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The Mag-Gripper: A Soft-Rigid Gripper Augmented with an Electromagnet to Precisely Handle Clothes

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***Abstract*— This paper introduces Mag-Gripper, a novel robotic gripper specifically designed for autonomous clothing manipulation. It is capable of improving grasp repeatability and precision, compensating uncertainties in the target grasping locations. We propose to approach the autonomous clothing manipulation challenge by involving a suitable magnetic force. For this reason, Mag-Gripper is equipped with an electromagnet capable of interacting with small metal parts properly placed on the garment to be grasped. Electromagnet exploitation is not a novelty in literature, but our design innovation consists in embedding the electromagnet in the structure of a jaw gripper. In so doing, we revisit a classic end-effector type, corresponding to the simplest representation of a hand capable of opposability, allowing easily controllable devices to perform grasps similar to the human pinch grasp. Mag-Gripper can find applications either in Research labs investigating Machine Learning-based clothing manipulation techniques either in companies having to manage a large amount of returns, either in home setting scenarios.**

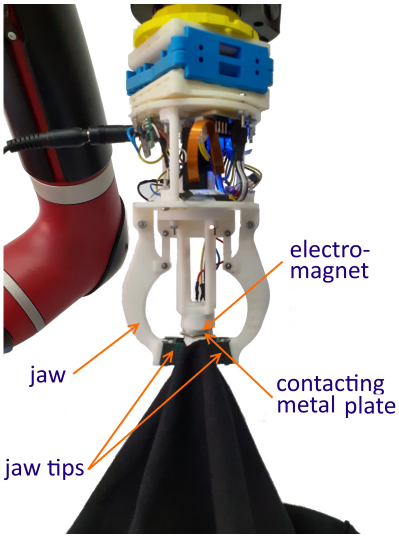

Fig. 1: Mag-Gripper: a novel gripper to manipulate clothes

I. INTRODUCTION

A. Motivations

Continuously evolving robot generations are spreading out in factories and in home settings as service robots. Today, small robots embedding some intelligent skills are taking the first steps in dwelling our homes, and in the next future a much wider diffusion is expected, both as assistants for housework and physically-impaired people. The capability of interacting in a dynamic environment requiring fine sensory perception and dexterity will play a fundamental role, since robots will be expected to perform some tasks autonomously (at least partially). Adapting robots to perform tasks requiring complex dexterity (*e.g.*, to manipulate deformable objects) poses new challenges. In particular, deformable objects cannot be grasped according to classic grasp planning methods [1], and their manipulation strategy strongly depends on the object configuration. Clothes are extremely deformable objects, whom configuration is significantly affected by the trajectory performed by the handling arm. Therefore, clothes are challenging because of their difficult perceivability and manipulation, due to the potentially infinite configurations they can assume. To bring clothes in a desired configuration, the sequence of the intermediate movements is paramount: Each sub-movement, along with the points where the cloth is grasped, causes a cloth configuration. Due to the deformable nature, relatively small changes in the grasping points location can produce a significant change in the final configuration assumed by the grasped garment. This variation of configuration can influence the outcome of the task, potentially causing a failure. On the contrary, grasping the garment in proper locations leads to a fast and effective task accomplishment, as shown in the video reported in [2] by a popular garments producer. As such, properly designed assistant robots could be able to fold our garments in the near future. To this aim, we propose a novel approach to the problem, exploiting both grippers and garments specifically designed to allow autonomous manipulation by robots. In the following, we detail the rationale and specifications of Mag-Gripper, a novel type of jaw gripper augmented with an electromagnet. Small metal parts embedded in the garment as ornamental or brand elements are involved in the attractive gripper-clothing approach. Our long-term vision involves cooperation between researchers in robotics and garments producers, so to realize clothes that can be easily manipulated by our gripper. In the meanwhile, Mag-Gripper features an immediate field of application in the robotic community: It is meant to be a support tool for the research in Machine Learning-based garment manipulation, where high repeatability in grasp location is required during the data collection.

