Finite Element Analysis of Asymmetric Inflatable Snapping Actuators

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Abstract

Snapping structures are widely used in soft robotics due to their ability to store and rapidly release elastic energy, enabling fast actuation and mechanically encoded behaviors. However, most existing snapping structures are designed symmetrically, while asymmetric snapping motion has received relatively limited attention. This work presents a finite element analysis of asymmetric inflatable snapping actuators (AISA) capable of generating controllable asymmetric snapping motion through an eccentric dome design. By introducing a geometric offset into a conventional snapping shell, the actuator exhibits directional snapping trajectories during inflation and deflation. Finite element simulations based on a fluid–structure interaction framework were conducted to investigate the influence of shell depth and eccentricity on the snapping behavior. The results show that appropriate combinations of geometric parameters enable stable asymmetric trajectories, while excessive or insufficient asymmetry leads to unstable deformation or numerical instability. The proposed actuator demonstrates a simple mechanical approach for achieving programmable asymmetric motion in soft pneumatic systems without additional electronic control.

1 Introduction

Soft robotics is advancing rapidly thanks to innovations in materials, design tools, and fabrication techniques. However, most existing systems still rely on bulky, tethered components such as valves and pumps, which limit their autonomy. In contrast, many biological organisms embed physical intelligence directly within their bodies, where geometry and material gradients naturally govern deformation and motion without centralized control [1]. Inspired by this concept, integrating physical control into soft robots offers a promising route toward compact, autonomous, and self-regulated systems.

One promising strategy for achieving physical control is the use of snapping structures [2]. Snapping structures can store elastic energy and release it rapidly once a critical threshold is exceeded. Common examples include curved beams and domes. Such mechanisms are particularly attractive for physical intelligence because they exhibit clear state transitions during actuation, analogous to binary states in computation, and can also introduce time delays that enable sequential behaviors. Through careful geometric design, snapping structures can therefore be programmed to achieve specific mechanical responses and functionalities.

Extensive research has explored this concept. For instance, Gorissen et al.[3] developed an inflatable jumping robot utilizing a simple snapping shell, achieving a jumping height of 42.9 mm independent of actuator size. Similarly, Comoretto et al.[4] integrated mechanofluidic memory into soft robots, using bistable snapping behavior to realize autonomous switching without electronic control. These studies demonstrate that snapping mechanisms can serve diverse functions in soft robotic systems, ranging from rapid actuation to embodied physical control.

Despite significant attention on energy storage and release in snapping structures, the asymmetric motion occurring during snapping transitions has been less explored. Most snapping structures are designed symmetrically, consisting of two identical sides. When an actuation force is applied, elastic energy is distributed and stored symmetrically within the structure. [5, 6]Once the applied force exceeds the snapping threshold, the structure loses stability and rapidly transitions to another state, releasing the stored energy. In practice, however, the two sides can never be perfectly identical, resulting in slight asymmetries during the snapping process. Consequently, one side often becomes mechanically weaker, leading to asymmetric snapping motion. To intentionally amplify this behavior, researchers have introduced geometric asymmetries such as localized cuts, thickness gradients, and offset curvatures, which help guide the snapping direction.

For example, Li et al.[7] demonstrated a semi-open elastomeric dome with a T-shaped cut that consistently snapped in a preferred direction under pneumatic pressure. Luo et al.[8] developed a multistable soft actuator in which internal asymmetries induced mixed-mode snapping between stable states. Bell et al.[9] introduced a thickness gradient into a bistable snapping shell to create an asymmetric snapping actuator, enabling mechanically programmed complex locomotion gaits under periodic fluidic actuation. These studies highlight the potential of geometric asymmetry in controlling snapping direction and motion.

In this work, we focus on the design of an actuator with a controllable asymmetric snapping direction. We first de-

veloped an inflatable snapping actuator with asymmetric geometric features and systematically investigated the influence of different design parameters on the snapping trajectory. The fabrication process is presented, and numerical simulations are conducted to analyze how various parameters affect the snapping behavior. Finally, we discuss potential applications of the proposed actuator.

2 Design and Simulation

2.1 Design of AISA

Inspired by the work of Van Raemdonck et al.[10], who developed an inflatable snapping shell with tunable snapping behaviors through geometric modifications, we designed an asymmetric inflatable snapping actuator (AISA) consisting of a sealed chamber and a functional snapping shell made from Silicone(Smooth-Sil 950). During inflation, the snapping shell responds to the internal pressure variation within the chamber. Specifically, an eccentric dome design is adopted to achieve asymmetric snapping behavior. Specifically, asymmetry is introduced by shifting the center of the dome by a prescribed offset distance, thereby weakening one side of the shell geometry (**Figure 1**).

