On the Use of Magnets to Robustify the Motion Control of Soft Hands

Sara Marullo, Gionata Salvietti, and Domenico Prattichizzo

***Abstract*—In this letter, we propose a physics-based framework to exploit magnets in robotic manipulation. More specifically, we suggest equipping soft and underactuated hands with magnetic elements, which can generate a magnetic actuation able to synergistically interact with tendon-driven and pneumatic actuations, engendering a complementarity that enriches the capabilities of the actuation system. Magnetic elements can act as additional Degrees of Actuation (DoAs), robustifying the motion control of the device and augmenting the hand manipulation capabilities. We investigate the interaction of a soft hand with itself for enriching possible hand shaping, and the interaction of the hand with the environment for enriching possible grasping capabilities. Physics laws and notions reported in the manuscript can be used as a guidance for DoAs augmentation and can provide tools for the design of novel soft hands.**

***Index Terms*—Grasping, grippers and other end-effectors, manipulation planning.**

I. Introduction

SOFT robotic hands are powerful end-effectors allowing compliant interactions with objects. The softness of the materials enables delicate manipulation and robust grasps [1] through the enhanced hand/object adherence, compensating also for uncertainties on the desired grasping points [2]. Nevertheless, the intrinsic underactuation of these hands yield a non-precise motion control. Furthermore, indeterminate kinematics and a priori unpredictable deformations lead classic strategies for hand modelling and control [3] to be no longer suitable, and up to now novel techniques are still far from being well-established. One driving force for soft hands inception was the simultaneous need of enhancing grasp robustness and stability, and the need of reducing hand complexity and encumbrance. However, current research on soft manipulation is turning again to complexity, both in design and control, in order to overcome the dexterity limitations due to underactuation and software/hardware motion coupling [4].

In this letter, we propose to equip soft hands with magnetic elements acting as additional degrees of actuation (DoAs) enriching the hand manipulation capabilities. Classic approaches to DoAs augmentation rely on the replication of the same actuation system, e.g. by increasing the number of inflatable chambers in pneumatic structures [5]. Interestingly, magnetic actuation for manipulation can be achieved by exploiting magnetic elements that can be easily embedded in existing hands and designs. Moreover, magnetic DoAs provide an actuation on specific locations of the hand. Hence, they can act synergistically with the more global effect provided by tendons and/or pneumatic actuators, arousing a complementarity that enriches the actuation system's capabilities. The magnetic attraction, indeed, realizes a physics-based guidance capable of compensating uncertainties due to softness and underactuation, besides the possibility of non-contact manipulation of thin and light objects, and an overall grasp stabilization.

A. Related Work

In the literature on robotics, magnets have been exploited especially as tools for locomotion and reconfigurability of milli-, micro- and nano-robots, often made of magnetic elastomers (MEs) [6] and meant for biomedical applications [7], [8]. Micro-manipulators [9], self-folding degradable [10], helical [11], aerial [12], millipede and flower-like [13] devices are examples of magnetically actuated small-scale robots exploiting external magnetic fields. Also locomotion for capsule robots has been investigated [14]. Concerning soft robots, magnetic elements have been used to realize magnetorheological valves for distributed control [15], as well as to modulate the pressure in the actuators by using magnetorheological fluids [16].

To model the kinematics of soft continuum robots, heat-assisted shape-morphing [17], continuation method and bifurcation analysis [18] have been investigated.

Concerning the simultaneous presence of various devices, proper magnetic field gradient has been used to independently control multiple robots moving on a plane [19], while electropermanent magnet connectors have been exploited to control the motion of two robots separated by a surface [20]. Attraction and repulsion can also be the working core of solid-state centimetres-long self-reconfigurable modular robots [21]. Concerning other applications of devices larger than small-scale,

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magnets were employed to drive catheters [22], [23], develop tracking systems [24], provide climbing robots with suitable adhesion force [25], and to allow fast and reconfigurable modular assembly [26].

In robotic grasping, magnets have been exploited to increase the force during adaptive pinch grasps [27], build tactile sensors for contact points location estimation [28], and devise a compliant, variable-stiffness gripper [29]. Recent works focus on food handling [30] and autonomous garment manipulation [31]. To the best of our knowledge, no works are focused on manipulation performed with soft robotic hands, exploiting the magnetic force for hand control and reconfiguration.

B. Contributions

In this letter, we propose to augment the motion capabilities of soft hands by means of magnetic force exploitation. Such augmentation relies on a behavior that can be modelled by means of contiguous magnetic funnels, and the overall effect of the funnels can be seen as a position control. Such funnels will be described in Section II-B, and details on the modelling of magnetic elements (permanent magnets and electromagnets) will be provided in Section II-A. Then, the interaction of the hand with the environment and with the hand itself will be examined, and relevant physics laws will be applied to position uncertainties compensation (Section III-A), non-contact manipulation (Section III-B) and DoAs augmentation (Section IV).

