cos\theta_2 + L_{35}\cos\theta_7 + L_{86}\cos(\pi - \theta_3)}{\cos\theta_8} + C_2 \quad (9)$$

where,  $C_1$  and  $C_2$  are the initial lengths of the tendon between 6 and 7 points and 5 and 6 points respectively.

Hence, from (8) and (9) the total displacement of the tendon is:

$$\Delta l = \Delta l_1 + \Delta l_2 \quad (10)$$

where, this displacement depends on the angles of the vector chains and therefore on the joint angles  $\varphi_1, \varphi_2$  and  $\varphi_3$ .

This total tendon's displacement is used for determining the pulley and the motor specifications, as described in Section IV.D.

### C. Static analysis of the fingers.

In the following, a static analysis considering that the finger is working without contact with the table and the thumb is presented. The static analysis of the finger is implemented in order to calculate an estimation of the maximum force (T) that should be applied by the actuator, along the tendon, in order to surpass the resistant of the mechanism and close the finger. The aim of this static analysis was to define and quantify the design parameters (critical dimensions) of the fingers that affecting the force (T). Thus, in order to minimize the tendon's force (T) this

analysis has been used in a recurrent process to improve the design of the finger and therefore reduce the required motors' power. The resistant force, that the tendon should overcome, is caused by the static friction between the tendon and the pivot points, the joint static friction and the spring torques. It is assumed that the maximum force on the tendon (T) is achieved when the finger is fully closed. Having the spring constants of joints 2 and 3 ( $K_2, K_3$ ) the required force is calculated. The geometric characteristics and the applied forces on the mechanism are shown in Fig. 7.

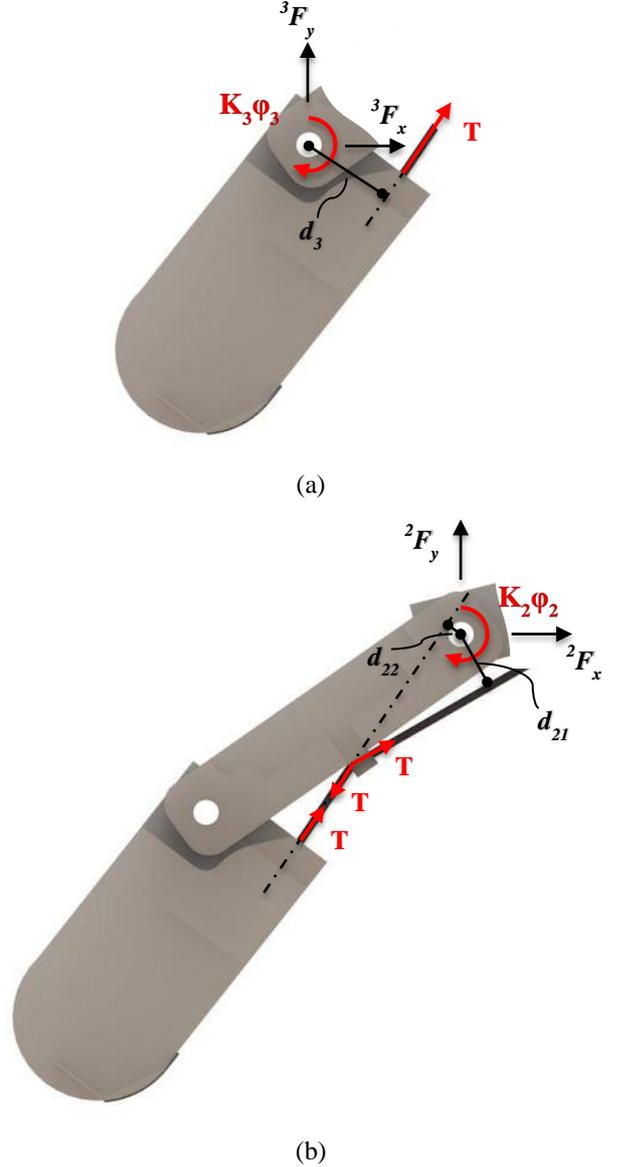


Fig. 7. Static analysis of one finger.