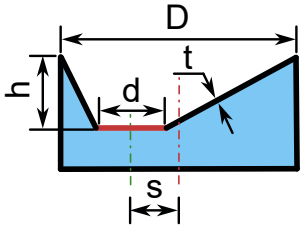

Figure 1 Structure design of AISA

Due to the eccentric design, one side of the shell possesses a larger effective contact area than the other. Consequently, the pressure-induced deformation on the larger side becomes more pronounced. During inflation, the larger side of the shell (the right side in this study) responds first and rises earlier, causing the center region of the shell to tilt toward the left. As the internal pressure further increases, the opposite side also deforms and rises, gradually restoring the center region to a horizontal configuration. During deflation, a similar but reversed process occurs. The right side collapses first, followed by the left side, resulting in the center region first tilting toward the right before returning to the horizontal state. Therefore, within a complete inflation–deflation cycle, the shell sequentially undergoes four distinct states: tilted left, horizontal, tilted right, and horizontal again. This shows the asymmetric nature of the snapping transition. More details on design, fabrication and integration of these actuators in a soft robotic walker can be found in [11].

The geometric parameters associated with the eccentric design strongly influence the asymmetric snapping trajectory. To investigate these effects, the dome depth and eccentric offset are tuned to generate different shell configurations. The detailed geometric parameters are summarized in (**Table 1**).

Table 1 Geometric parameters of AISA

Parameter	Symbol	Value(mm)
Shell height & Eccentric offset	h & s	1.6 & 2.2 3.0 & 2.0 3.4 & 1.0 4.0 & 3.0
Tip diameter	d	3.0
Shell diameter	D	10.0
Shell thickness	t	0.2

2.2 Finite element simulations

A numerical simulation of the inflation–deflation process was conducted in *Abaqus/CAE 2025* using a fluid–structure interaction (FSI) framework with a `*FLUID CAVITY` definition. A dynamic implicit analysis was performed to capture the deformation evolution under controlled volumetric loading and to evaluate the corresponding pressure–volume response.

The membrane was modeled as a Neo–Hookean hyperelastic material [12, 13] with shear constant $C_1 = 0.34$ MPa. Rayleigh damping was introduced with coefficients $\alpha = 0.0001$ and $\beta = 0.0001$ to suppress numerical oscillations. Both the inflation and deflation stages lasted 1 s, using a Dynamic, Implicit step with nonlinear geometric effects enabled. The time increment was limited between $\Delta t_{\min} = 1 \times 10^{-5}$ s and $\Delta t_{\max} = 1 \times 10^{-4}$ s.

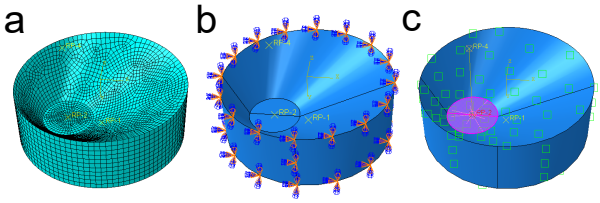

Figure 2 a) Mesh model of the AISA. b) Boundary conditions and constraints applied to the model. c) Bonding of the tracking point.

A prescribed fluid flux was implemented through the `*FLUID FLUX` function to apply a ramp volumetric flow rate with a peak value of 0.4 mL s^{-1}. **Figure 2**(a) shows the mesh configuration of the actuator model. The structure was discretized using S4R reduced-integration shell elements with a global mesh size of approximately 0.3 mm. To reproduce the experimental boundary conditions, the base plane was fully constrained as a fixed boundary condition, as illustrated in **Figure 2**(b). In addition, a 5 mm support bar was tied to the central plane of the actuator to amplify the snapping displacement during deformation, as shown in (**Figure 2**)(c).

3 Results

We conducted simulations on models with different parameter combinations under identical loading conditions. The results show that the snapping trajectories vary significantly with changes in shell geometry and eccentricity.