II. Magnetic Funnels

In the following, the expression *magnetic elements* will denote either permanent magnets or electromagnets. After having outlined the main features of such devices concerning the focus of this manuscript, we will describe the concept of *magnetic funnels* that can be generated by such magnetic elements.

A. Permanent Magnets and Electromagnets

Electromagnets or permanent magnets can be used to exploit the magnetic force according to different strategies, depending on the envisaged use case. Electromagnets, indeed, can be thought of as permanent magnets that can be turned on and off when desired.

Electromagnets are composed of a conductive coil with a variously shaped, usually ferromagnetic, core. When the coil windings are supplied with electrical current, a magnetic field is generated. Turning off the current, the magnetic field associated with the coil vanishes, whereas the contribution provided by the core lasts. To exploit the magnetic interaction only when needed, avoiding undesired interactions with ferromagnetic objects possibly present in the environment, this contribution should be as small as possible. Hence, magnetic cores with low remanence are recommended (e.g., composed of soft iron, ferrites, silicon steels).

Permanent magnets, differently from electromagnets, after the magnetization process show a permanent magnetization due to the coupling of atomic moments, and are capable of generating magnetic fields without external intervention. The constitutive materials of permanent magnets can be classified as soft or hard depending on the ease of magnetization/demagnetization (coercivity). Once magnetized, the magnet's capability of re-orienting its magnetic domains according to another external field is called permeability. Neodymium alloys (e.g., NdFeB) are examples of widespread, hard, rare-earth permanent magnets with relatively low permeability.

Since this work is focused on robotic manipulation (i.e., on the exploitation of magnetic elements embedded in hands and objects), using electromagnets rather than permanent magnets is preferable, as they allow exploiting the magnetic attraction only when desired. Moreover, DC electromagnets are preferable to AC ones, since the drawbacks (e.g., time-dependent attraction/repulsion, eddy currents, overheating) are less relevant. If needed, moreover, a cooling system (e.g., thermally-conductive materials, electrothermal devices) can be used.

Furthermore, to limit the encumbrance, the magnetic elements should be small.

In the following, we will show how the physics laws related to such devices can be exploited to robustify the motion control of soft hands and to augment the number of DoAs of such devices.

B. Physics-Based Funnels

The magnetic elements we will consider have to be suitable for the embedding in a robotic hand (especially in the fingertips), hence their size should be in the range of maximum 2.5 centimetres in length, height and depth. Consequently, such magnetic elements can be modelled as magnetic point dipoles [32] as a first approximation.

Let us consider an unconstrained, initially still magnet C_1 represented as a point dipole with moment $\mathbf{m}_1$ and located in $\mathbf{p}_t$ at time t, immersed in the magnetic field $\mathbf{B}$ generated by a second magnet C_2. Such a C_2 element is represented likewise as a dipole with moment $\mathbf{m}_2$ and constrained in the origin of a reference system for the sake of simplicity. C_1 will spontaneously move along a trajectory minimizing the potential energy U held by C_1 and due to $\mathbf{B}$ (generated by C_2) [33]. The position of C_1 at time $t+1$ is given by

$$p_{t+1} = \underset{\mathbf{p} \in I(\mathbf{p}_t)}{\operatorname{argmin}}\, U(\mathbf{p}, \mathbf{p}_t, \mathbf{m}_1, \mathbf{m}_2), \tag{1}$$

where $\mathbf{p}_{t+1}$ belongs to the neighborhood I of $\mathbf{p}_t$.

As it will be clear in the following, $\mathbf{m}_1$ and $\mathbf{m}_2$ are vectors related to the modelling of the magnetic elements C_1 and C_2, and depend on the pose (position and orientation) of the magnetic elements. Clearly, such vectors mathematically depend on the time through the dependence of the pose on the time. As it can be seen in Fig. 1, the potential energy generates *funnels*, whose tips correspond to points with low energy. Since the funnels we are considering are intrinsically interconnected by physics, they are sequential, providing an hardware-based position control without discontinuity.