The torque that the tendon produces around the third joint, as shown in Fig. 7(a), is:

$$M_3 = Td_3 \quad (11)$$

where,

$$d_3 = \frac{|(x_6-x_5)(y_5-y_3)-(x_5-x_3)(y_6-y_3)|}{\sqrt{(x_6-x_5)^2+(y_6-y_3)^2}} \quad (12)$$

is the vertical distance between the tendon and the third joint where  $x_i$  and  $y_i$  are the horizontal and vertical coordinates of the points shown in Fig. 6, respectively.

From the free body diagram of phalanx 3, Fig. 7(a):

$$\Sigma M_3 = 0 \Rightarrow Td_3 = K_3\varphi_3 \Rightarrow T = \frac{K_3\varphi_3}{d_3} \quad (13)$$

Where the force that should be applied along the tendon can be calculated in relation to the joints angles.

Alternatively, from the free body diagram of phalanx 3 and 2, as shown in Fig. 7(b), the same procedure can be followed. The torque that is applied by the tendon on the second joint is:

$$M_2 = Td_{21} + Td_{22} - Td_{22} = Td_{21} \quad (14)$$

where,

$$d_{21} = \frac{|(x_7-x_6)(y_6-y_2)-(x_6-x_2)(y_7-y_6)|}{\sqrt{(x_7-x_6)^2+(y_7-y_6)^2}} \quad (15)$$

$$d_{22} = \frac{|(x_5-x_6)(y_6-y_2)-(x_6-x_2)(y_5-y_6)|}{\sqrt{(x_5-x_6)^2+(y_5-y_6)^2}}$$

and

$$\Sigma M_2 = 0 \Rightarrow Td_{21} = K_2\varphi_2 \Rightarrow T = \frac{K_2\varphi_2}{d_{21}} \quad (16)$$

Thus, the maximum needed force that should be applied on the tendon is calculated from (13) or (16) and in the position where the finger is fully closed, which is 12N.

In addition to the above analysis a large number of experiments were conducted in order to find the additional force that is needed when the fingers should grasp a piece of fabric in order to handle it securely. For these experiments, a dynamometer is adjusted at the end of the tendon, which is pulled in order to close the finger and grasp a fabric. The maximum recorded force (about 14N) includes the tendon's maximum force, the joints'/tendon's frictions and the spring torques. This is rational and very close to the force calculated by the above static analysis, where the frictions are not included.

A number of additional experiments are executed, where the gripper was in contact to the table in order to produce the trajectory shown in Fig. 5. In this set of experiments, the recorder by the dynamometer force is larger (about 18N) as it was expected, since the finger is in contact with the table in a part of the following trajectory. This force is used to choose suitable servo motors that will drive the fingers through the tendons.

#### D. Details of the prototype gripper.

The mechanical and electrical details of the gripper are shown in Fig. 8. The two fingers (pointer and middle) are

actuated by two servo motors, while a pulley has been attached on each of them in order to pull the tendon.

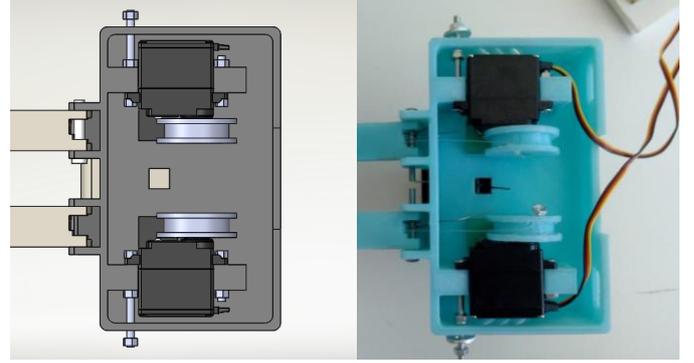


Fig. 8. The inside of the gripper.

The diameter of the pulleys is calculated according to the displacement  $\Delta l$ , that has been determined in (10), and in combination with the preferred total rotational angle of the motor. Two pulleys, with diameter of 24mm, have been designed and attached on the servo motors as shown in Fig. 8. To fully close the finger, the pulley should be rotated  $140^\circ$  by the motor, since:

$$\Delta l = \varphi r \Rightarrow \varphi = \frac{\Delta l}{r} \text{ (rad)} = \frac{180\Delta l}{\pi r} = 140^\circ \quad (17)$$

The HS-85MG servo motors are used, which are quite common and have a very low cost. The produced maximum torque of the servo is 3~3.5 kg.cm and the motors' output shaft operates in an area of  $180^\circ$ . The combination of motor-pulley can pull the tendon with a force up to 24.5~28.5N. The servo motors are controlled by the Phidget 1061 which is controlled by an external PC. The basic advantage of the proposed gripper is that it is based on a very simple control scheme. Actually, it is an open loop control concerning the movements of the fingers, where their actual positions are not measured through their joints, but it can be calculated and therefore estimated through the displacement of the tendon. The control of the tendon's displacement is accomplished by controlling the servo motors' angles.

