A bistable pneumatic actuator based on flexible metamaterials

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Abstract

In this work, we combine the programmable mechanical response of flexible mechanical metamaterials with pneumatic actuation, with the aim of constructing soft machines with mechanically programmed actuation patterns. We design and fabricate flexible metamaterials that undergo snap-through instabilities under tension, enabled by the unit cell comprising double-clamped curved beams. Specifically, we test snapping metamaterials with cylindrical topologies, each composed of a repeating array of four unit cells along the circumferential direction. These metamaterials are fabricated using FDM 3D printing with NinjaFlex filament (TPU 85A), and their nonlinear mechanical response under tension is characterized using a uniaxial testing machine. We design a linear actuator by coupling the flexible metamaterial with a pneumatic single-acting cylinder, thereby placing the nonlinear elasticity of the metamaterial in parallel with the piston. The actuators are characterized in terms of their snapping pressures using a measurement setup comprising a motorized syringe pump for controlled inflation and a pressure sensor.

1 Introduction

Future robots are expected to operate in highly unstructured environments, where unforeseen interactions with the external world may occur, or even be necessary. This presents challenges to current control algorithms, which need to possess a consistent level of adaptivity. Conversely, adaptivity appears easy and natural for the biological organisms that abound in our world. The adaptivity of biological organisms arises from the intelligent use of the physical properties of their bodies, a crucial aspect enabling them to embody low-level control schemes and thrive in unstructured environments [1].

Inspired by this concept, a paradigm shift is underway in robotics, where control schemes are not solely programmed within the high-level abstraction of algorithms but are also embodied into the physics of the materials used to construct the hardware [2]. This shift is particularly evident in the field of soft robotics, where traditional control schemes struggle due to the infinite parameters of their configuration space [3]. However, the complex mechanics of soft robots, while challenging from an algorithmic perspective, can offer advantages from a physical standpoint.

Many mechanical nonlinearities present in soft materials have been utilized to achieve functionalities that would otherwise require numerous bulky and rigid components, such as solenoid valves, pumps, compressors, and microcontrollers. Soft valves, utilizing snapping membranes as mechanisms [4], [5], can induce pneumatic self-oscillation and incorporate fluidic logic gates to generate fluidic digital circuits [6]. Such circuits have been employed to control the walking gait of soft robots in open-loop configurations [7]. One advantage of the high deformability of soft materials is the ability to create monolithic mechanisms that do not require component assembly and can thus be easily 3D printed. Recently, an entirely soft robot, including its self-oscillatory pneumatic logic circuit, has been fully designed and printed as a single piece [8]. Beyond self-oscillation and logic, the mechanical nonlinearities of soft materials have been harnessed to implement another type of control scheme: sequential actuation. Many snapping inflatable actuators—actuators with a non-monotonic response—can be interconnected to the same pressure supply in an underactuated configuration and driven in a discrete sequence. This is achieved by designing each actuator with different snap-through pressure thresholds or by implementing flow restrictors between actuators to generate pressure drops. This method can generate underactuated motion asymmetries (e.g., metachronal waves [9] or walking gaits [10]) or even complex sequential patterns (e.g., playing a melody [11]).

This work is situated in such a context and presents preliminary results towards a new design of a semi-soft pneumatic actuator, which leverages the nonlinearities of flexible mechanical metamaterials [12]. The objective is to explore the large design space of mechanical metamaterials and their fabrication space in terms of 3D printing parameters, such as infill density and geometry, which can impact the mechanical characteristics. By expanding the design and fabrication space of nonlinear soft actuators, more complex control schemes can be integrated into soft robotic systems.

In particular, we focus on mechanical metamaterials that exhibit bistability. We realize a bistable semi-soft actuator by placing a bistable metamaterial in parallel with a single-acting pneumatic cylinder. We first introduce the design of the metamaterial and its assembly into an actuator, and describe the manufacturing process, as well as the experimental setups. Furthermore, we present and discuss the results obtained from the mechanical characterization of the metamaterials, as well as the pressure snapping points characterization of the bistable actuator.

2 Design and Fabrication

2.1 Snapping metamaterial with cylindrical topology

The design of the semi-soft bistable actuator consists of a mechanical metamaterial with a cylindrical topology placed in parallel to a single-acting cylinder used in entertainment toys (Lego Technic pneumatic piston). The low force required to deform the metamaterial (< 5N) makes the “toy” piston a suitable actuator for the scope of this research. The cylinder’s chamber has a cross-section area of 26.45 mm^2.

The key requirement for the metamaterial is to exhibit a non-monotonic force-displacement curve under tension, which means it undergoes a snap-through instability when a local force peak is reached, switching between two stable configurations (bistability). We opt for a flexible metamaterial composed of a unit-cell made of double-clamped curved beams. Such beams have a snapping transition analogous to the von Mises Truss. This family of flexible non-linear metamaterials have been already reported by several authors [13], [14], [15], [16]. To have a symmetric design, we adopt a cylindrical topology composed of an array 1x4 of unit cells and placed the single-acting cylinder in the middle, so that the axis of the metamaterial and the piston coincide. In this way, the force is exerted in the middle point of the cross-section, avoiding bending deformations of the metamaterial.