In the more general case of moving magnets, the Least Action Principle holds, whose non-relativistic expression is

$$\min\, I = \min \int_{t_1}^{t_2} (T - U)\, dt,$$

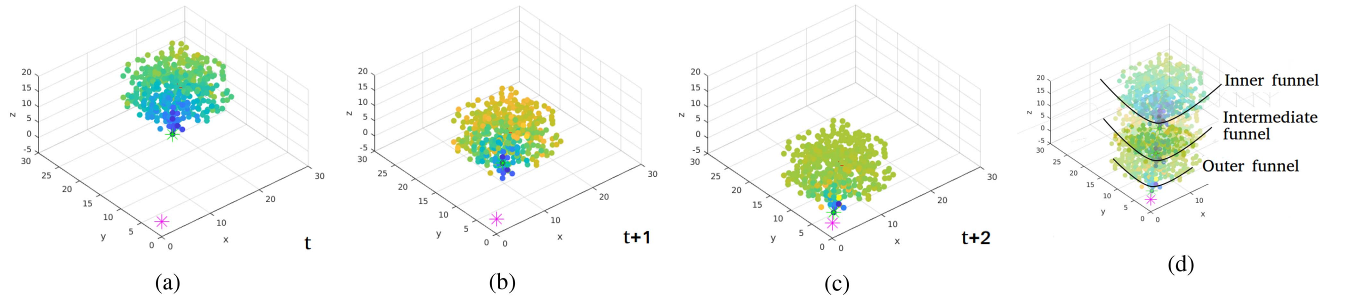


Fig. 1. Pictorial representation of the potential energy related to the magnetic elements C_1 (represented with a red circle at the center of the neighborhood) and C_2 (whose position is represented by a purple star). The value of the potential energy U in points belonging to a neighbourhood of $\mathbf{p}_t$ (location of C_1) is represented by heatmap-coloured circles, the smaller the potential energy, the cooler the color. The green star indicates the point belonging to the neighbourhood and minimizing the system potential energy. Same reasoning applies to a neighborhood of $\mathbf{p}_{t+1}$ (Fig. 1(b), and of $\mathbf{p}_{t+2}$ (Fig. 1(c), and so on. As it can be seen in Fig. 1(d), the potential energy generates sequential funnels, that are capable of providing physical guidance without discontinuity (i.e. C_1 approaches spontaneously C_2).

where T and U are the kinetic and the potential energy, respectively, and t denotes the time variable. In this case, considerations similar to those above are valid.

III. Hand and Object/Environment Interactions

A. Guidance

The control of soft and underactuated hands frequently suffers from uncertainties due to the manufacturing process, the control strategy modelling and the actuation system [34], [35]. In the robotic trajectory-planning framework, sequential optimization funnels have been identified [36] to compensate for uncertainties on the target pose estimate [37]. In Section II-B, we showed that magnetic elements can generate sequential magnetic funnels. Hence, exploiting such a magnetic system can allow to compensate for a finger misplacement.

In Section II-B, magnets C_1 and C_2 have been assumed unconstrained and constrained, respectively, for the sake of simplicity. The aim was to show from a conceptual perspective the existence of magnetic funnels acting as hardware controllers exploiting a non-contact force to reach the target location. However, in the real-world situations we are considering, magnets have to be embedded in robotic hands, objects and/or in the environment. Hence, (1) should be considered together with

$$\mathbf{F} - \boldsymbol{\beta}\dot{\mathbf{p}} = \mathbf{M}\ddot{\mathbf{p}}, \tag{2}$$

where $\mathbf{F}$ denotes the magnetic force, while $\boldsymbol{\beta}$ and $\mathbf{M}$ are tensors encapsulating the damping and inertia felt by the dipole and due to the embedding in the hand/object structure. Unfortunately, the dynamics of a soft and underactuated hand is so complex (and usually indeterminate) that no closed-form of Eq. (2) is possible. Hence, a simulator is needed to have insights on the actual hand/object motion related to the magnetic force.

In the following, a lumped-parameter model of the pneumatic RBO Hand 2 [38] based on the P10 actuator [39] will be considered. The hand consists of 4 pneumatic actuators; by design, each finger is capable of bending about an axis orthogonal to the finger principal direction, realizing a spiral rolling. Also the palm is actuated.

Regarding the modelling of magnetic elements, the values adopted hereinafter are inspired by those of off-the-shelves components. This applies especially to the specs related to the geometric shape of electromagnets and permanent magnets, as well as to the wire diameter, number of windings and current supplied to the electromagnet. As described in the following, the magnetic permeability and remanence of magnets are known in the literature or can be estimated.

Let us consider a manipulation sequence prescribing a delicate interaction with an object in specific points. Let us suppose also that an undesired displacement between the desired contact point on the hand and the desired point on the object is present. This undesired displacement can be due to uncertainties affecting the hand nominal working pressure (caused by real-world pressure leakages or uncertainties on the valves' opening time), or they can be due to the difficulties of executing fine control movements for affordance exploitation (as in the case of grasping a mug by means of its handle, see Fig. 2(a)). If an estimate of the displacement between the desired point on the hand and the desired point on the object is available, simulation by software allows to properly select the magnetic elements that are capable of compensating for undesired displacements.