A simple sensing system for detecting the successful grasping of a fabric has been designed to be incorporated on each of the fingers, as shown in Fig. 9. The concept is based on very thin metallic laminates installed on the surface of each of the fingertips. Actually, these are parts of an electrical circuit that detects the presence or not of a fabric when the fingers are closed. The effectiveness and the feasibility of this detector is investigated with a number of experiments where a wide variety of fabrics, with different types and composition, were tested using a simple multimeter. The results shown that almost all fabrics (with the exception of a small number of woven fabrics with very sparse weaves) behave as an insulator and therefore can be detected by the proposed sensing system.

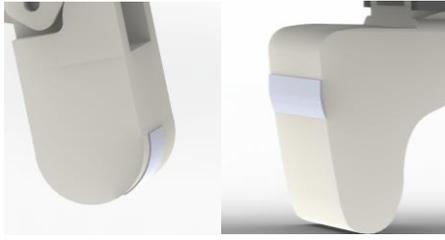


Fig. 9. Sensing system for checking the successful grasping of a fabric. Pointer or middle finger (left) and thumb finger (right).

Furthermore, the two fingertips of the moving fingers (pointer and middle) will be covered, in a future version of the gripper, with a silicon rubber material in order to increase the friction between the fingertips and the fabric. Therefore, the effectiveness of the grasping is going to be improved.

## V. EXPERIMENTS AND RESULTS

For proving the gripper's performance and testing its agility, the grasping of several fabrics is performed. For the experiments the prototype gripper is mounted on a scara robot (Adept Cobra s800). A force sensor is attached on the wrist of the robot, i.e. between the gripper and the robot. Each grasping experiment starts with the robot approaching the table (with the thumb finger) until a predefined force is reached. Then, the appropriate sequence of the fingers' motion is applied according to the handling scenario. Five different scenarios were tested: 1) the fabric should be grasped from a corner, 2) from an edge, 3) from the top and anywhere inside the area of the fabric, 4) from an edge that protrudes from the table while the fabric has been previously moved slightly outside the table's surface and finally 5) from a corner of a folded fabric, which is the most difficult case, in order to unfold it in a later step.

In the first experiment scenario<sup>1</sup> (Fig. 10.a) the gripper approaches one of the fabric's corners. This is the most effective and easy way to handle the fabric as the "grasp" is succeeded with flying colors. In this case, the middle finger that applies the pinch reveals a great unfolded surface for the other finger to accomplish the grasp.

In the second scenario<sup>2</sup> (Fig. 10.b) the gripper approaches an edge of the fabric. The grasp is started with the middle finger so as to pinch the fabric then the pointer finger is moved in order to grasp the fabric while before the end of its movement the middle finger is opened in order to release the folded part of the fabric. When the pointer finger finishes the grasp then the middle one grasps again the fabric. Finally, both fingers grasp the fabric without folding it.

In the third scenario<sup>3</sup> (Fig. 10.c) the gripper pinches the fabric by a random point inside its area. This case is the simplest one, as it doesn't require any moving sequence. The only thing that is needed is to close both of the fingers or only one of them depending on the size of the fabric.