The curved beams are parametrized using the trigonometric function $y(x) = h/2[1 - \cos(2\pi x/l)]$ in the interval $[-l/2,0]$, as reported in [17]. The design parameters are reported in Table 1 and depicted in Figure 1A. The other subfigure (1B) displays the 3D design of the metamaterial, where we additionally increase the wall height of 10 mm above and below the architected structure to improve mechanical stability. The overall size of the metamaterial is 34 mm in height and 37 mm in diameter.

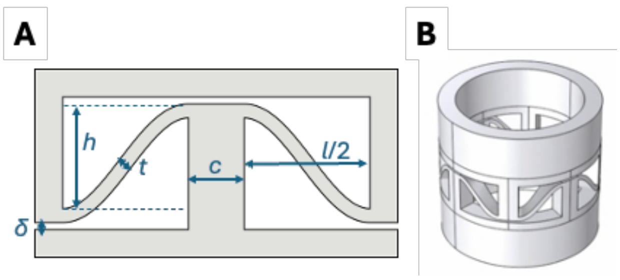

Figure 1. A) Design parameters of the metamaterial unit cell in plane. B) CAD design of the final metamaterial with cylindrical topology.

2.2 Fabrication process

The flexible metamaterials are fabricated via FDM 3D printing (Prusa MK4) using flexible TPU filament (NinjaFlex TPU Shore 85A from NinjaTek). The sample is printed with the cylinder axis of the metamaterial perpendicular to the print bed, using support of the same material, which is subsequently cut out. We use honeycomb infill geometry and print samples with two different infill density (40% and 80%) to check whether the infill density influences the snapping force thresholds. As the curved beams are only 1 mm thick, the infill density only affects the mechanical properties of the thicker support beams and walls. Figure 2A shows a picture of metamaterial in the two stable states.

Additional holders to assemble the metamaterial with the piston are printed using PLA. Figure 2B depicts the components of the assembly of the bistable actuator.

Parameters	Dimensions (mm)
l	18
c	4
t	1
h	7.5
δ	0.5

Table 1. Dimensions of the unit cell

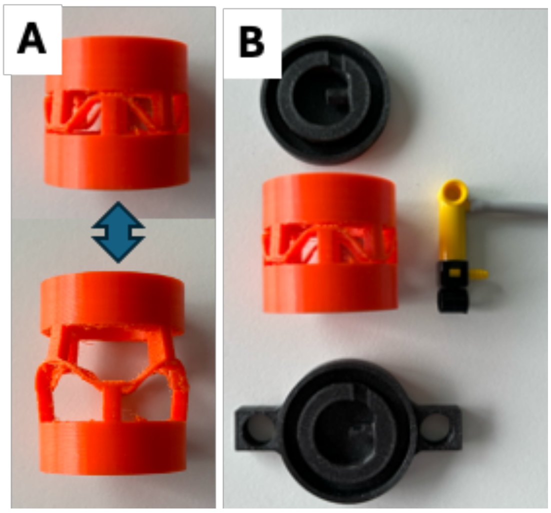

Figure 2. A) Metamaterials in the two stable states. B) Components of the bistable actuators: metamaterial, single-acting cylinder, and holders.

3 Experimental setups

3.1 Force-displacement test

The metamaterials are tested under tension using a universal testing machine (zwickiLine from ZwickRoell, with load cell 50 N). The test consists in a prescribed linear displacement of 15 mm to ensure the tests finish in the post-snapping configuration and a return travel back to the starting position. In the full experiment the test is cycled 5 times at a displacement rate of 30 mm/min.

3.2 Pressure snapping test

The bistable actuators, composed by assembling in parallel the metamaterial and the piston, are characterized in terms of snapping pressure. The setup consists of a motorized syringe pump driven by a stepper motor (NE-501 OEM Syringe Pump from KF Technology) to generate a controlled air compression in the actuator and a pressure sensor (DRMOD-I2C-R6B for positive pressure and DRMOD-I2C-RV1 for negative pressure from B+B Thermo-Technik GmbH) in between the actuator and the syringe to measure the pressure. The data from the pressure sensor are acquired with an Arduino Uno board.

4 Results and discussion

The results of the characterization of the mechanical metamaterials are depicted in Figure 3. Both samples have a clear non-monotonic force displacement curve, and the snapping thresholds can be accurately determined. All curves cross the zero-force line, which indicates that both samples are consistently bistable over the multiple cycles. As expected by soft materials, large hysteresis loops form during the loading-unloading cycle.

We refer to the positive force peak of the loading cycle as the snap-through point, where the transition occurs from the designed configuration to the metastable. We call snap-back point the force valley of the unloading cycle, where the sample goes back into the original configuration. We observe that the sample with 80% infill density has ~30% higher snap-through, and ~60% higher (in absolute values) snap-back points compared to the one with 40% infill density. As mentioned, the infill density only affects the stiffness of the support structures of the metamaterial, as the thin curved beams are completely filled by the few layers of TPU. Nevertheless, the support stiffness significantly affects the snapping points due to changes in the boundary conditions of the thin beams.

