A new theorical approach for hiper-redundant actuators

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Contents

1 Description of a single actuator

A linear Lorentzito can be designed and built in many different ways by choosing different materials and geometries. The aim of this thesis is to design and test Lorentzitos as an alternative solution to commercial linear actuators in mimicking natural contractive movements and to implement the concept in a prototype. Therefore, not the best theoretical possible linear implementation is described, although some suggestions are going to be made. On the contrary, low cost and simplicity are more important for this first stage.

The proposed structure will be called **Parallelepiped Linear Lorentzito** because it resembles a composition of parallelepipeds. It consists of a magnetic structure to generate the $\vec{B}$ field, an inner conductor to carry an $\vec{I}$ perpendicular to the magnetic field, a tendon to transmit the movement, a region that solves the linkage problem and a case which contains all that elements. Two different structures shown in Figure 1a and Figure 1b will be presented.

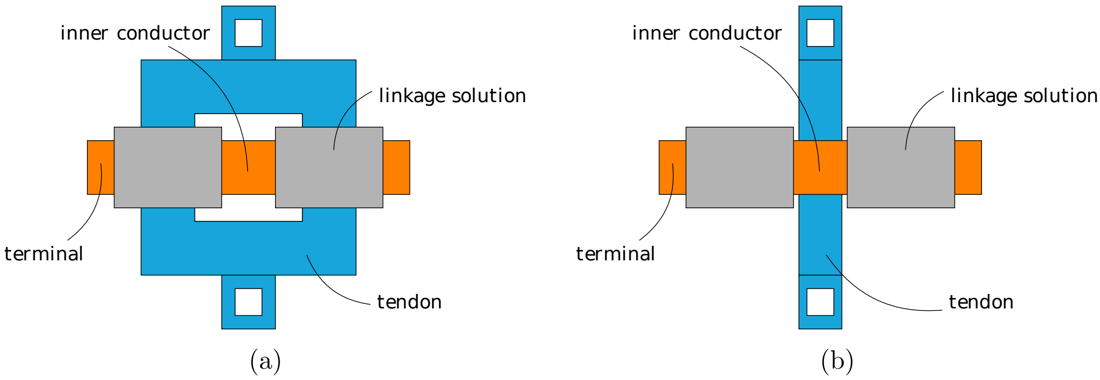


Figure 1: (a) Structure A and (b) structure B of the linkage solution.

The only difference between both structures is where the tendon is attached to the inner conductor. In Figure 1a the tendon is attached to two points leaving a space for the magnetic structure in the centre (not represented in the Figure). On the other hand, the structure shown in Figure 1b is only attached to one point. The motion has to be transmitted to the tendon from the centre of gravity of the inner conductor to avoid angular momentum since a linear Lorentzito is being designed. This implies that the magnetic structure needs a hole through which tendon will move.

2 Magnetic structure

The magnetic structure will generate the higher possible $\vec{B}$ field in a direction as perpendicular as possible to the current $\vec{I}$ flowing through the inner conductor.

The wire carrying current density will be considered rigid and will only be allowed to move in one dimension. Therefore, the $\vec{B}$ field has to be a constant vector field in order to generate a force that varies linearly with the current. In order to choose the magnetic configuration, cost, inner B value and mass are considered the most important parameters to optimize. Low cost is important because resources for this thesis are limited. Inner B value have to be as high as possible to ease the observation and measure of the Lorentz force in the actuator. Mass is important since this actuator is meant to imitate a muscle and useful muscles must develop enough force to lift themselves. Therefore, the lighter the Lorentzito the easier it will be to implement an artificial muscle.

