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# Design and characterization of soft microactuators based on interconnected pneumatic networks

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**Abstract**
This paper shows the advantages of introducing pneumatic networks in flexible bending microactuators, in terms of motion complexity and new functionalities. A bending microactuator made out of silicone rubber is designed with an embedded pneumatic network in the inner chamber to be compatible with a bonding-free fabrication process using micro-moulding. The pneumatic network is formed by wire electrical discharge grinding of a micro rod, having the negative shape of the inner chamber, which is placed in a micromilled mould. The deformation is simulated using FEM analysis and compared to a previous developed design. The microactuator is then characterized in terms of deformation vs. pressure input, showing a significant improvement in terms of bending performance. The microactuator achieves a fully curled configuration at 50 kPa, enabling the possibility of being applied as soft microgripper.

Soft robots, soft actuators, silicone rubbers, micro-moulding

## 1. Introduction

Soft robotic systems are capturing the interest of scientists and engineers due to their inherent characteristics [1]. Softness, compliancy and low cost make soft robots preferable to conventional robots in applications where delicate tasks and human interaction occur. Elastic inflatable actuators are one of the most studied components of soft robots and the variety of motions they can achieve relies on the shape and dimensions of the pneumatic networks within the structure of the actuators [2]. Extending the soft robotics concepts to the micro scale paves the way for the development of applications in fields such as minimally invasive surgery, microfluidics and bio-MEMS. Current soft microactuators are characterized by regular geometries of pneumatic chambers such as rectangles or cylinders, which limit the motion performances in bending, twisting or extension [3]. This constraint can be overcame by designing the pneumatic chamber with more intricate shapes, creating micro pneumatic networks. This paper focuses on soft bending microactuators which are fabricated with the same bonding-free micromoulding process described by Gorissen et al [4], where to make the cylindrical inner voids, tungsten carbide micro rods are placed in a micromilled two-parts mould. To introduce the pneumatic networks, the micro rod is machined using an in-house developed wire electrical discharge grinding (WEDG) process. The details about this process are described in another paper written by the same authors [5]. The pneumatic network shape is then replicated from the micro rods to the inner cavity of the microactuators. In the first section of this paper a new design of a microactuator having an enhanced bending performance is simulated with the nonlinear FEM software Abaqus and compared with the original design. Subsequently the fabrication process is described and the microactuator is eventually characterized.

## 2. Design and simulations

The proposed microactuator differs only for the shape of the pneumatic cavity, whereas the outer structure is the same as the original design developed by Gorissen et al [4]. A soft bending actuator is a 10 mm long cylinder with 1 mm diameter. The inner cavity is 8.8 mm long, with an eccentricity of 0.14 mm with respect to the symmetry axis of the actuator that guarantees the bending motion. In the original design the inner cavity was a cylinder with a constant 0.6 mm diameter. Here, the pneumatic networks are then introduced as periodic variations of the diameter of the inner chamber, corresponding to localized changes in the thickness of the membrane. The thinnest membranes experience a higher deformation under pressurization, localising the inflation and acting as compliant balloon-like joints. The pneumatic networks here developed, denoted as "saw", consist in regular pattern of two alternated (0.6 and 0.7 mm) and equispaced (0.4 mm) diameters. In this way, an array of multiple bending points is generated causing the actuator to fully curl on itself, drastically increasing the bending capability compared to the original design where the maximum achievable bending angle was 170 degrees. The new design as well as the original one are depicted in Figure 1A and 1B.

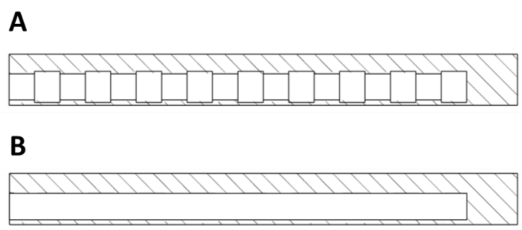


**Figure 1.** Section view of the microactuator with pneumatic network (A) and original design (B).

### *2.1. FEM simulations*

The deformation of both original and new bending microactuators is simulated with Abaqus, a commercial FEM software indicated for nonlinear problems and widely used in soft robotics. A fluid-structure interaction approach is adopted in order to have more accurate results and catch nonlinear behaviours: the inner cavity is modelled as filled with incompressible fluid and a constant fluid flow is imposed as input. Since the microactuator is made of Dragon-Skin (Smooth-On), the material properties follow an hyperelastic incompressible Ogden model ($\mu_1$=55.1 kPa and $\alpha_1$=2.82) as reported by Jandron et al [6]. The results in terms of tip trajectory are compared with the original design and plotted in Figure 2.