Let us consider the current fingertip location in $\mathbf{p}_f$ (associated to that uncertainty) and the target location on the object in $\mathbf{p}_T$. Let us assume that a small magnetic element (modelled as point dipole) is embedded in the hand, and that another small magnetic element (modelled as point dipole as well) is located on the target point on the object. To prevent potential magnetic disturbances acting on the hand during other manipulation steps, a fingertip of the device is equipped with an electromagnet, while a permanent magnet is located on the object (this last choice allows to do not have the need of an additional voltage source located on the object). Let us suppose also that the object is such that its weight force is greater than the magnetic force (or, equivalently, the object position is constrained).

According to the charge model for magnets, a dipole with moment $\mathbf{m}_1$ generates a magnetic field $\mathbf{B}_1$ which depends on the distance vector $\mathbf{r}$ from the dipole, and can be expressed as

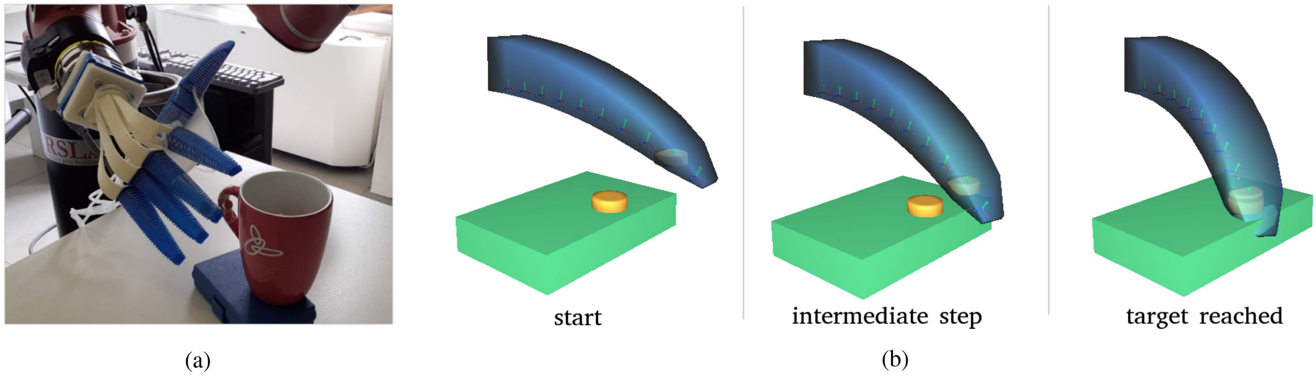


Fig. 2. Hand interacting with the object: magnetic guidance for affordance exploitation. (a) Grasping a mug on its handle. (b) Steps of magnetic guidance allowed by the exploitation of an electromagnet located on the hand finger and a permanent magnet located on the mug handle.

Eq. (3):

$$\mathbf{B}_1(\mathbf{r}) = \frac{\mu_0}{4\pi}\left[\frac{3\mathbf{r}(\mathbf{m}_1\cdot\mathbf{r})}{r^5} - \frac{\mathbf{m}_1}{r^3}\right], \tag{3}$$

where μ_0 is the magnetic permeability of free space.

The dipole with magnetic moment $\mathbf{m}_1$ acts on a second dipole with moment $\mathbf{m}_2$ through the wrench $\mathbf{w} = [\mathbf{F}, \boldsymbol{\tau}]'$, where the dipole-dipole interaction force and the torque are given by:

$$\mathbf{F} = -\nabla U = \nabla(\mathbf{m}_2\cdot\mathbf{B}_1) = \frac{\mu_0}{4\pi}\frac{3}{r^5}\Big[(\mathbf{m}_1\cdot\mathbf{m}_2)\mathbf{r} + (\mathbf{m}_1\cdot\mathbf{r})\mathbf{m}_2 + (\mathbf{m}_2\cdot\mathbf{r})\mathbf{m}_1 - \frac{5(\mathbf{m}_1\cdot\mathbf{r})(\mathbf{m}_2\cdot\mathbf{r})\mathbf{r}}{r^2}\Big] \tag{4}$$

and

$$\boldsymbol{\tau} = \mathbf{m}_2 \times\ \mathbf{B}_1, \tag{5}$$

where $\mathbf{r}$ is the distance vector between the two dipoles, i.e. $\mathbf{r} = \mathbf{p}_2 - \mathbf{p}_1$.