To sum up, high $\vec{B}$ field and low mass cheap structures are sought. These characteristics can be obtained by a Halbach cylinder configuration (Halbach, 1985). A Halbach cylinder is a hollow cylinder made of oriented magnetization pattern, defined by Equation 1, whose coordinates are defined in Figure 2a.

$$\vec{M} = M_r[cos((k-1)(\phi - \frac{\pi}{2}))\hat{\rho} + sin((k-1)(\phi - \frac{\pi}{2}))\hat{\phi}] \tag{1}$$

A uniform inner field is given when $k = 2$, that sets an inner field defined by Equation 2.

$$\vec{H} = M_r ln(\frac{R2}{R1})\hat{y} \tag{2}$$

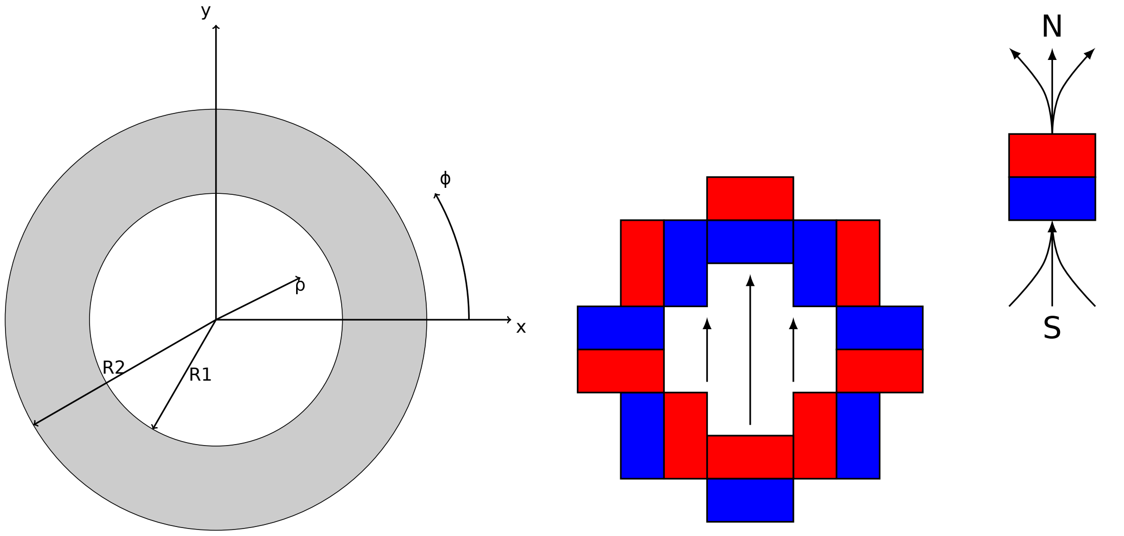
Those configurations can also grant a small value of B outside a certain region enhancing the magnetic isolation between actuators which is relevant if placed together. It is important to poit out that, given a non infinite length, Halbach cylinders are affected by end effects which will curve the inner field at the base of the cylinder.

Halbach spheres are the three dimension generalization of Halbach cylinders. Its inner field given by $k = 2$ is defined by Equation 3. Being closed structures, there aren not end effects in Halbach spheres.

$$\vec{H} = \frac{4}{3} M_r ln(\frac{R2}{R1})\hat{y} \tag{3}$$

Although spheres can get higher and more uniform fields, they are more difficult to build and leave less space to its bore. Therefore, a Halbach cylinder will be used as the magnetic structure.

Halbach cylinders are a theoretical differential configuration that has to be approximated in a definite number of segments (Manlio G. Abele, 1993). Circular segments are more expensive than cubic magnets, so cubic magnets have been chosen to approximate the Halbach cylinder. Furthermore, they are easily stackable at four different magnetic orientation. The approximation of the Halbach cylinder made of cubic magnets is shown in Figure 2b.



(a) (b)

Figure 2: (a) Theoretical implementation and (b) aproximaiton made of cubic.

Amongst permanent magnets, NdFeB generates the strongest magnetic fields in the smallest size and weight commercially available (Lucas et al., 2014). Therefore, NdFeB are going to be used. They are fragile and have a lower Curie temperature than other types of permanent magnets (supermagnete, 2018). That means that they can be demagnetize at lower temperatures than other material. Nevertheless, those temperatures are around 353 K, high enough for this application. Moreover, the magnets fragility is not relevant since they are going to be in a case which protect them tightly.

