euspen's 20th International Conference & Exhibition, Geneva, CH, June 2020
www.euspen.eu

Advances in soft robot actuation and their morphological control

E. Milana[1], B. Van Raemdonck[1], S. Peerlinck[1], D.Reynaerts[1*], B. Gorissen[1,2]

[1] *Department of Mechanical Engineering, KU Leuven and Flanders Make*
[2] *John A. Paulson School of Engineering and Applied Sciences, Harvard University*

[*] *dominiek.reynaerts@kuleuven.be*

Abstract
Robotic systems have been going through a staggering evolution over the past decades, with new generations of robots, increasingly dexterous and intelligent, being developed at an unprecedented rate. Where robots are traditionally thought of as rigid systems, the introduction of compliant materials in robotics has sprouted a new robotic family tree. Because of their versatility and compliancy, these soft robots are uniquely suited to accomplish delicate tasks where a safe interaction with humans or other biological systems is preeminent: minimally invasive surgery, elderly care, exoskeletons and, more recently, even video game industry. All these applications require robots that are able to interact safely in an unstructured environments. In this context, conventional rigid robots, made out of rigid links and actuators with a fixed number of degrees of freedom, typically fail because of the extreme complexity and cost of sensor and control systems.
Recent advances in soft robotics showed that this limitation can be avoided. For example, grabbing a delicate object using a soft actuator does not necessitate sensor feedback. Further, by actively harnessing structural nonlinearities, functionalities can be encoded within the distributed hardware of the system, drastically lowering the computational power needed for control. This paper will highlight recent advances in soft robotic technology with applications ranging from minimally invasive surgical tools to biomimicking artificial cilia and walking robots that harness morphological control.

Soft robots, soft actuation, morphological computing

1. Introduction

The digital revolution drastically changed the world around us, leading to robots that outperform humans in terms of accuracy and speed. Due to their computational power they now are even breaching the borders of (artificial) intelligence. However, these machines typically perform badly when interacting with unpredictable environments such as navigating uneven terrains or handling amorphous objects. Still those tasks are typically 'easy' for organisms. This discrepancy comes down to a difference in general architecture. Conventional robots consist of sensors and actuators with linear characteristics that are controlled through software in which all complexity is localized. Each degree of freedom features a closed feedback loop with dedicated sensor, actuator, and control elements. However, in nature these functions are not concentrated in separate building-blocks, but are rather distributed throughout the body. In extreme cases functionality arises even without a traditional sense of cognitive computation [1] (e.g. the catching of a fly by the Venus flytrap).

Reproducing this distributed functionality where for example actuators also become sensors necessitates a hardware architecture that can both influence and be influenced by the environment. This leads to a paradigm shift where robots are designed with a stiffness comparable to the environment's. This idea instigated the research field of soft robotics, where typically materials are used with moduli in the order of 10^4-10^9Pa [2]. One consequence of applying these materials is a poor dynamic performance and low controllability. However, as we will show in this paper, it also leads to new capabilities that are unparalleled by rigid robots. Firstly this paper will focus on the direct consequences of using soft materials, the ability to achieve large deformations and the ability to be intrinsically safe in interactions with organisms. Secondly, the focus will shift towards a secondary consequence that originates from these large deformations: the emergence of reversible nonlinear relationships between input and output that can be harnessed to create new functionalities without software control, like valveless actuator sequencing.

2. Harnessing softness

Typically, soft robots are made out of polymers that can withstand several tens to hundreds of percent strain before failure. Those polymers owe their flexibility to an architecture of linked polymer chains which can rotate, slide and (dis)entangle to reversibly store energy with little stress build-up. Since their moduli are comparable to (or even lower than) that of biological tissue, they are inherently safe when making contact with organisms [3]. Therefore the application domain of surgical tools is highly investigated within the field of soft robotics. Moreover, the resemblance of the used polymers to biological materials allows soft robots to closely mimic the behaviour of natural organisms. Both application domains, surgical tools and biomimicking systems, display the power of using softness in small-scale robotics design, and will be detailed in the next two sections.