More specifically, let us consider a single-coil electromagnet with a cylindrical, ferromagnetic core. Solenoid and core magnetic moments (denoted with $\mathbf{m}_s$ and $\mathbf{m}_c$) can be treated as dipole moments, generating the electromagnet overall moment $\mathbf{m}_e = \mathbf{m}_s + \mathbf{m}_c$. A solenoid with N windings, supplied with a current i, and with cross-sectional area S generates a moment $\mathbf{m}_c = Ni\mathbf{S}$, whose direction is perpendicular to S and oriented according to the right-hand rule (principle of equivalence between turns and magnetic dipole).

Concerning the permanent magnet located on the object and the ferromagnetic core of the electromagnet, the magnetic remanence specific of the material allows to estimate the residual magnetization per unit of volume through the constitutive relation:

$$M_r = B_r/\mu_0. \tag{6}$$

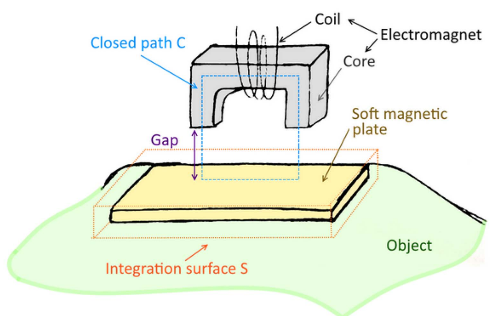
Differently from the material constituting the permanent magnet located on the object, the electromagnet's core is usually made of a soft ferromagnetic material. By exposing the soft ferromagnet to an external magnetic field, its magnetization increases according to the material's M-H hysteresis curve. However, the residual magnetization is sufficient for a conservative estimate, hence we can assume $M = M_r$. Then, the magnitude of the permanent magnet magnetic moment $\mathbf{m}_2$, as well as the magnitude of the electromagnet ferromagnetic core $\mathbf{m}_c$, can be estimated through $m = MV$, where V is the volume of the considered magnet.

To provide an example, let us assume that the undesired displacement between the target point on the object and the grasping point on the hand is $\mathbf{r} = [25, 10, 4]$ mm. Consistently with what has been argued above, let use equip the finger (actuated with 10 kPa) with an electromagnet located in the 8-th node of the finger lumped parameter model, and pinpoint the target point on the object with a permanent magnet. Structure and supply specs of the electromagnet are $i = 0.41$ A, $S = 133$ mm^2, $N = 1200$, and an iron-silicon core ($B_r = 0.49$ T) is present. Furthermore, let us suppose that the permanent magnet is a N52 NdFeB ($B_r = 1$ T), with a cylindrical shape of 10 mm diameter and 5 mm height. Simulation shows (Fig. 2(b)) that the system with the above mentioned features is capable of acting as an attractive controller, compensating the initial gap between finger position and target.

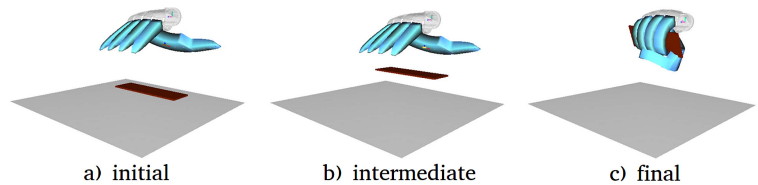
B. Non-Contact Manipulation

Thin and flat objects are usually difficult to grasp with robotic end-effectors. Most of the time the problem is addressed with a soft end-effector establishing a so-called *sliding grasp* [40], which is a triadic interaction between object, end-effector and environment. However, light objects are prone to fall off the support during the manipulation pre-grasping phase, leading to task failures. In this subsection, we will consider such objects, either embedding ferromagnetic parts by design (like paper clips, coins,...) or by purpose (e.g., by adding a small plate with ferrite on the handle of a comb). Since we are considering objects of common usage to be grasped by a robot, and we want to avoid undesired interactions between the target object and other objects present in the environment and possibly embedding ferromagnetic parts, we will consider to equip the target object with soft magnetic materials with high magnetic permeability.

By equipping the end-effector with an electromagnet (N turns run by current i), the non-contact latching force can be exploited to generate an attractive motion of the object towards the end-effector, as long as the magnetic force is greater than the weight



(a)



(b)

Fig. 3. Hand interacting with the object: non-contact manipulation. (a) Representation of relevant elements and quantities for magnetic non-contact manipulation. Between the electromagnet (composed of core + coil) and the soft magnetic plate located on the object, there is a gap of length l_g and cross-sectional area A_g. Integration path and surface required for force computation are reported. (b) Example of intermediate steps in non-contact manipulation exploiting the magnetic attraction.

force of the object. To properly channel the magnetic field, a U-shaped magnetic core with high permeability will be considered, as in the arrangement shown in Fig. 3(a).