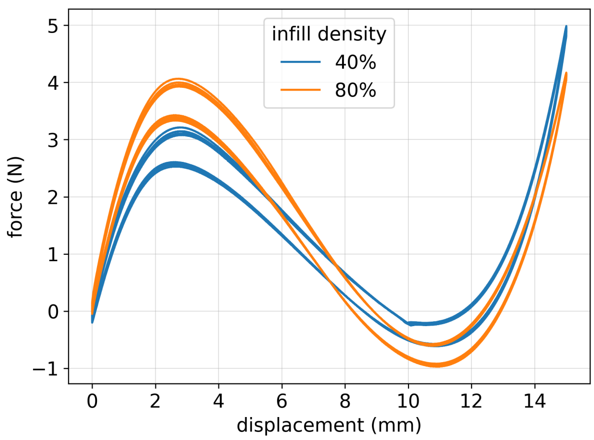

Figure 3. Force-displacement curves of the metamaterial with infill density 40% and 80%.

Further, considering the cross-section area of the piston's chamber, we compute the snap-through and snap-back forces into pressures and compare them with the pressure thresholds measured in the pressure snapping test. The results are reported in Figure 4. The calculated expected values align with the measured values. The slightly higher

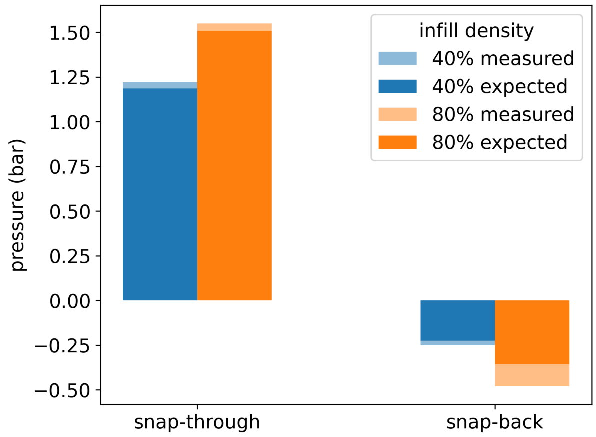

Figure 4. Snap-through and snap-back pressures of the actuators featuring the metamaterials with infill density 40% and 80%, both measured and expected from the force-displacement curves.

measured values can be attributed to friction in the piston and viscous losses in the tubing.

Our bistable actuator behaves as follow; when the piston is pressurized, a normal force is exerted on the metamaterial. If the force exerted by the piston is below the snap-through point, the displacement of the actuator is minimal and the elasticity of the metamaterial drives back the piston when the cylinder is depressurized, acting as a linear spring. However, when the force exceeds the threshold, the metamaterial snaps and the actuator has a quick and large displacement. As the metamaterial is bistable, the actuator remains in the metastable configuration (Figure 4B) even when the piston is depressurized, and an external force or negative pressure is needed to snap the back to the initial state (Figure 4A).

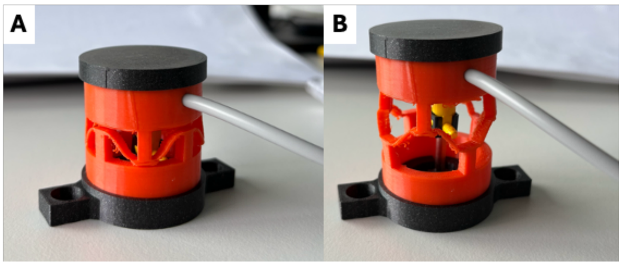

Figure 4. The bistable pneumatic actuator in the two stable configurations: the designed (A) and the metastable (B) ones.

5 Conclusion

These preliminary results demonstrate that it is possible to realize bistable and in general nonlinear actuators by harnessing the large design opportunities offered by 3D printed flexible mechanical metamaterials. We also show that for a fixed geometry, the snapping pressure thresholds can be tuned by the infill density chosen during the printing process, offering new strategies for tuning nonlinear mechanical response of soft actuators.

Next steps will include replacing the rigid piston with a soft inflatable segment, to have an entirely soft bistable actuator. At this stage, the selection of the single-acting cylinder was driven by the absence of a spring or elastic reaction inherent in this type of actuator. In contrast, typical soft inflatable extending actuators, typically made of rubber, possess their own intrinsic elastic reaction, which combines with the elastic reaction of the metamaterial. This cumulative stiffness tends to linearize the overall system response, counteracting the bistable effect we aim to achieve. Therefore, further research is necessary to develop zero-stiffness inflatable soft segments that do not compromise the nonlinearity of the metamaterial. Promising work goes towards wrinkled pouches [18].

Further, we will implement multiple nonlinear actuators in a single fluidic circuit, to generate physically controlled motion sequences in soft robotic systems.

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6 Literature

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