B. Previous Work on Cloth Manipulation

In the last decade, research on autonomous cloth manipulation has received great boost. This task can be decomposed in two sub-tasks: unfolding and folding. The former being aimed at bringing the cloth from a random configuration to a known one (usually corresponding to have the garment

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lying flat on a table), while the latter is aimed to actually accomplish the required manipulation starting from that known configuration. Typically, the cloth pose is not known *a priori* and a perception system is needed. Regarding the unfolding task, the most popular approach consists in re-grasping the object until the target configuration is reached. In [3], a geometric approach is proposed, consisting in identifying two grasping points on the garment outline capable of generating an half-folded cloth configuration, to which shape analysis techniques are applied to estimate the novel re-grasping points. In [4], a 2D perception and a Markov Hidden Model are used. In [5], 3D perception and fiducial markers located on the garment are used to compute a mesh of the object, and a Support Vector Machine is employed to implement a greedy policy for the next grasping point estimation. In [6], a data-driven approach joint with Random and Hough forests is used for garment recognition and to estimate the grasping points in a probabilistic planning framework taking into account uncertainties related to the estimation process. In [7], a simulation environment is used to compare the synthetic data in it with a reconstructed mesh of the physical garment to grasp, and mapping the re-grasping points on the synthetic mesh to the physical garment. The main difficulties encountered in the above cited works are: *i)* the time required to accomplish the task; *ii)* the uncertainties on the estimate of the final grasping point; *iii)* the risk of loosing the object during multiple re-grasping. In a more recent work [8], a hierarchical structure of Convolutional Neural Networks is used to recognize the garment category and grasp it directly in two points, avoiding multiple grasps and decreasing the required completion time.

Regarding the folding task, early works proposed geometric approaches [9] relying on the gravity-based folding: in [10], the cloth is assumed to be representable as a simple polygon, and the task is accomplished by moving a portion of the garment over another one, having a segment termed *g-fold* as separation line. Following this approach, in [11] the garment-polygon matching was improved and in [12] the garment flexibility taken into account. In [13], a complete pipeline from picking up a garment to folding it exploiting the *g-folds* is presented. More recent works arise from the synergy between Machine Learning and Robotics, relying on Deep Learning, Learning from Demonstration (LfD) and Reinforcement Learning. In those works, the robot is taught to learn the folding task by means of a set of demonstrations provided by a human operator. In [14], a deep convolutional autoencoder joint with a deep time delay neural network is used to process data acquired via teleoperation. In [15], a LfD with Deep P-Network is used to learn a T-shirt folding. In [16], Dynamic Motion Primitives are exploited with LfD and RL. When dealing with Machine Learning techniques, it is well-known that to achieve a good learning process (*i.e.*, good generalization capabilities), a large and consistent dataset has to be provided to the machine. In particular, when a given cloth manipulation task has to be learnt by means of human demonstrations, the multiple demonstrations have to start all with the same initial garment configuration [16]. To this aim, grasping the cloth always in the same points is fundamental, since clothes are extremely deformable objects and relatively small changes in the grasping points can cause significant errors in the initial configuration. This is why in [16] the gripper maintains the contact with the garment during the entire learning process.

C. Previous Work on Grippers for Cloth Manipulation

In [17], a taxonomy of the grippers that have been used in works on deformable objects manipulation is presented. As highlighted in the paper, usually those grippers are not specifically thought for interacting with clothes, which are extremely deformable objects. Indeed, the most commonly used tools are the parallel-jaw grippers, whose surface tips supposed to contact the object have a rectangular shape. The gripper can then interact with the object by taking the longer or the shorter rectangle side parallel to the table on which the cloth lies, depending on the desired closing motion. Multi-fingered hands (such as those used for instance in [18]) allow to exploit in a more complex way the abduction motion and can allow a more dexterous manipulation (*e.g.*, to identify the boundary of clothes [19]). Few hands are designed to establish specific interactions with clothes: in [20], force sensors are placed on the tips to perform garment classification according to the material roughness. In [21], an underactuated three-fingered hand capable of generating human-like grasping movements exploiting environmental constraints [22] is presented. However, when these tools are used to manipulate clothes, the grasping task is mainly performed by sliding on the table surface and enclosing a portion of the garment between the jaws. This approach: *i)* restricts the cloth manipulation to occur on a tabletop; *ii)* requires that an enough portion of the fabric is constrained between the tips to avoid undesired slippage. However, *i)* cloth manipulation can be performed also in the air [5], [16], and this is important also in the light of the growing need of assistive robotic tools; *ii)* grasping by sliding the fabric on the table surface introduces unpredictable variations in the configuration taken by the garment after the grasp has occurred. This is due to the fact that the portion of the tissue actually constrained by the tips is the consequence of the interaction between the garment, the robot and the environment, and the related changes are difficult to face for vision-based Machine Learning techniques.