From Ampere's circuital law:

$$\oint_C \mathbf{B} \cdot d\mathbf{l} = \mu_0 I_{tot} = \mu_0 N i$$

and magnetic circuit analysis, accounting for $\mu_{air} \sim \mu_0$ and $\mu_{core} \gg \mu_0$, follows

$$B_g = \frac{\mu_0 N i}{2 l_g},$$

where B_g is field in the gap and l_g the gap length.

The attraction force is computed by exploiting the Maxwell's stress tensor [41]:

$$\mathbf{F} = \frac{1}{2\mu_0} \oint_S B_n^2 \, ds \, \mathbf{n},$$

where B_n is the component of the field orthogonal to the surface S, $\mathbf{n}$ is versor outgoing from S, and S is the surface identified by the orange line in Fig. 3(a).

Due to the magnetic core high permeability, the field is channelled orthogonally to S. Hence,

$$\mathbf{F} = \frac{\mu_0 \, N^2 i^2 A_g}{4 l_g^2} \mathbf{n}$$

generates an attractive motion of the object towards the hand.

To provide an example, let us suppose to equip the hand with an electromagnet located in the 4-th node of the palm lumped parameter model. Electromagnet structure and supply specs are $N = 1200$, $i = 0.41$ A, $A_g = 1$ cm^2, and the core is made of soft ferromagnetic material ($B_r = 0.49$ T). The thin, light object is located on a table distant 6 cm and represented by a parallelepiped with size $l_1 = 5$ cm, $l_2 = 15$ cm, $l_3 = 0.3$ cm, and mass 25 g (similar to a hair comb). A cylindrical N52 NdFeB permanent magnet with 10 mm diameter and 5 mm height is located at half of the object length. As shown in Fig. 3(b), the proposed system is able to generate a magnetic attraction capable of exceeding the object's weight force, achieving the desired motion.

IV. Interaction of the Hand With Itself: DoAs Augmentation

The intrinsic underactuation of soft hands on one side leads to a control simplification, on the other side entails a limitation of the possible manipulation capabilities. Therefore, to provide soft hands with more dexterous movements, current research on hand design is frequently steering towards increased complexity, resulting in classical drawbacks (weight, encumbrance,...) joined to specific control issues due to underactuation, and modelling issues related to soft material deformation [5].

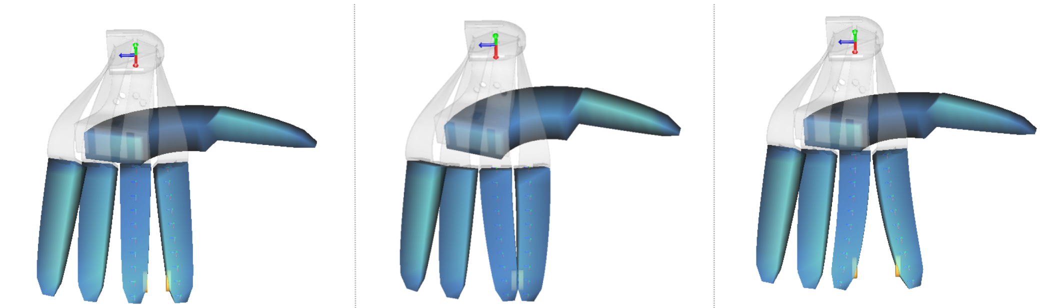
Here we propose to exploit magnetic elements as actuators to augment the spectrum of movements that the hand can perform. As an example, let us consider the RBO Hand 2. By design, fingers adduction/abduction cannot be performed, unless a different actuation is attained. Let us consider index and middle fingers, modelled via lumped parameters as above, equipped with magnetic elements in the fingertips. To exploit magnetic wrenches only when desired, let us consider to use electromagnets. For the sake of simplicity, two cylindrical electromagnets with single coil, C_i and C_m, are located in r_i and r_m, respectively (the subscripts i and m are related to the index and middle fingers, respectively). The dipole moment of such elements can be figured out as described in Section III-A.