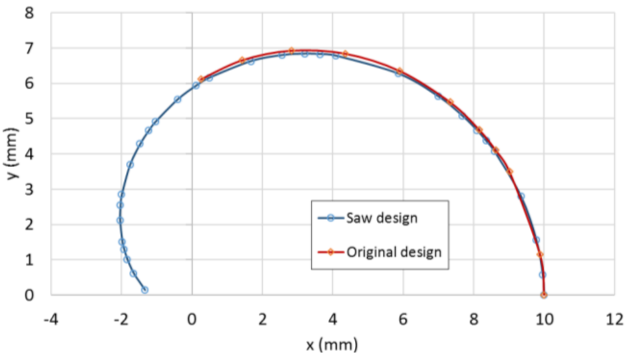


**Figure 2.** FEM-modeled tip trajectories of the new actuator ("saw"design) vs. original design.

## 3. Fabrication

The microactuators are fabricated through a micromoulding process. The mould is composed by a bottom and a top part, both micromilled. The bottom part contains a cavity where to place the micro rod, whose profile is machined by WEDG to form the geometry of the "saw" pneumatic network. The two parts are shown in Figure 3. A coating of liquid release agent (Devcon) is applied on the parts to ease the demoulding phase. Dragon Skin liquid polymers are mixed in a 1:1 ratio and poured in the mold after degassing. The mould is placed for 1 hour in an oven at 60 °C to cure. This process does not require any bonding step, which typically determines a structural weak spot, greatly improving the mechanical performances of the microactuator.

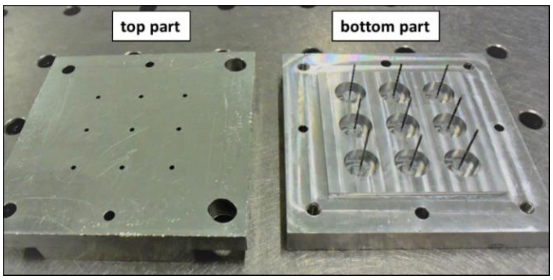


**Figure 3.** Two halves of the micromould.

## 4. Characterization and discussion

The bending microactuator is connected to a pressure source and actuated at different pressure values. Camera pictures of the deformation were taken in order to calculate the tip trajectory, as can be seen in Figure 4A. Due to the clamping, the length of the active part is shortened, thus a second FEM simulation, which takes into account the clamping, was performed in order to have a clear comparison with the experimental configuration (Figure 4B). Indeed, the microactuator exhibits an enhanced bending motion compared to the original design, in good agreement with the numeric calculations: at a pressure value of 50 kPa, the structure fully curls over itself, showing similarities with the deformation that at much larger scale characterizes soft robotic actuators. In Figure 5, the measured and simulated tip trajectories are depicted. While in the simulation all the membranes inflates in unison, in the experiment the inflation procedes gradually from the bottom to the tip of the actuator, causing the small discrepancy in the trajectory shown in Figure 4 and 5.

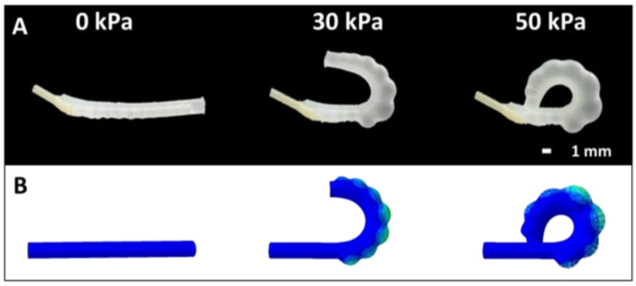


**Figure 4.** Soft bending microactuator configurations in the undeformed state, at half stroke and fully curled configuration.

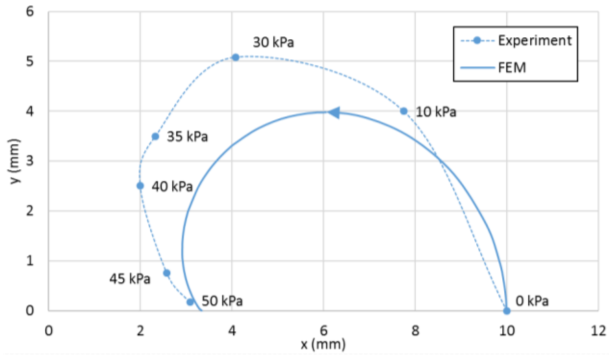


**Figure 5.** Measurements of the tip trajectory during pressurization.

## 5. Conclusion

A new soft bending microactuator, having a pneumatic network within the inner chamber, has been designed and fabricated through a bonding-free micromoulding process. Both simulations and experiments have shown that this design performs a greater bending motion compared to previous versions of such microactuators. Fully curled deformation is reached at 50 kPa, enabling the device to be adopted as microgripper in future works. The micro pneumatic network approach strongly relies on the process developed within the same research group of wire electrical discharge grinding of micro rods, which enables the shaping of the inner chambers of microactuators compatibly with a bonding-free process. This technique open doors to future designs that envision such motions as curling of microtentacles and multiple-points bending, permitting the development of more complex soft microrobotics devices.

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