D. Contribution

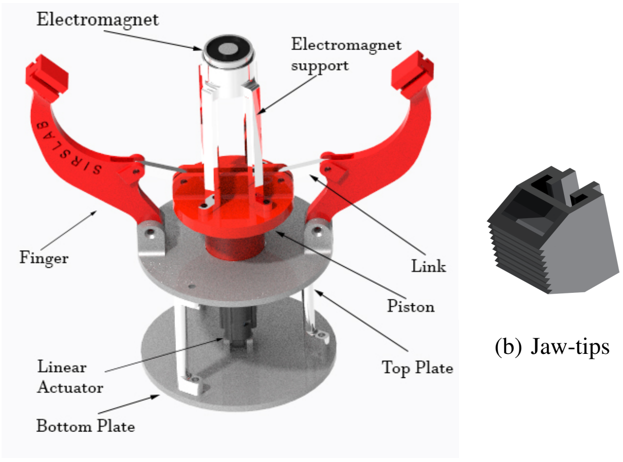
In this paper, we want to suggest a novel approach to the execution of autonomous clothing manipulation, by exploiting the presence of an attractive magnetic force established between the gripper and the garment. As a suitable tool, we present Mag-Gripper, an augmented jaw gripper embedding an electromagnet. As it will become clear in the following, this design choice allows to achieve a repeatable extended point-like grasp: Since the location where a clothing is grasped causes its configuration after the grasp has occurred, having a repeatable grasping capability results in having repeatable clothing configuration. Hence, Mag-Gripper wants to be a possible solution to cope with the issues mentioned in Sec. I-B and I-C. To the best of our knowledge, no grippers exploiting the magnetic force so far have been exploited for clothing manipulation. Moreover, the difference with commercially available grippers exploiting the presence of a magnet [23] is that we want to exploit the magnetic force only to establish the contact between the gripper and the garment, whereas the presence of a permanent magnet would need an opposite magnetic field to allow the object detachment any time the grasp has to be released. After the extended point-like grasp has occurred, the magnetic force is no more needed: the electromagnet is deactivated to avoid overheating and a secure grasp maintenance is achieved by exploiting the gripper jaws. In our approach, the garment has to embed a metallic part. During data acquisition for Machine Learning-based approaches, these parts can be easily inserted by researchers in the desired locations to meet grasp precision requirements. However, the implementation of autonomous garment manipulation applications for the general public will be possible only by establishing a synergy between companies and researchers, and such a synergy will be encapsulated in novel clothing production lines specifically thought to allow autonomous manipulation. These novel garments will have the needed metal parts embedded as ornamental or brand elements, such as buttons and small plates.

II. THE MAG-GRIPPER

Mag-Gripper has been designed to be lightweight, modular and with a limited encumbrance. The prototype has been designed via CAD and realized with additive manufacturing techniques (material used is ABS M30), which allowed small production cost and short production time. The gripper is similar to a jaw gripper, but the novelty we propose consists in having realized an *augmented* jaw gripper: in its central part, there is an electromagnet mounted on the top of a linear actuator. By activating the electromagnet, a magnetic field is generated, which causes a magnetic force attracting the metal part attached to the cloth. Due to the attractive motion of the metal part, a collision between the end-effector and the cloth occurs, and is detected by a small resistive force sensor (FSR), which is located near to the electromagnet. The contact is deemed to be occurred when the force measured by the sensor exceeds a given threshold, triggering the closing motion of the jaws. The proposed gripper exploits the advantages of both the electromagnet and the parallel-jaws: the former allows to grasp the cloth in the desired point, while the latter allow a secure grasp maintenance during the cloth manipulation. In other words, the uncertainty brought by the soft fingertips of the jaws is tamed by the action of the electromagnet.