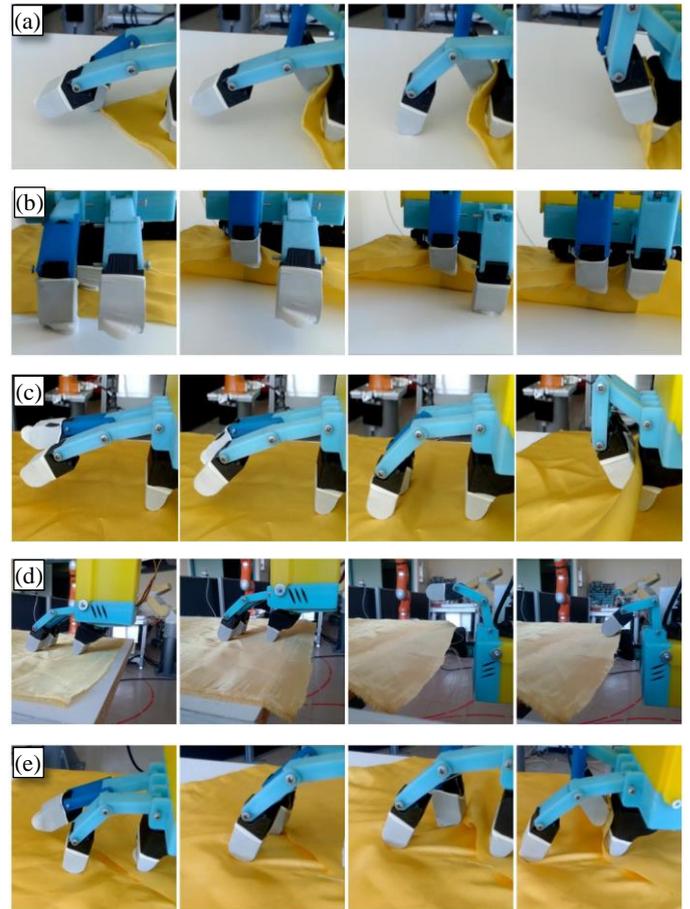


Fig. 10. Different experiments scenarios for grasping a fabric.

In the fourth scenario (Fig. 10.d), all the three fingers are touching the fabric and manipulate it in order to guide it outside the table's perimeter. When a small sufficient part of the fabric is protruded from the table, then the gripper is rotated (pitch) by  $90^{\circ}$ , and clamps the fabric using both fingers.

Finally, the last scenario<sup>4</sup> (Fig. 10.e) is more complex and interesting than the previous ones. In this task the fabric is folded and the gripper has to pinch it from the folded corner in order to unfold it in a later step. In order to accomplish this task there is a need to separate the task into two subtasks. First, the gripper has to stretch the fabric as friction is needed to separate the folded layer of fabric. Therefore, the pointer finger is partially closed and then slightly released in order to apply a tension on the lower layer of the fabric and stretch it between the pointer and thumb fingers. During the second subtask, the middle finger pinches the folded corner without drifting the lower layer of the fabric, since it is held firmly by the two other fingers.

The successful accomplishment of the above scenarios proves the effectiveness of the gripper as well as its versatile advantage to complete different handling tasks. Moreover, it has been tested in different fabric types where it operates adequately except in the cases where the fabric has a very low surface friction (e.g. lining fabrics). However, this can be

<sup>1</sup> <http://youtu.be/QcU6X9BOsDI>

<sup>2</sup> <http://youtu.be/sJBZnCSZxLw>

<sup>3</sup> <http://youtu.be/YLWQfAfMDho>

<sup>4</sup> <http://youtu.be/HYQfEp16D4s>

solved by increasing the fingertips' friction using a silicon rubber material for covering them, as has been described in the previous section.

The experimental prototype of the gripper is produced on a domestic 3D printer with fused deposition modelling (FDM) and using polylactide (PLA) thermoplastic material. The cost of the printing materials (including the 3D printing process) and the mechanical components, but without the electronic parts (servo motors and driver) is lower than 5 Euros.

## VI. CONCLUSIONS AND FUTURE WORK

In this paper, the conceptual and the detailed design as well as the prototype of a new gripper for grasping and handling fabrics are presented. This concept and design is inspired by the human grasping actions when the fabric is laid on a table folded or not. The proposed gripper is manufactured with a very low cost, following state of the art 3D-printing techniques. A kinematic and static analysis is presented and verified experimentally, for determining the specifications of the gripper (dimensions, tendon's force, pulleys and motors). In addition, a number of experiments are conducted, where the gripper performance is demonstrated.

The investigation of the human performance according to the fabrics type and properties and in conjunction to the handling tasks will be our research directions for the gripper's future upgrading so as to support the gripper with intelligent control strategies in a higher level. An automated decisions making system (based on machine vision information) for finding the ideal location on the fabric [9] in order to grasp it with optimum efficiency, is under consideration.

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