Artificial muscles as hyper-redundant actuators

TR/Laboratorio de Robótica y Control/ETSIT

Developed by **Laboratorio de Robótica y Control**

Authors:
Daniel Galera Nebot
Álvaro Gutiérrez Martín

2019-04-02

Contents

1 Motivation

In technological solutions of motion, servos, stepper motors, and motors are commonly used. Circular actuators prevail even when an adapter is necessary to generate a non circular motion. On the contrary, in nature, the core of motility usually starts with a contractive behaviour (Clark, 1981). Contraction, which is fundamentally a linear movement, is the main strategy to generate movement in multi-cellular beings. Among those, free rotation has only been found in digestive systems of bivalves and gastropods (Owen, 1982). This is the only biological structure found in animals that behaves similar to a motor, and it has not a motion purpose. Nevertheless, at a molecular scale, flagella motors are a common solution to motion that can be considered as a circular actuator. This structure (Namba and Vonderviszt, 1997) is widely used by unicellular beings but it does not have a counterpart in multicellular systems. That lack of rotating locomotion has been previously discussed (Dawkins, Richard, 1996; Diamond, 1983) showing that wheels are less efficient in order to accomplish movements in complex and unpredictable terrain. It suggests that using rotatory actuators could not be the best option to move structures bigger than cells and maybe only historical reasons had lead us to develop general purpose machines with this kind of actuators. On the contrary, muscles are the most common tissues found in animals that perform a contraction with a motility purpose. Even when muscles are not present in metazoa, other contractive structures are used to generate a contraction. Examples of those structures are found in Porifera (Nickel et al., 2011) and Placozoa (Behrendt and Ruthmann, 1986; Ruthmann et al., 1986).

It is undeniable that rotatory actuators are highly efficient in solving many problems. However, in general purpose machines or adaptable robots, which must operate in nature, it seems advisable to test contraction solutions as the basis of motion (Dawkins, Richard, 1996; Diamond, 1983). In most animals, contraction starts in myocytes grouped in tissues that compound muscles. In this thesis, this scheme will be imitated to attempt motility based on contraction. This inspiration leads to solutions that need the counterpart of the myocytes, which will build up artificial contractible tissues.

Many technologies have been developed inspired by nature, most of them focusing on the concept of linear or bending actuators. Soft robotics (Trivedi et al., 2008; Carmel, 2013; Rich et al., 2018) is a promising area which imitates the natural way of motion that could be commonly used in future robotics applications. They can perform precise and powerful movements (Li et al., 2017). Hyper-redundant robotics are also present in biomimetic robotics (Koopaee et al., 2018). Nevertheless, those structures act as the whole muscle imitating the functionality rather than the internal structure. Thermal driven actuators (Wu et al., 2018) and electroactive polymers (Mirfakhrai et al., 2007) generate movement due to their internal structure. However, electroactive polymers are still limited by their degradation (Bar-Cohen et al., 2017) and thermal driven actuators which have been implemented successfully in muscle-mimicking technologies (Saharan et al., 2017) are slower than magnetic actuators such as electric motors.

In order to adapt the advantages of magnetic actuators to a contractive structure based on contractive building blocks, solenoid valves are the sole commercial option available. Small solenoids were tested in a first approximation to the myocytes approach. However, small solenoids have different problems: a continuous usage heats the core, bending it and generating malfunctioning unless the component is refrigerated. Moreover, many little solenoids cannot lift their own weight and all sizes present a high energy consumption. Those characteristics make clear that solenoid valves are not suitable to be hyper-redundant actuator in robotics. Therefore, because no commercial actuators are found to be suitable, the first step to achieve the building block of an artificial muscle is to design the myocytes counterpart.

2 Modelling a linear Lorentzito

A first device, consisting of two copper wires with parallel currents, was tested. However, the mechanical resistance to deformation of copper made the Lorentz force approach useless. Geometries which multiply the force between wires, like springs, resulted in higher resistance to the material deformation. Moreover, high consumption and temperatures in wires were reached, getting even less force than in commercial solenoid valves dismissed. Therefore, the solely usage of wires and electricity seems a useless way to produce force and motion from Lorentz force. This test pointed out that the magnetic field $\vec{B}$ must be amplified to get higher forces with less consumption and heating. Furthermore, every mechanical deformation worsens the device performance, so they have to be avoided. These preliminary tests lead to a concept of an actuator consisting of a high $\vec{B}$ field area (to maximize Lorentz force) in which a single and not bendable conductor (to avoid mechanical losses) carries a current and is moved according to the Lorentz force. This force pulls linearly the conductor, which can be attached to any element to transmit the force. Because of its similarities to a cell and the Lorentz force usage, linear **Lorentzito** is proposed as its name, and will be used from now on in this thesis.