A. Components

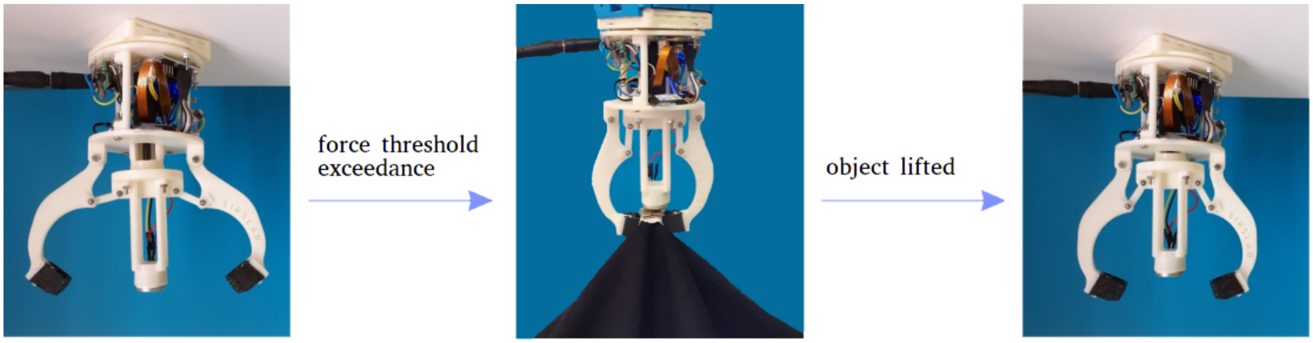
The Mag-Gripper is an augmented jaw gripper, a sketch of which is shown in Fig. 2a. In the gripper central part, between the jaws, there is a linear actuator (PQ12-30-12-P by Actuonix), at the top of which an electromagnet (KS0320 by Keyestudio) is mounted. Thanks to a set of pin joints and connecting links, the motion of the actuator allows both to approach the electromagnet to the cloth, and to open/close the jaws. Thus, the proposed gripper has one degree of actuation, which allows the gripper to be lightweight (181 g, including all the electronics) and with limited encumbrance, taking into account the considerations in [17]. The closed structure width is 9 cm. The maximum opening size of the jaws is 13 cm. When the jaws are at the maximum opening distance allowed by design, the most prominent part is the electromagnet and the distance between the electromagnet and the base is 15.3 cm. When the jaws are completely closed, the most prominent part is given by the jaw tips, and the distance between the tips and the base (bottom plate in Fig. 2a) is 15.5 cm. The circular base has 5 cm diameter, and the links connecting the two circular surfaces enclosing the electronics are 5 cm long. To have a robust structure, the gripper base, the jaws and the locations assigned to the actuator and the electromagnet are 3D-printed in ABS. Conversely, the jaw-tips are hollow and realized in TPU, to ensure a more compliant interaction with the cloth. The tips are designed with grooves (see Fig. 2b) to increase the friction during the contact with the objects, thus reducing undesired slippage. The gripper microcontroller is an Arduino Pro Mini with an ATmega328P (running at 16MHz, 5V input voltage). Gripper control is achieved via position control, by exploiting the actuator feedback position and the polarity inversion through the L293B motor-drive. The electromagnet is activated or deactivated through a logic input (H/L), which is a function of the actuator position and sensor measurements (see also Sec. II-B). The gripper receives commands through a Bluetooth connection (RN42 module by Microchip) and its working voltage is 12 V.



(a) Mag-Gripper CAD

(b) Jaw-tips

Fig. 2: Sketches of the Mag-Gripper. (a) isometric view. (b) zoom on the jaw tips which is slided at the end of the finger tip; notice the grooves and the hollow structure, where the grooves provide friction to avoid slippage.



Pre-grasping Grasping Release

Fig. 3: Mag-Gripper working configurations. During the pre-grasping, the electromagnet slot is the most prominent part of the structure, to allow the attractive motion of the metal plate without undesired collisions between the jaws and the cloth.

B. Working principle

In Mag-Gripper, the electromagnet plays a fundamental role during the approach to the object, while the jaws allow a secure grasp maintenance. As soon as the central cart moves, two orthogonal motions are generated: the first one, along the direction of the actuator, corresponds to the electromagnet approaching direction, the second one lies on the plane orthogonal to that direction, and corresponds to the motion of the jaws. To avoid unwanted collisions between the jaws and the object during the approaching phase, and collisions between the jaws and the electromagnet, three working configurations have been defined: pre-grasping, grasping and release. The working configuration can be seen as a function named *conf* of three independent variables: *ae*, which stands for activation of the electromagnet, *sr*, i.e., sensor reading, and *at* i.e., translation of the actuator,

$$conf(ae, sr, at) = \begin{cases} pre-grasping \\ grasping \\ release \end{cases} .$$

As mentioned in Sec. II-A, during the *pre-grasping* phase, the distance between the jaws is the maximum allowed and the electromagnet is the most prominent part of the gripper. This allows the electromagnet to approach the cloth without collisions between the cloth and the jaws. This configuration is reached as soon as the electromagnet is activated, the force sensor starts sending the measured values and the motion of the linear actuator has not yet started. After the gripper has entered in the pre-grasping phase, the actuator starts translating to approach the object. The contact is considered to have occurred when the force sensor measures the exceedance of a given threshold. This allows the gripper to enter in the *grasping* configuration: the jaws close and the electromagnet is deactivated (no more needed). The motion of the linear actuator is prevented through a position control, until the release command is sent and the gripper enters in the *release* configuration: the electromagnet is still deactivated, the sensor readings are discarded and the linear actuator is commanded to move so to allow an opening distance between the jaws equal to one half of the maximum allowed (see Fig. 3). Notice that the jaws closing motion relies on the force sensor measurements. This is why, in principle, Mag-Gripper can work also without the electromagnet (see also Sec. III-C).