To fulfil the adduction motion, the dipoles have to be arranged so that the sequence of poles is N-S-N-S (or, equivalently S-N-S-N). The magnetic elements C_i and C_m are subjected to the magnetic wrenches $\mathbf{w}_i$ and $\mathbf{w}_m$, respectively:

$$\mathbf{w}_i = [\mathbf{F}_i, \boldsymbol{\tau}_i],' \quad (7)$$

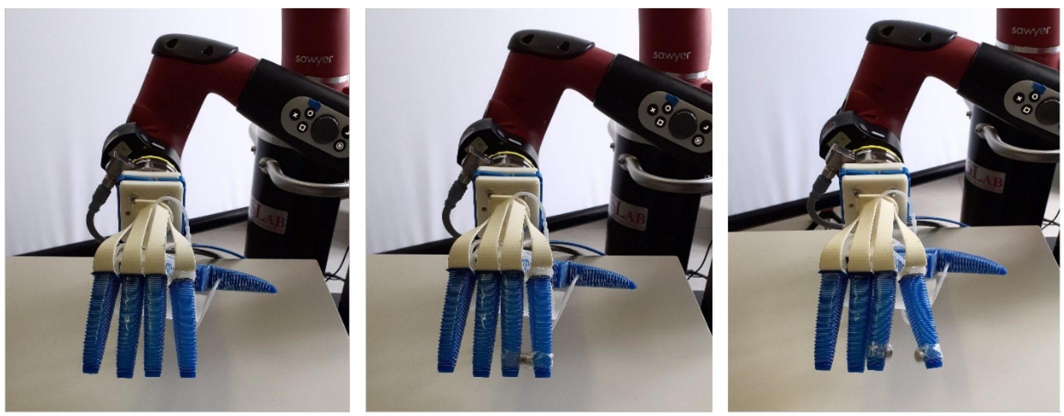
$$\mathbf{w}_m = [-\mathbf{F}_i, \boldsymbol{\tau}_m],' \quad (8)$$

where $\mathbf{F}_i$ is the magnetic force in Eq. (4) with $\mathbf{r} = \mathbf{r}_i - \mathbf{r}_m$, while $\boldsymbol{\tau}_i = \mathbf{m}_i \times \mathbf{B}_m$ and $\boldsymbol{\tau}_m = \mathbf{m}_m \times \mathbf{B}_i$. $\mathbf{B}_m$ is the magnetic field experienced by C_i and induced by C_m, whereas $\mathbf{B}_i$ is the magnetic field experienced by C_m and generated by C_i.



(a) Initial configuration (b) Adduction (c) Abduction

Fig. 4. Hand interacting with itself: Augmentation of DoAs. Starting from the hand initial configuration (a), the exploitation of small electromagnets located in the fingertips allows (b) adductive and (c) abductive motion between fingers.



(a) Hand without magnets (b) Adduction by magnets (c) Abduction by magnets

Fig. 5. Hand interacting with itself: Adductive (b) and abductive (c) motion between fingers allowed by small electromagnets located in the fingertips.

To achieve abduction of fingers, instead, the dipoles can be arranged so to generate repulsion between magnetic elements, i.e. N-S-S-N (or, equivalently, S-N-N-S). Eq. (7) and Eq. (7) still hold.

To provide an example of DoAs augmentation by magnetic actuation, let us equip middle and index fingers with cylindrical electromagnets ($S = 133$ mm^2, $N = 1200$, $i = 0.41$ A, with iron-silicon core with $B_r = 0.49$ T), located in the 8-th node of the fingers lumped-parameter model. As shown in Fig. 4, the proposed system of electromagnets is able to generate the adductive motion (initial gap between the fingertips of 2.8 cm).

By inverting the verse of the current flow in one electromagnet (i.e., by inverting the verse of its magnetization), the same system of electromagnets exploits the magnetic repulsion and can realize abduction of fingers, as shown in Fig. 4, generating a distance between the fingertips of 4.3 cm. A possible realisation with the RBO Hand prototype is depicted in Fig. 5.

V. Discussion

Magnetic field modelling is challenging, and the dipole approximation for magnetic elements (first term in the multipole expansion) holds for small-sized devices as long as they are not too close. However, since the aim of this work is to provide tools for the design of soft hands embedding magnetic elements, what is relevant is to conservatively choose proper values for the parameters describing the magnetic elements in such a way that such elements are able to trigger the desired motion. Then, the magnetic guidance will be in charge of realizing the desired contact. If a more accurate model of the magnetic interaction is required, some closed-form results are available for specific configurations of the magnetic elements [42], or simulation software for magnetism can be used (e.g. COMSOL, QuickField,...).