2.1 Nerve-cell-tendon model

Motion in actuators works and can be understood by the following process: by applying energy, a low potential energy space is set. Therefore, a free moving part affected by that potential is displaced to that space, generating motion. Generally, the moving part affected by the change of the potential is different from the part that gets energy to create that low potential space condition, as in electric induction motors or solenoid valves. In a Lorentzito, the simplest solution is an electrical wire which can act as the source of potential change and the source of movement. Therefore, all the elements attached to the wire move unless a variation is made to the actuator. That variation must be done because dragging any element connected to the conductor is an obstacle to get the maximum work of the actuator. The scheme proposed in Figure 1, which avoids this obstacle by separating the moving part from the potential generator part, is biologically inspired by myocites: it is similar to a nerve-cell-tendon block. In that block, the nerve is what transmits the signal that generates the low potential energy condition. The cell is what moves and the tendon is what transmits the motion. Therefore, the nerve is electrically connected to the cell and electrically isolated from the tendon. The cell is mechanically attached to the tendon and mechanically isolated from the nerve.

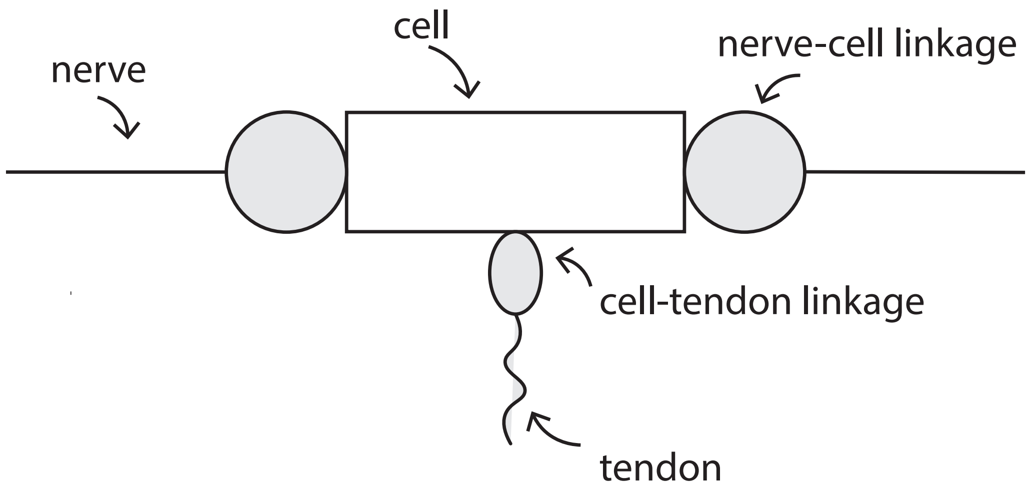

Figure 1: Nerve-cell-tendon model.

Any mechanical resistance or elasticity in the cell-tendon junction will decrease the final force transmitted to the tendon. That will be measured as the stretch ratio λ_t of the tendon's material (see Equation 1). Therefore, the non-ideal behaviour of nerve-tendon connection is represented by λ_t.

$$\lambda_t = \frac{l_t}{l_{wt}} > 1 \tag{1}$$

where l_t is the length of the tendon when a force generates a mechanical tension on it and l_{wt} is the lenght of the tendon when no force is applied to the tendon.

In terms of electricity, any conductor with higher resistivity than the movable part will consume more energy to generate the same force, resulting in a worse performance. Moreover, the nerve should be mechanically isolated from the cell-tendon sub-block, which has to be firmly connected, so it does not hinder the motion. The non-ideal behaviour of the the nerve-cell connection is modelled by the nerve-cell friction coefficient $\nu_{n-c} > 0$. An ideal nerve-cell-tendon implementation has $\lambda_t = 1$ and $\nu_{n-c} = 0$

2.2 The linkage problem

Attaching two pieces rigidly, as needed in the cell-tendon sub-block, is an easy problem. However, connecting two pieces electrically allowing a free and independent movement is not a simple task if the cell-tendon sub-block must be kept rigidly attached. This problem is named as the linkage problem. Therefore, a linkage problem appears in the junction between the artificial nerve and the cell. To partially or fully avoid the transmission of movement from the cell to the nerve, current must be transmitted without a rigid joint. An electric connection through a gas, plasma or liquid conductor with low friction between the non attached conductors could be used. Nonetheless, elastic conductors which provide low friction and stiffness could also be used. These four different joints between the nerve and the cell define a classification for Lorentzito: solid , liquid, gas and plasma nerve-cell connection. In this thesis only the liquid electrical connection will be analysed.

2.3 Electrical liquid connection

In a liquid electrical nerve-cell connection, as shown in Figure 2, electricity is transmitted through a liquid electrical conductor. Using that liquid as a joint provides very low friction and high conductivity. To avoid corrosion of salt solutions in conductors, metal alloys with low fusion point temperatures are the best option. Moreover, it is important to notice that any water-based solution could produce gases because of electrolysis, which is an undesirable effect. Nevertheless, liquid metals could be corrosive or toxic, and it should be taken into account for the selection of materials and shields to avoid deterioration and liquid leakages. Furthermore, a sealed region is mandatory in order to confine the liquid. This region will be the main source of ν_{n-c}. This electrical connection is the one proposed in this thesis for the Lorentzito actuator.