2.1. Minimally Invasive surgical tool

When in contact with biological tissue, it is impossible for soft robotic actuators to impose detrimental stresses to the surrounding tissue. As such, safety is an inherent feature of the

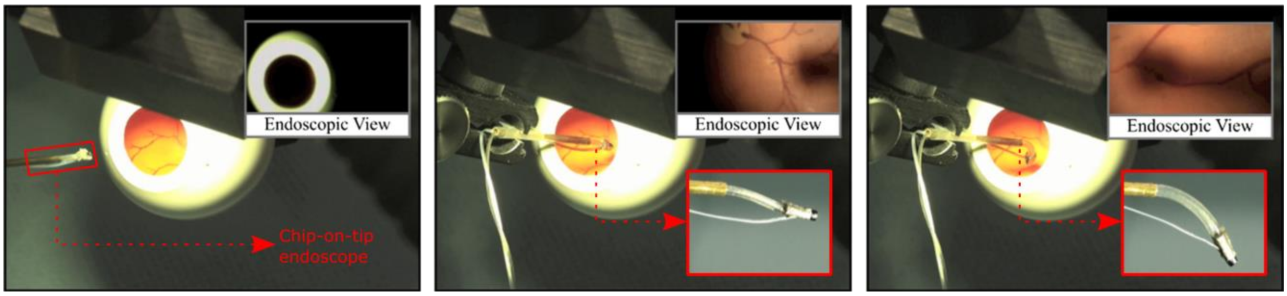

Figure 1. Active endoscope that consists of a CMOS camera that is mounted on the tip of a soft robotic bending actuator to increase its field of view

robot's hardware and does not depend on active software control. To demonstrate the ability to use soft robotics in a surgical context, an elastic actuator has been developed that shows a bending deformation when inflated [4]. With a CMOS camera mounted on the distal end of the actuator, it functions as a chip-on-tip endoscope that can extend its field of view by bending off-axis. This active endoscope is tested in a surgical context: in a mock-up ophthalmological procedure the full retina can be visualised from a single access port, as is shown on figure 1. The developed active endoscope actuator has a square cross section of 1.1 x 1.1 mm^2 and has a total length of 12mm. It is able to bend 45° at a supply pressure of 280 kPa and is able to go from straight to fully bent in less than 0.1 seconds.

2.2. Biomimetic Cilia

Cilia are cell organelles that induce fluid flow at microscopic scales. According to the scallop theorem, fluid propulsion at low Reynolds numbers necessitates asymmetry in the actuation scheme since all inertial effects are negligible and time is cut from the Navier-Stokes equations leading to the linearized Stokes form [5]. For cilia, asymmetry can take different forms, acting on a single cilium (spatial, orientational and temporal asymmetry) and on the level of a cilia array (metachronal asymmetry). Theoretically, it has been shown that spatial (cilium's tip follows a different path between forward and backward stroke) and metachronal (phase difference between cilia) asymmetry are essential for achieving low Reynolds flow propulsion. However it is extremely difficult to mimic these mechanisms using conventional robotic technologies, since large bending deformations are needed at a small scale.

The high deformations of soft robotic pneumatic bending actuators are well suited to mimic nature's cilia deformations [6]. A dual degree of freedom bending actuator is fabricated with two inflatable channels in a monolithic silicone rubber structure. Sequential inflation of the channels results in an asymmetric pattern resembling natural ciliary movement (spatial asymmetry). This beating has been shown to result in a net fluid propulsion in a highly viscous environment, and new insights in the hydrodynamic mechanism behind this propulsion have been distilled from these experiments [7] that until now were only theoretically predicted.