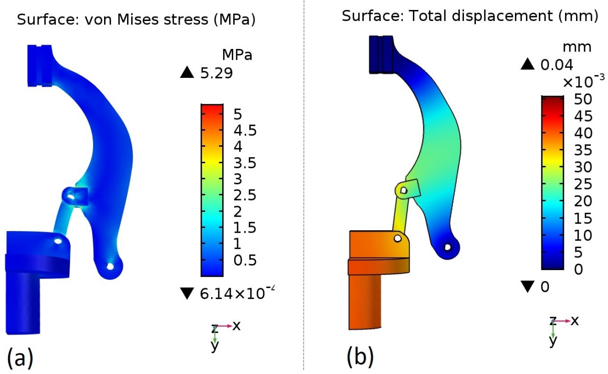
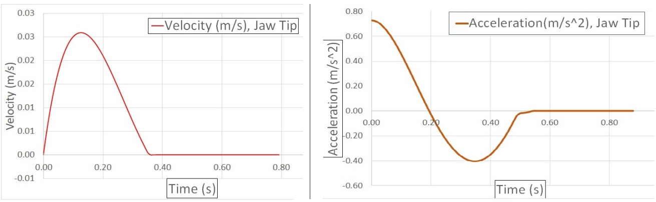


Fig. 4: FEM: (a) Stress Von Mises (MPa), (b) Maximum Displacement (mm).

C. Finite Element Modelling

Finite Element Analysis and Dynamic Analysis of the gripper have been carried out using COMSOL Multiphysics Software. Boundary load of 18 N (Linear Actuator maximum force) was applied in the y-axis direction. The gripper was cut half to simplify the geometry and a symmetric constraint was applied to compute the solution. Tehtrahedran elements were used for meshing. A mesh convergence test was also carried out on the basis of maximum element size, which suggested that when element size is between 0.00180 m to 0.00375 m the results are almost similar. Hence, maximum element size of 0.00218 m was selected. The result of FEM is depicted in Fig: 4. The maximum stress experienced is 5.29 MPa and it is exerted on the link between finger and piston, showing it as the most vulnerable part. For the case of dynamic analysis, a constant force of 18 N was applied and the corresponding velocity and acceleration plots of the jaw tip are shown in Fig. 5.



(a) (b)

Fig. 5: Dynamic analysis: (a) Velocity and (b) Acceleration plot of the jaw tip (F = 18 N).

III. EXPERIMENTS

We propose Mag-Gripper as a tool for autonomous manipulation of clothes, by exploiting the presence of a small metal part on the garments. Grasping the object in the desired points is the first condition to be met in order to achieve the required manipulation. Experiments with a Sawyer collaborative robotic arm (by Rethink Robotics) were performed to test the actual capabilities of the proposed gripper. To this aim, we investigated: *i)* how the performance are related to the size of the metal plate and the cloth weight; *ii)* which is the role played by the electromagnet on the configuration taken by the cloth after the grasp has occurred; and *iii)* how to compensate possible uncertainties on the estimate of the grasping points. For the sake of simplicity, we assumed the desired location of the grasping point to be fixed on the garment (*i.e.*, on a shoulder), and a fiducial marker located in that position had been used to retrieve an estimate of the desired pose with respect to the robot base. The cloth was located on a tabletop and an overhead camera (ASUS Xtion) was used during the marker detection phase. The trajectory planning was implemented in the *MoveIt* framework [1], and it was decomposed in three different steps: *i)* go 4 cm over the estimated location; *ii)* go down until the contact between the gripper and the metal part has been detected; and *iii)* lift the garment for 20 cm. Communication between the devices (robot, gripper, PC) run via ROS (Robot Operating System).

In the following, five different sets of experiments are described. For the sake of simplicity, the gripper orientation was fixed so to have a not occluded view of the scene from our desk. However, it can be chosen arbitrarily. Unless otherwise stated, the garment to grasp was the T-shirt included in the YCB dataset [24], and the square metal plate had a side of 1.8 cm.