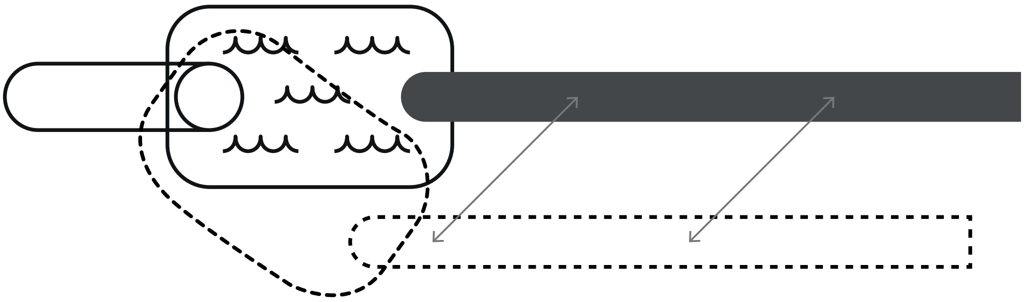

Figure 2: Depiction of a liquid electrical connection based on liquid joint.

2.4 Cell-tissue-muscle model

By clustering Lorentzito in series and parallel, as if they were cells of a muscle, a bigger linear actuator can be precisely designed. If those actuators are considered as tissues, then some of them can be arranged as muscles in order to perform complex movements. Therefore, a set of simple linear actuators can accomplish very complex movements, such as those present in the human body or animals. That is the ultimate goal of designing this actuator. Nevertheless, reaching that goal is out of the scope of this thesis.

References

Bar-Cohen, Y., Cardoso, V., Ribeiro, C., and Lanceros-Méndez, S. (2017). Electroactive polymers as actuators. In *Advanced Piezoelectric Materials*, pages 319–352. Elsevier.

Behrendt, G. and Ruthmann, A. (1986). The cytoskeleton of the fiber cells of trichoplax adhaerens (placozoa). *Zoomorphology*, 106(2):123–130.

Carmel, M. (2013). Soft robotics: A perspective—current trends and prospects for the future. *Soft Robotics*, 1(1):5–11.

Clark, R. B. (1981). Locomotion and the phylogeny of the metazoa. *Bolletino di zoologia*, 48(1):11–28.

Dawkins, Richard (1996). Why don't animals have wheels? *The Sunday Times*.

Diamond, J. (1983). Transport mechanisms: The biology of the wheel. *Nature*, 302:572 EP –.

Koopaee, M. J., Gilani, C., Scott, C., and Chen, X. (2018). chapter Bio-Inspired Snake Robots: Design, Modelling, and Control, pages 246–275. IGI Global, Hershey, PA, USA.

Li, S., Vogt, D. M., Rus, D., and Wood, R. J. (2017). Fluid-driven origami-inspired artificial muscles. *Proceedings of the National Academy of Sciences*, 114(50):13132–13137.

Mirfakhrai, T., Madden, J. D., and Baughman, R. H. (2007). Polymer artificial muscles. *Materials Today*, 10(4):30–38.

Namba, K. and Vonderviszt, F. (1997). Molecular architecture of bacterial flagellum. *Quarterly Reviews of Biophysics*, 30(1):1–65.

Nickel, M., Scheer, C., Hammel, J. U., Herzen, J., and Beckmann, F. (2011). The contractile sponge epithelium sensu lato - body contraction of the demosponge tethya wilhelma is mediated by the pinacoderm. *Journal of Experimental Biology*, 214(10):1692–1698.

Owen, J. (1982). *Feeding strategy*. University of Chicago Press, Chicago.

Rich, S. I., Wood, R. J., and Majidi, C. (2018). Untethered soft robotics. *Nature Electronics*, 1(2):102–112.

Ruthmann, A., Behrendt, G., and Wahl, R. (1986). The ventral epithelium of trichoplax adhaerens (placozoa): Cytoskeletal structures, cell contacts and endocytosis. *Zoomorphology*, 106(2):115–122.

Saharan, L., de Andrade, M. J., Saleem, W., Baughman, R. H., and Tadesse, Y. (2017). igrab: hand orthosis powered by twisted and coiled polymer muscles. *Smart Materials and Structures*, 26(10):105048.

Trivedi, D., Rahn, C. D., Kier, W. M., and Walker, I. D. (2008). Soft robotics: Biological inspiration, state of the art, and future research. *Applied Bionics and Biomechanics*, 5(3):99–117.

Wu, L., Karami, F., Hamidi, A., and Tadesse, Y. (2018). Biorobotic systems design and development using tcp muscles. *Proc.SPIE*, 10594:10594 – 10594 – 11.