Using multiple 2DOF bending actuators in an array, as shown in figure 2, allows for mimicking the collective metachronal asymmetry seen in ciliary carpets. A phase difference can be imposed on the pneumatic signals of subsequent artificial cilia, resulting in tuneable beating patterns of the array. This enables a thorough study of the hydrodynamic interaction in cilia arrays and will provide insight in the mechanisms behind low Reynolds number fluid propulsion and micro-mixing.

3. Harnessing Nonlinearities

The previous paragraphs show that an artificial cilium featuring two separately controlled actuators can generate an asymmetric motion that induces fluid flow at low Reynolds numbers. This requires two supply lines and valves for every cilium so in an array with phase offsets the amount of supply lines and valves becomes excessive. A technological need therefore exists to simplify the control system and generate an asymmetric actuation sequence from a single pneumatic input.

This need can be addressed by introducing a concept called morphological computing, in which the hardware takes over control tasks from the software [8]. Morphological computing is an aspect of a wider theory called embodied intelligence, which conceives that intelligence is not merely confined in the brain of an agent, but emerges from the peculiarities of its physical body.

The field of soft robotics is uniquely suited to explore the world of embodied intelligence for two reasons. Firstly, soft structures are intrinsically underactuated, which is exploited in for example soft grippers to grab arbitrary objects with a minimum of control. Secondly, morphological computing is known to result from nonlinearities and nonlinear characteristics are ubiquitous in soft robots because of their large deformations and hyperelastic materials.

So far, nonlinearities have been largely avoided in soft robotics research in order to gain software controllability [9]. However, initial research efforts [10]–[12] focussed on exploiting these nonlinearities show the huge potential of this new paradigm. To display this potential to "distribute" computation in the body we will report two methods to embody discrete sequencing of soft actuators without the use of valves. As such actuation is not controlled by software, but instead by the robot's hardware morphology.

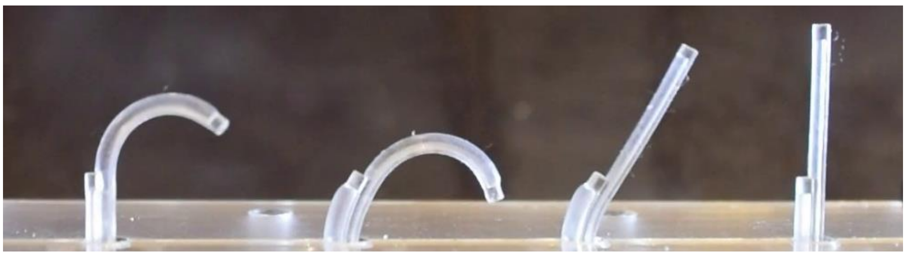

Figure 2. Soft inflatable artificial cilia, showing individual and collective asymmetries, used for fluid experiments in viscous flows.