3 Inner conductor

The inner conductor is the part which carries the electrons. The current (I) that passes through a conductor depends on the electric resistance (R) of the wire. A low resistance means also that less power (P) is needed to get the same force, shown in Equation 4.

$$P = \frac{I^2}{R} \tag{4}$$

The resistance value is defined by Equation 5.

$$R = \frac{l}{A\sigma} \tag{5}$$

where σ is the electrical conductivity $[\Omega^{-1}m^{-1}]$, l is the length $[m]$ of the current path through the conductor and A is the cross-sectional area $[m^2]$ of the conductor through that path. If a more detailed analysis is needed, it is important to notice that σ is a temperature dependant parameter.

It is clear that big areas are desirable to decrease the resistance. That means that the maximum area should be covered by the conductor movement. The magnetic structure (see Figure 2b) leaves a prism whose base is a cross as a bore. Therefore, the maximum possible area covered in rectilinear displacement is obtained by another prism that fits in one arm of the cross.

The length is also related to the electric resistance and the power consumption. As length grows, electric resistance and power consumption grow too. On the other hand, the longer the conductor the bigger the force on it, considering that the conductor is in the $\vec{B}$ field. Both, resistance and force, depend linearly on the length, as shown on Equation **??** and Equation 5. Nevertheless, if the conductor height is greater than the magnetic structure's height, the $\vec{B}$ field will be smaller at sides and less orthogonal to electric current. That will produce less force in volumes where the resistivity is the same.

In conclusion, the best inner conductor shape, given the previous magnetic configuration (see Figure 2b), is a prism whose base is a square and its height is the same as the magnetic structure. This configuration maximizes the possible displacement of the conductor minimizing its resistance. The conductor is represented in orange in Figure 1a and Figure 1b. Side conductors, painted in orange too, and inner conductors are the same piece.

The material chosen for the inner conductor is copper. It has a good electric and temperature conductivity and is easy to acquire and mould. However, it is a diamagnetic material which will decrease and alter the magnetic field through itself. Moreover, diamagnetic materials' magnetic permeability is less than air magnetic permeability, which could decrease the B value in its surroundings and hence, the Lorentz force value. In future versions, it would be advisable to test ferromagnetic o paramagnetic materials which will strengthen the magnetic field. Nevertheless, scattering effects on electrons spins in the electric current could cancel the enhacement.

3.1 Inner conductor configurations

The inner conductor is the source of motion, so different configurations on its geometry and number can modify the behaviour of the actuator. If only one conductor is placed in the inner cavity, the movement can be transmitted to n tendons in the same direction (if external mechanisms are not added). Therefore, the movement will be very similar to a solenoid valve. However, if two conductors are placed in the inner conductor space, two independent directions can be transmitted to tendons, allowing more complex behaviours such as contraction. Moreover, two conductors will attract or repel each other because of the $\vec{B}$ field produced by their currents which would add up to the force transmitted.

Another interesting option to analyse is the direction of movement. If two artificial nerves are linked to the inner conductor, only two direction of movement will be possible since electric current can only flow in two different directions along the same path. For each additional pair of nerves attached to the inner conductor, one possible direction of movement can be added. It is important to notice that those directions will always share a plane. That is because the $\vec{B}$ field is assumed constant in direction and the cross product of the Lorentz force only allows movements perpendicular to that direction, which defines a perpendicular plane to $\vec{B}$ direction. That means that no matters which is the electric current direction, if $\vec{B}$ field is fixed, the Lorentz forces will always be contained in a plane. Therefore, for a linear actuator, there is no sense in building a Lorentzito with more than two artificial nerves, since only two directions are needed. For a planar actuator, three artificial nerves will be needed. That is because a set of two linearly independent vectors is basis to a plane ($\mathbb{R}^2$) and three points are needed at least to define two linearly independent vectors. Moreover, if $\vec{B}$ field is not considered constant in direction, a spacial Lorentzito can be designed with movements in three dimensions.

4 Tendon

The tendon, which transmits the Lorentz force, must be attached to the inner conductor, which is the source of motion. It has also to be accessible from the exterior of the actuator and rigid enough to avoid mechanical losses by deformation **??**. Its shape has to be adapted to what the Lorentzito is attached to. Nevertheless, in this thesis a generic shape will be proposed with no specific purpose, so only rigidity and accessibility will be covered.