A. Dependency on the metal plate dimensions

By means of this set of experiments, we investigated two aspects related to the metal plate size: *i)* how the number of successful grasps changes by varying the plate dimensions and *ii)* the repeatability of the grasp execution. Regarding the former issue, we termed *successful* a detected grasp occurred in correspondence of the metal plate and maintained without appreciable changes during the lifting phase. Regarding the second investigated aspect, we meant to have a measure of repeatability by estimating the area of the garment contacted by the electromagnet when multiple grasp attempts were performed with the same target. To have this measure, we covered that extremity with a thin rubber layer and put a thin layer of tempera colours on it. During the contact with the metal plate, the color laid down on the plate, leaving a mark of the executed trial. After 10 grasp attempts, we estimated the radius of a circumference containing all the color marks on the plate by measuring the distance between the two furthest points with a caliper. After each trial, the rubber was cleaned to avoid a dry color layer which would have reduced the magnetic force. The usage of the thin wet tempera color layer did not reduced appreciably the attraction up to 0.5 cm of distance between the plate and the electromagnet. Three different metal plates were used. They had a squared shape with side of 1.0 cm, 1.8 cm and 2.5 cm, respectively. Results are reported in Table I. Notice that in the bimanual clothing manipulation presented in [4], a grasp configuration is termed successful if both the left and the right grasps occurred within 5 cm from the estimated most likely grasps.

TABLE I: Number of successful grasps on the YCB T-shirt and radius of the estimated contacting area between end-effector and plate when the grasping attempts are repeated 10 times. Results are related to the size of the metal plate.

Square side	Success	radius [mm]
1.0 cm	8/10	15.1
1.8 cm	9/10	21.2
2.5 cm	9/10	24.5

B. Dependency on the cloth weight

To have an insight on how the performance of Mag-Gripper are influenced by the cloth weight, 4 different garments were used to be autonomously grasped 5 times: the YCB T-shirt, a mid-season pullover, an old bib and a terry guest towel. Objects weight and thickness are reported in Table II. Besides the number of successful attempts, we report also the mean distance that was required between the electromagnet and the garment to allow the magnetic force to cause the desired attractive motion of the cloth towards the electromagnet.

TABLE II: Objects used to have an insight on how the Mag-Gripper performance are related to the objects weight and thickness. Number of successful grasp attempts and required distance between the electromagnet and the plate are reported. The metal plate with side 1.8 cm was exploited.

Object	Weight	Thickness	Successes	Distance
T-shirt	125 g	0.4 mm	5/5	6 mm
Pullover	266 g	0.7 mm	5/5	5 mm
Bib	43 g	1.3 mm	5/5	3 mm
Towel	148 g	2.5 mm	4/5	2 mm

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[1] https://moveit.ros.org/

Fig. 6: Estimate of the fabric portion involved in the grasp, with and without the electromagnet exploitation (blue and green marks, respectively). A smaller portion produces less wrinkles, increasing the grasp precision.

C. *Dependency on the electromagnet (gripper opening size)*

By means of this kind of experiments, we investigated which is the role played by the electromagnet on the configuration taken by the cloth when the grasp has already occurred. To this aim, we compared the area involved in the grasp with and without the exploitation of the electromagnet. In other words, we performed 10 attempts providing the garment with the metal plate (E experiments) and then more 10 attempts after removing it (WE experiments). In both the sets of experiments, the gripper closing motion started when the contact between the gripper and the cloth had been detected by the force sensor. In both the set of experiments, a thin layer of tempera colors was added on the jaw-tips to mark the areas involved in the grasp execution. In Fig. 6, the green marks correspond to the areas contacted without exploiting the presence of the electromagnet, while the blue coloured marks are the areas of interaction when the grasp execution relies on the force of attraction between the gripper and the cloth. In the first case, the distance between the corresponding centres of the marks is about 10 cm (avg), while in the second case the same distance is about 5 cm (avg). When the metal part is lifted by the electromagnet, the portion of the fabric involved in the grasp is smaller than the one involved without the electromagnet exploitation. This reduces the possibility of wrinkling the fabric, increasing the grasp precision and repeatability.