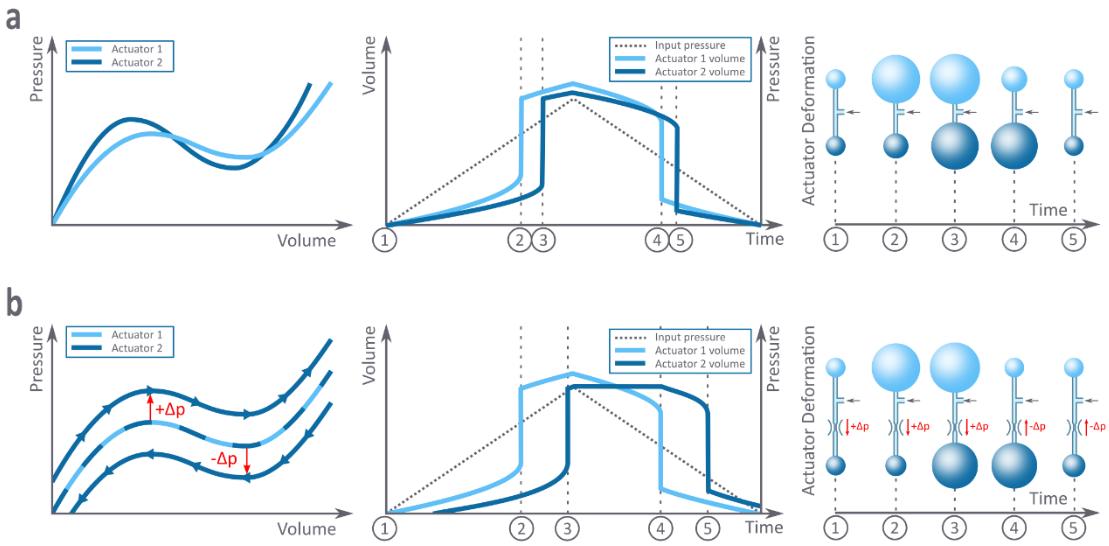

Figure 3 Sequencing mechanisms for nonlinear actuators: a) quasi-static sequencing, b) dynamic sequencing

The sequence being discrete means that when a specific actuator responds, the other actuators in the system need to maintain their previous configuration. Therefore, actuators need to have a sort of discretised response, an on-off internal mechanism, which is triggered when a pressure threshold is reached.

Such a mechanism is present in spherical party balloons that go through a reversible elastic instability at constant pressure as soon as a critical pressure is reached. It results from their pressure-volume characteristic (PV-curve) that features a peak and a valley separated by a region of negative stiffness as shown in figure 3a. When the pressure in the balloon exceeds that of the peak during inflation or drops below that of the valley during deflation, a snap-through instability occurs. The same phenomenon occurs in other soft actuators with a non-monotonic PV-curve.

Connecting actuators with such a PV-curve together and controlling the pressure at a single point results in a discrete sequence of inflations and deflations. The exact sequence is determined by two effects. Firstly by the position of the peaks and valleys of the PV-curve in the case of quasi-static sequencing and secondly by introducing pressure drops over flow restrictors in dynamic sequencing. Both methods are discussed in the following sections with applications of respectively an artificial cilium and a tetrapod walking robot.

3.1. Quasi-static sequencing

In the quasi-static case, dissipation caused by flow of the working fluid is neglected. This condition can be reached experimentally for slow inputs and short and wide tubes. Considering a simple system with two parallel connected actuators, each having their own *p(v)* characteristics, without pressure drops. At each point in time, the two actuators will see the same pressure magnitude (1) and the total volume can be found by summing the volume inside actuator 1 and actuator 2 (2). The response of the system while inflating or deflating follows from the stability condition of the total energy in the system (3).

$$p(v) = p_1(v_1) = p_2(v_2) \quad (1)$$

$$v = v_1 + v_2 \quad (2)$$

$$\frac{\partial E}{\partial v_1} = p_1(v_1) - p_2(v - v_1) = 0 \quad (3)$$

The following scenarios are possible depending on the PV-curves of the two actuators: no sequencing, partial sequencing and full sequencing, be it symmetric or asymmetric [13]. When both actuators have linear PV curves, the overall response is proportional to the input, thus having no sequencing. Sequencing only occurs if at least one of the actuators has a nonlinear PV curve. For example, partial sequencing occurs if one has a PV curve with a pressure plateau at high volumes. When increasing the volume in the system, initially both actuators deform. On reaching the pressure plateau, however, only the nonlinear actuator continues to deform while the linear one remains in the same configuration. While there is a clear sequence, it is the same on inflation and deflation: partial sequencing.