Lorentz force allows a linear movement in two possible directions. If only one tendon is placed at one side of the actuator, each direction of movement will be associated with a push or a pull movement. Therefore, to transmit pull and push movements, no matter the side the tendon is placed to, two tendons are necessary. To simplify it, both tendons will be implemented in one single piece, as shown in Figure 1 in blue. The tendon could be partially in contact with the linkage solution and the inner conductor. Nevertheless, as described in the linkage problem, it has to be mechanically isolated from the electric terminals. The material chosen is PLA because it is easy to print in three dimension printers and is rigid enough.

5 A linkage solution

To solve the linkage problem defined before **??**, a solution based in liquid conductors is proposed. Metals, which are the better electric conductors, generally melt at high temperatures. Reaching high temperatures may often require an undesirable additional energy consumption. Nevertheless, some metals and eutectic alloys reach liquid state at low enough temperatures. Among them, some are toxic for humans like mercury and others are very reactive, like NaK alloy. From the most stable and safe for human health, an eutectic alloy called galinstan (Liu et al., 2012) has been chosen. It is made of gallium, indium and tin. Its melting point is 254.15 K and its boiling point is above 1573.15 K. It is a wide enough temperature interval to enable electrical connection through a liquid in many different situations.

The liquid in the linkage solution must be confined in a sealed defined region to avoid leakages. One end point of each rigid terminal of the actuator and the end points of the inner conductor must coexist in that region to allow the electric current transmission. The tendon can be partially submerged in the liquid metal as in Figure 1a or isolated from it as in Figure 1b. If it is partially submerged, the confinement must be elastic enough to allow the tendon movement without restriction. That will be accomplished with elastic membranes. These membranes will be the interface between the liquid and the air through the tendon. The design of those membranes' shapes is not trivial.

To understand the problem of designing these membranes, two types of transformation of a three dimensional surface will be defined. The first one is a stretch transformation in which two infinitesimal points change distance from each other, defining that distance as the minimum length path through the surface. The second one is a rotative transformation in which the defined distance is constant, but the relative position in three dimensions to at least one point is changed.

If the membrane changes its shape only by a rotative transformation, no energy will be stored and consequently no energy lost, because of the elastic properties of the membrane. That problem is similar to those solved by the Nash embedding theorem (Nash, 1954). The surfaces derived from that kind of problems are out of the scope of this thesis. Therefore, an heuristic technique has been developed to avoid stretching transformations as much as possible. It consists of creating a plane membrane as thin as possible and then wrinkle it to a fixed smaller area, that allows pseudo-rotation transformations that only modify the wrinkles and that almost do not stretch the surface. The material chosen for this membranes is latex, being a very elastic material and easy to purchase.

6 Case

The case is where all previous described parts will be placed together. It will isolate as much as possible the moving parts to prevent its deterioration. It will also prevent the breakdown of the actuator, since it can restrict the motion of the tendon and the inner conductor in better ways than the magnetic structure, because the material chosen for its construction does not have the conditioning of other parts.

An stackable shape is mandatory for the case in order to allow the construction of a complex actuator from singles Lorentzitos. The material chosen for the Lorentzitos designed in this thesis is PLA. This is because it is easily printable in 3D printers and is rigid enough. Nevertheless, to avoid mechanical looses, the case needs an extremely low friction coefficient so other materials such as PTFE or BAM should be tested in future implementations.

The case will also fix a position to the terminals. If no additional structure is placed or anything else is specified, the free movement of the inner conductor could lead it to get stuck with the terminals. This stuck can be avoided by physical walls. Nevertheless, if wire like solutions are implemented to connect electrically the inner conductor and the terminals in a linkage solution, some considerations must be taken into account. These stucks are prone to happen in solutions where the inner conductor can freely move in its longitudinal direction. An analysis is described then to avoid the stuck.