D. *Target uncertainties compensation*

When dealing with vision-based grasp planning, it is common to have to cope with pose errors due to the camera calibration process. Usually, a number of transformations are needed to retrieve the desired grasping point in the reference system used for the trajectory planning. This causes the propagation of the estimation error. To this aim, we introduced by purpose an error of 1 cm on the x and y coordinates of the estimated grasping point, and 10 grasping attempts were performed. During 7 grasps trials the electromagnet was still capable of attracting the cloth. However, in 3 out of these experiments, the force sensor did not detect the occurred contact, since it had happened in a lateral location not involving the sensor (the sensor radius is about 3 mm).

E. *Common small objects with metal parts*

This set of experiments was aimed at testing the Mag-Gripper capability in grasping small objects different from clothes. Two small boxes, a comb, hair barrettes and paper clips have been used. On the top of the boxes and on the comb handle the squared metal plate with side 1 cm (used also in Sec. III-A) was located. The other objects were already provided of metal parts. The heavier object (box) weighted 25 g. The size of the objects spanned between 0.1 cm x 4.5 cm (paper clip) and 4.5 cm x 6.5 cm (box). An overall of 12 grasp attempts have been performed, achieving a success rate of 100%.

IV. DISCUSSION

A. *On the dependency on the metal plate dimensions*

This set of experiments was aimed at investigating the role played by the metal plate size in the grasp execution.

In all the failures, the contact between plate and electromagnet actually occurred but was not detected by the force sensor, since it occurred in a location not involving the sensor. Hence, the garment lifting phase was not triggered and the robot remained stuck.

In respect to the estimate of the actual contacting area between the end-effector and the plate, as it can be foreseen, the larger is the plate, the larger is the contacting area. That area could be represented as a circle enclosing the plate, since the contact between the plate and the electromagnet can occur everywhere on the plate, as long as there is a superposition of the two surfaces. The location variability is due to the manual collocation of the marker on the plate, but also to errors related to the camera calibration.

Interestingly, one successful grasp related to the plate with side 1 cm allows a further consideration. During that attempt, the contact between end-effector and plate occurred. However, suddenly the plate fell down before the electromagnet deactivation. The magnetic force generated was capable of re-establishing the contact in time and the gripper successfully lifted the T-shirt. This suggests that by properly managing the electromagnet deactivation time, Mag-Gripper could be used to cope with the possibility of loosing the contact with the object, ending up in a successful grasp.

B. *On the dependency on the cloth weight*

Experiments aimed at having insights on how much the Mag-Gripper performance rely on the cloth weight revealed that the thickness of the garment is more relevant than the overall object weight. As it can be noticed by looking at the fourth column of Table II, the thicker the garment is, the smaller the distance required to attract the metal part is. This is due to the fact that changing the thickness results in varying the local mass the electromagnet has to attract. If the local mass increases, the electromagnet needs to be closer to the plate to cause the attractive motion of the metal part. These results suggest that the electromagnet should be chosen either to grasp specific clothes or in a conservative manner, by considering a set of interesting objects and ensuring to be capable of grasping the thicker one. However, this gives us

(a) WE experiments (b) E experiments

Fig. 7: Grasps performed with and without electromagnet exploitation, left and right subfigures, respectively. The electromagnet exploitation allows a more repeatable cloth configuration, without wrinkles.

the possibility to remark that the choice should be context-related: in some cases, an unnecessary strong magnetic field can introduce some disturbances in other devices which are present in the robot workspace. Moreover, we want to stress the importance of having an attractive motion between the gripper and the cloth without the need of getting in contact with the environment to grasp the garment. This capabilities allows an intrinsically safer robot-environment interaction, besides the possibility of performing aerial grasps [25].

C. On the dependency on the electromagnet (gripper opening size)

Regarding this set of experiments, as it can be seen in Fig. 6, when the grasp execution relies on the presence of the electromagnet (E experiments), the distance between the jaws during the grasp is smaller than the case where the electromagnet is not exploited (WE experiments). This is due to the fact that the closing motion of the gripper starts as soon as the contact between the end-effector and the cloth is detected. However, in the WE experiments, the gripper needs to reach the table before detecting the occurred contact. As a consequence, when the jaws start closing, the distance between the jaws is close to the maximum allowed (13 cm by design). On the other hand, in the E experiments, the magnetic force attracts the plate before the gripper reaches the table, and the cloth takes a somehow conic shape. This is the reason why the distance between the jaws is smaller in the E experiments than in the WE experiments.

Moreover, a qualitative consideration should be done. As it can be seen in Fig. 7, when the WE experiments are performed, the part of the cloth located between the jaws is significantly crinkled. This is due to the fact that the grasp is executed by sliding the jaws on the table. The contacts points between cloth and jaws do not change and the minimum distance between these points (*i.e.*, the distance without considering the wrinkles) is gradually smaller and smaller, but there is still a portion of fabric constrained to lie between the jaws.