For full sequencing, there needs to be asymmetry between inflation and deflation. This is possible when the two actuators have non-monotonic PV-curves. By tuning the pressure of the peaks and valleys of those curves, the actuator responses can be discretised due to the snap through instabilities in the system. When two actuators see the same pressure, the one with the lower pressure peak will snap first when inflating. On the other hand the actuator with the higher valley will snap back first to its undeformed configuration when deflating. In the case where both the peak and the valley of one actuator are higher than those of the other, the sequence is symmetric. In the other case, as depicted in figure 3a, the sequence has the desired asymmetry where the first one inflating is the last one deflating. This actuation asymmetry is directly linked to the motion asymmetry of artificial cilia, that is needed to generate fluid flow. Thus single inflow artificial cilia can be made by combining two nonlinear actuator segments into one inflatable structure. This has been realized in a large scale actuator, as shown on figure 4a, where a small area is swept during consequent inflation an deflation, while having only one single supply line.

3.2. Dynamic sequencing

The degree of asymmetry in a sequence of nonlinear pneumatic actuators is proportional to the difference in snapping pressures of the actuators. In the quasi-static case, those pressures are the values of the local extrema in the PV curves of the actuator. To increase the asymmetry in the sequence of interest, the peak of one actuator should therefore rise above that of the other while simultaneously its valley should drop below that of the other.

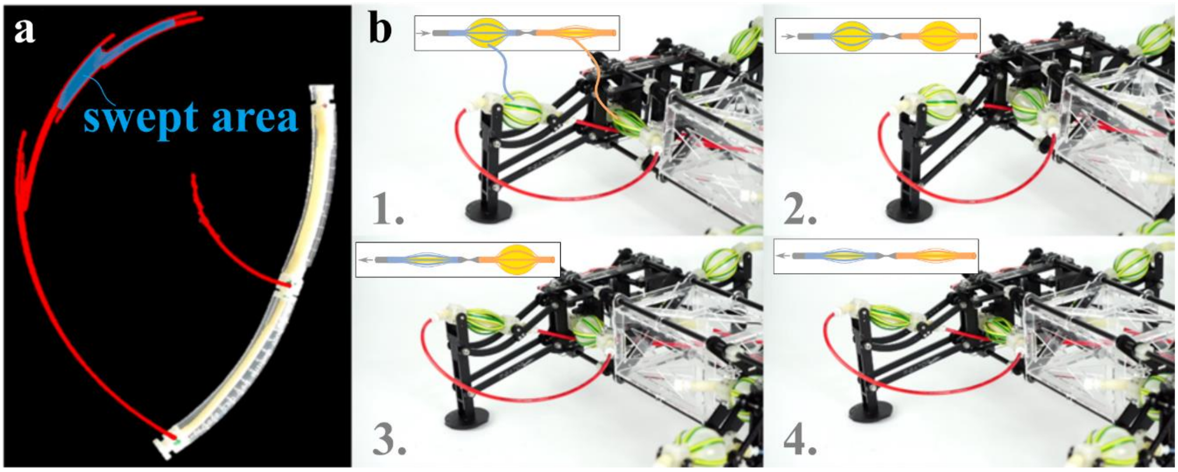

Figure 4 Soft robotic devices with morphological control of actuation sequence: a) cilium-like actuator, b) walking tetrapod

Tuning for these opposite tendencies is hard with the design of the nonlinear cilia actuators used in figure 4a.
However, the deliberate introduction of dynamic pressure drops between actuators achieves the same effect, as shown in [11]. Equation 1 then no longer holds. Instead, it becomes:

$$p_1(v_1) = p_2(v_2) + \Delta p \tag{4}$$

Δp, the pressure drop over the restrictor between the actuators, is calculated from the flow through it as demonstrated in [14]. In the most simplified model, Δp is a constant of which the sign depends on the direction of the flow. On inflation of actuator 2, Δp is positive so the required pressure at the inlet of the restrictor to snap the actuator is higher than the peak in its PV curve. The PV curve of actuator 2 therefore appears to be shifted up from the perspective of actuator 1, as illustrated in figure 3b. The opposite effect occurs on deflation.
The use of dynamic pressure drops to generate a deterministic sequence of inflations and deflations was demonstrated on a walking robot platform. The robot featured four legs, each consisting out of a rigid hinged mechanism and two inflatable actuators with a nonlinear PV curve, where all eight actuators were designed to have the same PV curve. By connecting multiple actuators together with specific flow restrictors, all actuators could be actuated in sequence to perform different gaits. Configurations with four, two and one common pressure supply line, shown in figure 4b resulted in forward motion of the tetrapod when triangular pressure signals were applied.