6.1 Analysis on distances on a liquid electrical connection Lorentzito

In this section, the location of the rigid terminals of the component, regarding the centre of the membrane, is analysed. This analysis is only relevant in implementations whose inner conductor can move freely in its longitudinal direction. To define the problem, the elements present in the the nerve-cell-tendon model in Figure **??** are simplified in Figure 3. In this figure, the green circles represent the electric terminals, the brown line represents the walls of the bore of the magnetic structure and the blue box represents the inner conductor. The linkages are not represented since they are considered variable. Black arrows point the direction of movement of the inner conductor and the yellow arrow points the direction of the current. The distances between relevant elements for this analysis are visually defined in Figure 4. Although Lorentzito needs two electric terminals, only one terminal is shown to simplify the figure. The hidden terminal is placed at the same distances.

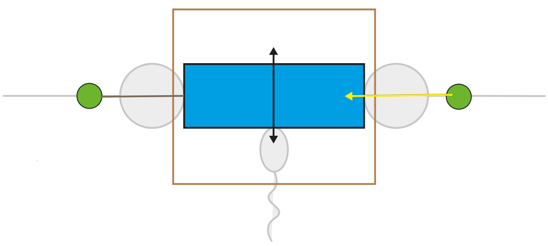


Figure 3: Geometric abstraction of the nerve-cell-tendon model to define distances in a liquid connection.

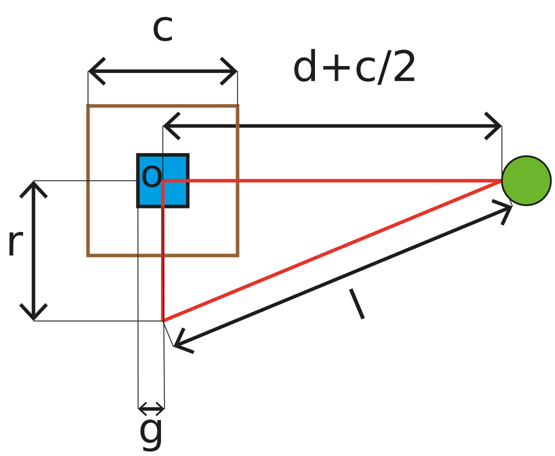


Figure 4: Graphic definition of the distances in a liquid connection.

O is the centre of the magnetic structure, c is the length of the magnetic structure in the direction of electric current, g is the distance between O and the end of the conductor in the direction of movement, $r-g$ is the maximum distance that the inner conductor can travel in the direction of movement from O, $\frac{c}{2}+d-g$ is the distance between O and the rigid terminals and l is the maximum length of a virtual line that connects the centre of the conductor and the centre of the rigid terminal of Lorentzito. This maximum length is gotten when $g=0$ as shown in Figure 4.

From this description, some conditions can be deduced that should be asserted to avoid stucks. In *Condition l*, shown in Equation 6, the minimum length of the electrical connection is defined by Pythagoras theorem in a right triangle.

$$l = \sqrt{(r-g)^2 + (\frac{c}{2} + d - \frac{g}{2})^2} \tag{6}$$

In that right triangle, one leg is the distance between a rigid terminal and the inner conductor $(r-g)$, when the centre of the inner conductor is placed at point O. This leg should be short in order to minimize the volume of the actuator. The other leg is the maximum distance the inner conductor can travel, $(\frac{c}{2}+d-\frac{g}{2})$. That movement is always perpendicular to the $\vec{B}$ field and the $\vec{I}$ current , which are fields with a constant direction, so it will follow a straight trajectory (shown as black arrows in Figure 3). This maximum movement sets the maximum distance that anything attached to the conductor can be moved. This sets, at a given current, the maximum amount of work and should be a design decision. Finally, l is the hypotenuse, so, as not to limit the maximum movement, this hypotenuse length must me reachable by the connection.

In *Condition d*, shown in Equation 7, the inequality must be verified to avoid the physical contact between the inner conductor and the rigid terminals.

$$d > \frac{l-c}{2} \tag{7}$$

Being l a possible length to the connection, the conductor can move horizontally in Figure 4, a distance equal to $l-(d+\frac{c}{2}-g)$. If this distance is greater than the separation between the inner conductor and the rigid terminals $d+\frac{c}{2}-g$, the conductor could touch them hindering the performance of the actuator.