If the aim is to grasp the cloth in a desired location, so to let the cloth assume a configuration that is easy to manage with vision-based Machine Learning techniques, the exploitation of the electromagnet seems to be a good way to proceed. Indeed, the conic-like shape taken by the cloth after the grasping allows to achieve a sort of pinch grasp, which results in a less disturbing configuration of the points located near the actual grasping point. This sort of extended point-like grasp allows a more predictable configuration of the cloth, which is an high deformable object with a potentially infinite ways of deforming.

D. On the target uncertainties compensation

The artificial introduction of uncertainties in the estimate of the grasping point pose was aimed at investigating to what extent the exploitation of the magnetic force can allow to grasp the object in the target location, thus realizing a compensation of the position estimation error. Disturbances of 1 cm acting simultaneously along the x and y coordinates result in a noised goal location actually about 1.4 cm far from the desired point. The fact that 7 grasps over 10 allowed the electromagnet to attract the plate is encouraging (with respect to a target error of 1.4 cm), yet not exciting.

However, the presence of the electromagnet suggests the possibility of performing a sort of *partially-blind grasp*. A blind grasp is meant to be a strategy to be applied when the vision system is not particularly reliable. According to this strategy, the robot is first commanded to reach the estimated grasping point and, if the contact between the object and the gripper is not detected, the robot starts following a predefined pattern inside a square of known side, similar to the one shown in Fig. 8. The basic idea is to span a small area around the estimated grasping point to exploit the magnetic attraction to cope with pose estimation errors due to a non-ideal vision system calibration. This motion pattern corresponds to a planar motion occurring at a given height with respect to the metal plate, so it can allow to successfully compensate uncertainties on the xy plane. However, the success of the blind grasping is highly dependent on the distance between electromagnet and garment. That distance, in turn, depends on the thickness of the cloth. To get a more generalized planning strategy, further investigations are needed. Notice also that if the plate dimensions are not sufficiently small and the attraction occurs near the borders, the grasp might be unstable.

In principle, the blind grasp could be taken to extremes to perform a *totally-blind grasp*, when the vision system is not present at all and a minimal *a priori* knowledge of the environment is given (*i.e.*, size and pose of the table where the cloth is located).

E. On common small objects with metal parts

This set of experiments was aimed at having insights on the Mag-Gripper capabilities of grasping objects different to clothes. In fact, we proposed Mag-Gripper as a tool for service robots suitable in home settings or in assistive robotics. In this respect, it could be useful to have a robot capable of grasping small objects of common usage. In particular, we considered objects (*i.e.*, comb, hair barrettes and paper clips) difficult to grasp either with a parallel-jaw gripper either with a more complex robotic hands, usually

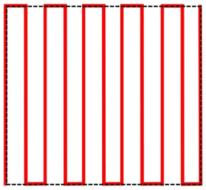

Fig. 8: Example of possible motion pattern (in red) for a *blind grasp*: it spans a small area (delimited with the dashed line) around the estimated grasping point to cope with pose estimation errors.

needing environment exploitation [22]. The challenging nature of these objects relies on the fact that they are flat and thin. The electromagnet was capable of generating a visually appreciable attractive motion, that allowed the grasps without the end-effector needed to reach the tabletop. As a note, we want to point out that the metal part located on the object could be small and lightweight, depending on the object: in a hair barrette it consists of a spring of length 5 mm.

V. CONCLUSIONS

In this work, we have proposed Mag-Gripper, a novel augmented jaw gripper designed for autonomous clothes manipulation. The only working assumption is to deal with garments provided with small metal parts. Mag-Gripper is equipped with an electromagnet: The electromagnet is exploited to establish an extended point-like contact with the garment, while the jaws allow a secure grasp maintenance during the manipulative motion. Experiments performed with a collaborative robotic arm showed that the exploitation of the magnetic force allows to perform a repeatable grasp execution and to compensate vision-related planar uncertainties on the estimated pose of the target grasping point. Moreover, the extended point-like contact caused by the electromagnet allow to perform grasp without unnecessary wrinkles, achieving clothing configurations more suitable to vision-based Machine Learning techniques for autonomous manipulation. Future work will focus on testing the gripper in robotic setups for bimanual autonomous clothes manipulation. Moreover, the proposed *blind grasp* strategy will be further investigated, as a method to be applied when the vision system is not sufficiently reliable.

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