4. Conclusion and outlook

In this paper we reviewed recent advances in soft robotics, concerning applications of small-scale fluidic actuators and an introduction to morphological control. Minimally invasive surgery and biomimetic solutions for miniaturized devices are foreseen as the application domains where soft microrobotics is going to play a major role. However, softness in actuation also introduces nonlinearities in their input-output characteristics, making traditional control schemes difficult to implement.

Nevertheless, in the perspective of embodied intelligence, nonlinearities have to be included in the design and harnessed to augment the functionality of soft devices. As example we implemented the concept of morphological control, where a network of nonlinear soft actuators can operate in a deterministic sequence using a single input.

Morphological computing and embodied intelligence, are bio-inspired paradigms, as animals do not have a straightforward control of each single muscle in their body, but rather a low-level control that coordinates and cooperates with morphological and compliant properties of the musculoskeletal system.

In our perspective, morphological computing and soft robotics will be paramount to further develop applications where agents adapt and interact with the environment through simplified control inputs.

References

[1] Forterre Y Skotheim JM Dumals J and Mahadevan L 2005 How the Venus flytrap snaps *Nature*.

[2] Rus D and Tolley MT 2015 Design, fabrication and control of soft robots *Nature* **521** 467–475.

[3] De Greef A Lambert P and Delchambre A 2009 Towards flexible medical instruments: Review of flexible fluidic actuators *Precis. Eng.* **33** 311–321.

[4] Gorissen B De Volder M and Reynaerts D 2018 Chip-on-tip endoscope incorporating a soft robotic pneumatic bending microactuator *Biomed. Microdevices* **20** 73.

[5] Purcell EM 1977 Life at low Reynolds number *Am. J. Phys.* **45** 3–11.

[6] Gorissen B de Volder M and Reynaerts D 2015 Pneumatically-actuated artificial cilia array for biomimetic fluid propulsion. *Lab Chip* **15** 4348–4355.

[7] Milana E Gorissen B Peerlinck S De Volder M and Reynaerts D 2019 Artificial Soft Cilia with Asymmetric Beating Patterns for Biomimetic Low-Reynolds-Number Fluid Propulsion *Adv. Funct. Mater.*

[8] Pfeifer R and Gomez G Morphological computation - Connecting brain, body, and environment, in *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 2009, **5436**, 66–83.

[9] Gorissen B Reynaerts D Konishi S Yoshida K Kim J-W and De Volder M 2017 Elastic Inflatable Actuators for Soft Robotic Applications *Adv. Mater.* 1604977.

[10] Overvelde JTB Kloek T D'haen JJ a and Bertoldi K 2015 Amplifying the response of soft actuators by harnessing snap-through instabilities. *Proc. Natl. Acad. Sci. U. S. A.* **112** 10863–8.

[11] Glozman D Hassidov N Senesh M and Shoham M 2010 A self-propelled inflatable earthworm-like endoscope actuated by single supply line *IEEE Trans. Biomed. Eng.* **57** 1264–1272.

[12] Hines L Petersen K Lum GZ and Sitti M 2017 Soft Actuators for Small-Scale Robotics *Adv. Mater.* **29**.

[13] Milana E Gorissen B Volder D and Reynaerts D 2018 Design of a bi-segmented soft actuator with hardware encoded quasi-static inflation sequence *2018 IEEE Int. Conf. Soft Robot.* 108–113.

[14] Gorissen B *et al.* 2019 Hardware Sequencing of Inflatable Nonlinear Actuators for Autonomous Soft Robots *Adv. Mater.* **31** 1–7.