In *Condition g*, shown in Equation 8, that inequality must be verified to ensure that the inner conductor is always in the constant $\vec{B}$ field region.

$$g < d + c - l \tag{8}$$

That means that it is always contained in the membrane. The conductor can move horizontally in Figure 4, an $l-(d+\frac{c}{2}-g)$ distance. If the centre of the conductor moves horizontally in Figure 4, more than $\frac{c}{2}-g$, a part of the conductor will be out of the constant $\vec{B}$ field region. The verification of Condition g is important in order to ensure a lineal response of the Lorentz force which ensures also a maximum response.

In *Condition k* , shown in Equation 9, k is the fraction of the inner conductor that can be outside the membrane when g, c, l and d are set.

$$k = 1 - \frac{l-d-\frac{c}{2}-\frac{c}{2}}{g} \tag{9}$$

This condition allows to set a limit to the minimum force that will pull the conductor considering that outside the membrane there is no magnetic field.

This four conditions have six variables, so there are two degrees of freedom. g and r are relevant in the power consumption and the maximum work of the actuator respectively.

Hence, is advisable to fix g and r before the others. k is relevant to the linearity of the force behaviour so it should be fixed next, ideally to the value $k = 0$, which means a linear response. c is a parameter very important in order to let the component lift itself and in some performance ratios defined in Chapter **??**. That means that c could be fixed by reasons alien to this four conditions. It is interesting to notice that only Condition l, shown in Equation 6, has the variable r and that the right triangle imposes three more conditions. The first one because the triangle inequality:

$$(r - g) + (\frac{c}{2} + d - \frac{g}{2}) > l \tag{10}$$

The other two because the hypotenuse is always greater than any of the legs:

$$l - (r - g) > 0 \tag{11}$$

$$l - (\frac{c}{2} + d - \frac{g}{2}) > 0 \tag{12}$$

7 Multiple actuators configurations

The Lorentzito actuator is proved to be better at small sizes compared to electromagnets. Nevertheless, minimizing the actuator's size will minimize the stroke too. Therefore, good figures of merit would be obtained for small sizes and very low range movements for each actuator. This movements could be too small to do many useful tasks that other linear actuators are able to accomplish. In order to extend the advantages of small actuators in wider ranges of movement, multiple linear Lorentzito must be attached.

If the purpose is to get longer paths of movement, every artificial tendon can be attached to another Lorentzito, creating a serial configuration as seen in Figure 5. This will only be useful if every Lorenzito is able to lift the next Lorentzito to which it is attached. If every Lorentzito in the configuration weights the same. The length can be controlled easily by the number of Lorentzito activated and, therefore, the maximum work will be bigger than in a single Lorentzito.

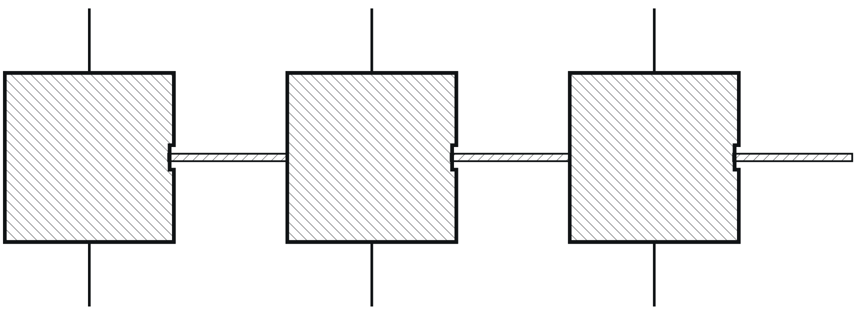


Figure 5: Serie Lorentzitos configuration.

Placing Lorentzito in series will not strength the final force. At the end of the configuration, the force will be the same as if only one Lorentzito would be pulling. So in order to increase the final force, the artificial tendons can be attached in parallel as shown in Figure 6.