The aim of this work was providing methodological tools for the exploitation of magnetic elements embedded in underactuated hands for augmenting the manipulation capabilities of such devices. To this end, by way of example, we carried out experiments in simulation by using the pneumatic RBO Hand 2. However, magnetic forces can be exploited also to change the behaviour of a tendon-driven hand, as we showed in a preliminary work [43]. When considering soft continuous or tendon-driven hands, what remarkably changes is the way in which forces and torques transmit through the fingers' structure. The presence of discontinuities in the softness due to different materials (i.e., elastic joints and links) strongly affects the configuration of the hand, which is related also to reaction forces generated by the hand itself. Hence, an accurate modelling of the contacts occurring between the soft-rigid elements is needed

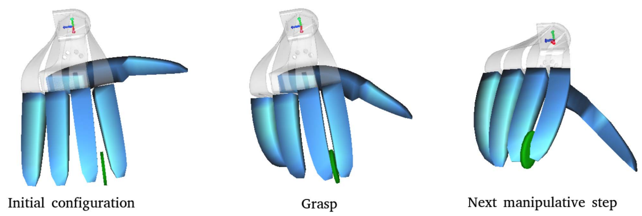


Fig. 6. Interaction of the hand with itself: A hand equipped with electromagnets in the fingertips manipulates a thin object.

to have faithful insights on the actual effect of the exploitation of magnetic forces in such devices.

Concerning the choice of permanent magnets, parallelepiped or cylindrical shapes are almost equivalent if embedded in soft-rigid hands, where they can be inserted in a 3D-printed link. Cylindrical and thin-shaped elements, instead, are particularly suitable to pneumatic hands for adherence reasons. In general, magnetic elements can be embedded in external elastic rings if needed (e.g., if the hand cannot be supplied with current for a variety of reasons).

Concerning ferromagnetic materials available with different grades (like NdFeB), the trade-off between grade and size must be chosen according to the needs, keeping in mind that thin magnets (about 1 mm) can be appealing for the reduced encumbrance, but are prone to realize a weak magnetic interaction. It is not uncommon that relatively small variations of size have a greater impact than a small change of grade.

Concerning applications, magnetic guidance can be a game changer when the interaction between object and hand must occur in specific locations, but uncertainties on the actual configurations are present. Moreover, in multi-contact interactions, magnetic elements could be embedded also in locations different from the ones in charge of establishing the main interaction, achieving an overall grasp stabilization, which is a common issue to deal with when grasping with soft-rigid hands (e.g., tendon-driven devices with rigid links connected by soft joints [44]).

Concerning the hand DoAs augmentation, it has potentially relevant applications either for hand shaping in pre-manipulation steps, either for enhancing in-hand manipulation capabilities. However, a remark should be done concerning abduction. If magnets are not strong enough to counteract material inertia and damping, no motion occurs. On the other side, if the magnets are not in a symmetric configuration with respect to the hand structure and if the hand is not stiff enough, after an initial finger separation, a novel hand configuration occurs, potentially ending up in an undesired fingers adduction. To prevent this situation, proper use-case-based non-backdrivable mechanisms can be designed.

Another application of the hand interacting with itself can be devised in the interaction with thin objects that can be trapped between the fingers and then moved away, as in Fig. 6. In this case, if the object is made of a non-ferromagnetic material such that the relative permeability $\mu_r \sim 1$ (as in the vast majority of objects of daily use), then the magnetic flux passes through the object as if the latter would not be present. What is relevant in this case is the object thickness in the region of interaction with the hand: it must not be large enough to make irrelevant the magnetic attraction between fingers. If the object is a permanent magnet, instead, a proper magnetic modelling of the object is needed. Moreover, it can be recalled that paramagnetic and diamagnetic materials do not provide significant effects at room temperature. If a material with high permeability is employed, furthermore, two closed magnetic circuits can be modelled, one for each finger (similarly to Section III-B), resulting in a double attraction finger-object.

VI. Conclusion

In this manuscript, we proposed to equip soft and underactuated robotic hands with properly located magnetic elements capable of acting as additional DoAs to robustify the motion control of the hand and to augment the device manipulation capabilities. Permanent magnets and electromagnets have been modelled by means of magnetic dipoles and the related physics laws were discussed in the light of achieving guidance and DoAs augmentation. The enhancement of the hand capabilities relies on the identification of contiguous, sequential magnetic funnels capable of implementing an hardware-based position control. The interaction of the hand with itself and with the environment has been investigated to apply such magnetic funnels to uncertainties compensation and affordance exploitation, non-contact manipulation of thin and light objects, grasp stabilization and augmentation of the hand's DoAs. Tools for the design of novel soft hands have been provided.

The exploitation of magnetic elements partially encapsulates a paradigm shift if applied to grasp planning. Classic grasp planning, indeed, concerns motions of the hand towards the object, while magnetic forces can cause attractive/repelling motions of the object towards/from the hand. In future work, we will propose a framework for grasp planning that will account for different motions and forces, with particular focus on in-hand manipulation. Such a manipulation, indeed, requires dexterous movements of fingers and fine control of all forces.

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