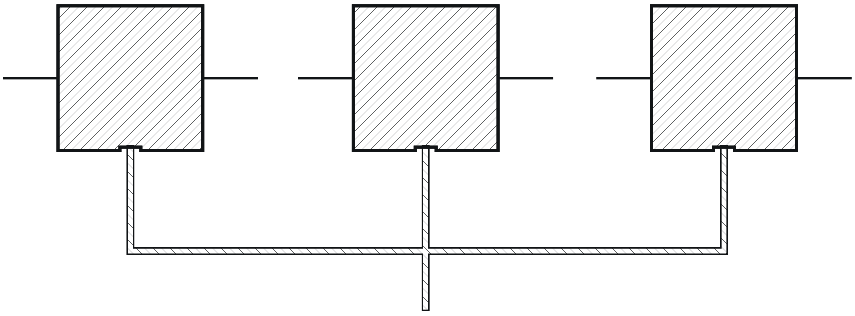


Figure 6: Parallel Lorentzitos configuration.

Those configurations allow to increase the work increasing the maximum force or the maximum displacement.

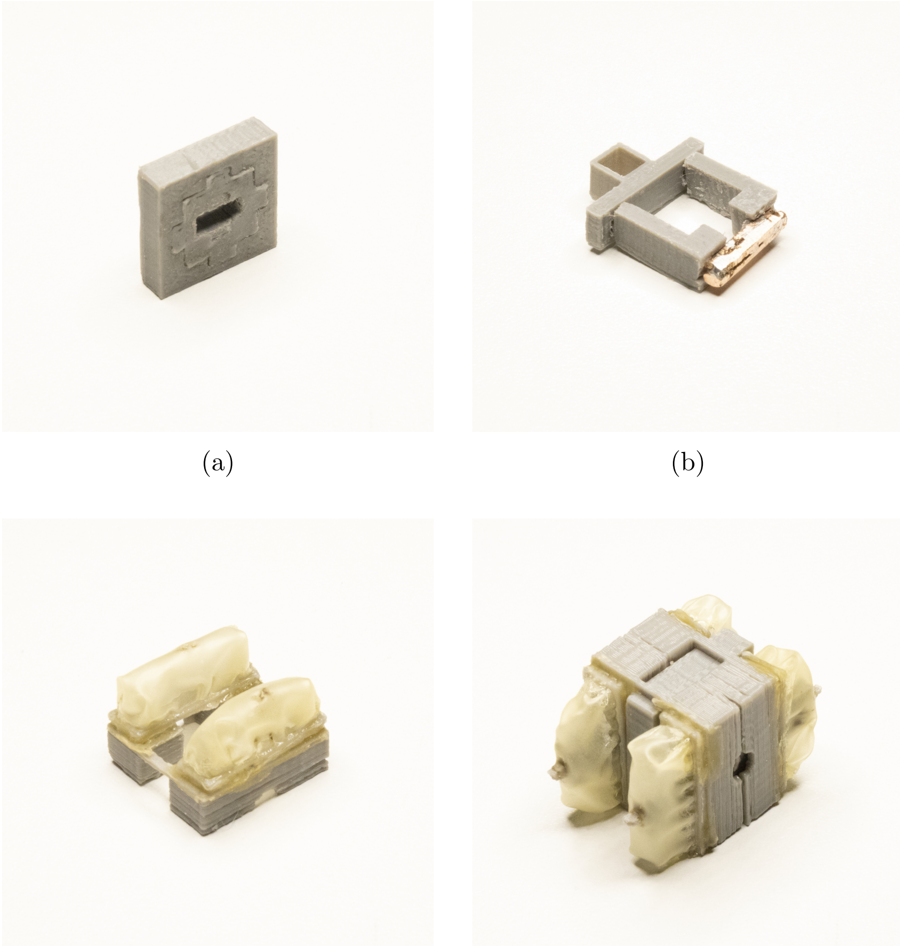
8 Implementation

In this section two different implementations are analysed. One is the implementation of the structure proposed in Figure 1a and the other is based on the structure proposed in Figure 1b. The ideas presented in the previous section inspire both but with two differences: where the tendon is placed and the shape of the linkage solution. In the first tests, equipment available is not able to supply electric currents higher than 7 A. Therefore, little sizes are desired to get high ρ values. However, minimum size reached in this thesis is that in whose magnets are cubes of three millimeter of edge.

8.1 First implementation

In the first implementation, the tendon is partially immerse in the liquid conductor and the linkage solution is a volume where tendon, inner conductor and electric terminals co-exist. Its parts are hereafter presented and explained.

The magnetic structure, shown in Figure 7a, has been designed in Autodesk Inventor 2018 (Autodesk) and lately printed in a Hephestos 2 (BQ) using PLA filament. The magnets are cubic NdFeB magnets of 3×10^{-3} of edge and 1.1 T of remanence. The inner conductor is a block of polished copper that slides in the bore of the magnetic structure, shown in Figure 7b. It is placed in the bore of the magnetic structure. The linkage solution implemented is shown in Figure 1a. Two membranes of latex are created to allow the tendon movement in each one of the two possible directions. They have wrinkles that allow the movement without hinder too much the motion of the inner conductor. They are placed on top of a PLA structure that envelope the magnetic structure.



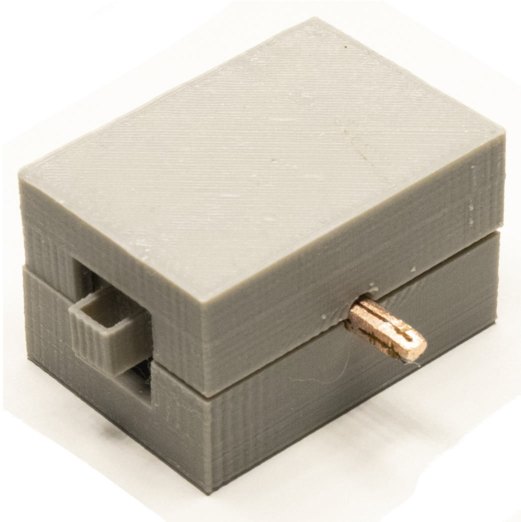
(a) (b) (c) (d)

Figure 7: (a) Magnetic structure, (b) half of a tendon and the inner conductor, (c) linkage solution, (d) magnetic structure, tendons and inner conductor.

The tendons, made of PLA, hold the inner conductor as shown in Figure 7b. They are polished to avoid mechanical losses through friction. The tendons, the inner conductor and the magnets are placed together as shown in Figure 7d.

The actuator is assembled as shown in Figure 8a. The case, shown in Figure 8b, holds the actuator in place and allows the movement of the tendons and the inner conductor through a hole. It includes the electric terminals where power supply will be connected.

(a)



(b)

Figure 8: (a) Linkage solution assembled and (b) Parallelepiped Lorentzito.

8.2 Second implementation

In the second implementation the tendon is not immersed in the liquid conductor and the linkage solution is a surface where only the inner conductor and the electric terminals coexist. As in the first implementation, all structural support has been designed in Autodesk Inventor and lately printed in a Hephestos 2 using PLA filament.

The inner conductor and the magnetic structure, shown respectively in Figure 9a and Figure 9b, are the same as for the first approximation. The tendon is shown in Figure 9c. It is connected to the inner conductor in its center.

(a)

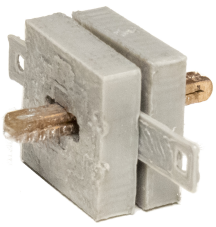
(b)

(c)

Figure 9: (a) Inner conductor, (b) magnetic structure and (c) tendon.

The linkage solution implemented is shown in Figure 10a. The linkage solution followed is shown in Figure 1b. Two membranes of latex are created in a shape similar to a planar surface. These shapes present a very low resistance to bend over any axis contained in the plane and high resistance to bend over any axis not included in the plane. Those are placed in a way that the inner conductor motion will produce a bending over an axis contained in the plane to lower the interference to its motion.

(a)



(b)

(c)

Figure 10: (a) Linkage solution, (b) assembly of inner conductor, magnetic structure and tendon and (c) case.

The tendon, made of PLA, holds the inner conductor between two magnetic rings as shown in Figure 10b. It is polished as the inner conductor to avoid mechanical losses through friction. The tendons, the inner conductor and the magnets are placed together as shown in Figure 10b. The case, shown in Figure 10c, holds the actuator in place and allows the movement of the tendons and the inner conductor through a hole.

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