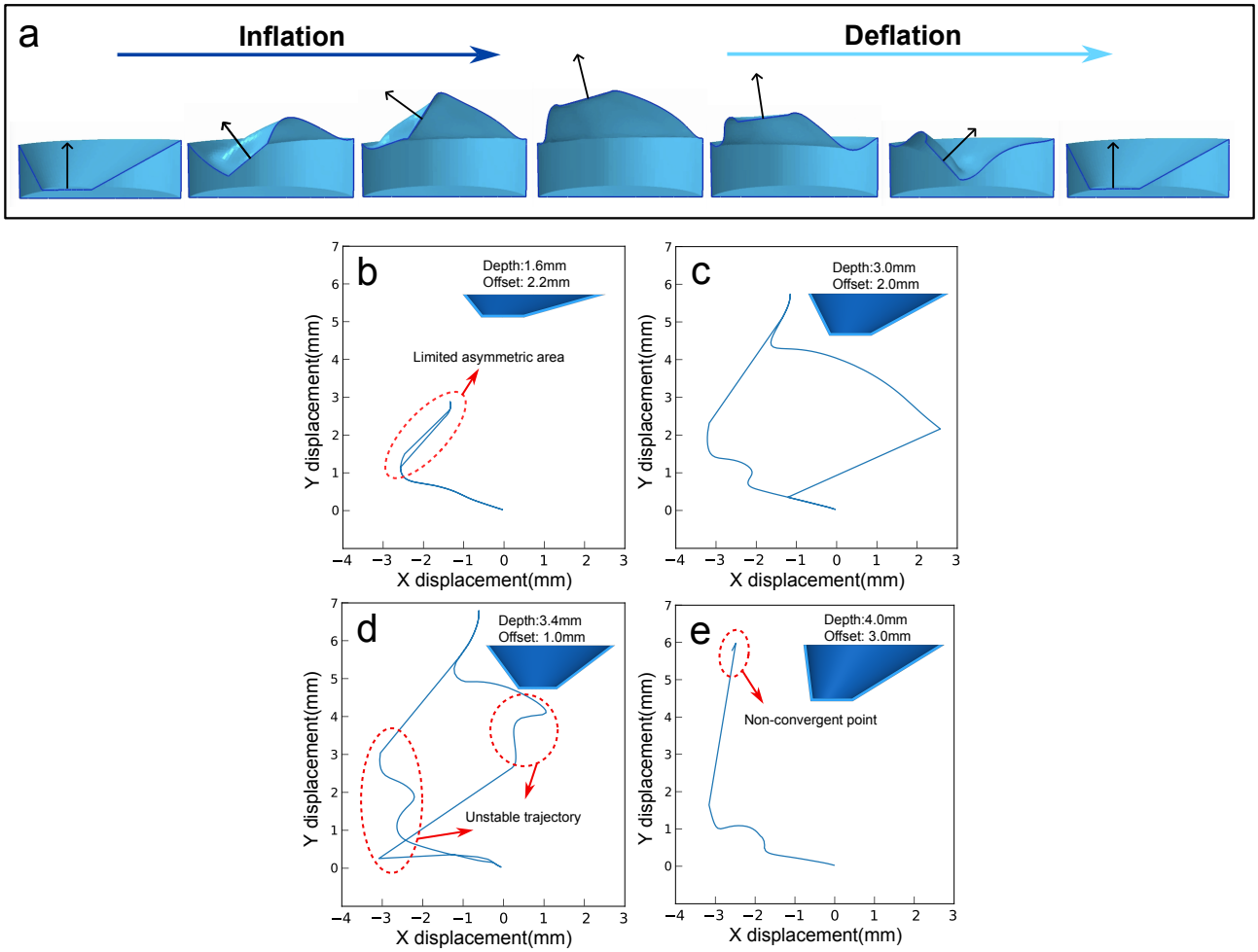

Figure 3 a) Illustration of asymmetric snapping during inflation–deflation cycle. b) Simulated trajectory for the parameter combination of 1.6 & 2.2. c) Simulated trajectory for the parameter combination of 3.0 & 2.0. d) Simulated trajectory for the parameter combination of 3.4 & 1.0. e) Simulated trajectory for the parameter combination of 4.0 & 3.0.

As shown in **Figure 3**(a), the complete inflation–deflation cycle of asymmetric snapping is illustrated. The black arrow represents the normal vector of the shell center, clearly demonstrating the asymmetric snapping behavior throughout the cycle. The figure also shows how the left and right sides of the shell experience different loading conditions during the cycle, ultimately resulting in asymmetric motion.

As shown in **Figure 3**(b), the parameter combination **1.6&2.2** corresponds to a shallow shell with a relatively large eccentricity. Under this condition, the overall trajectory appears nearly symmetric rather than asymmetric. Nevertheless, a small asymmetric region can still be observed during the snapping process. This indicates that the eccentric loading effect is still present. However, because the shell depth is too small, the available deformation space for asymmetric motion is limited, preventing the asymmetric behavior from fully developing.

In **Figure 3**(c), the parameter combination **3.0&2.0** produces a deeper shell while maintaining a large eccentricity. In this case, the actuator exhibits a stable and well-defined asymmetric trajectory. The increased shell depth provides sufficient deformation space during snapping, allowing the eccentric geometry to effectively guide the asymmetric motion throughout the inflation–deflation cycle.

As shown in **Figure 3**(d), the parameter combination **3.4&1.0** still generates an asymmetric trajectory, but the motion becomes noticeably unstable. Although the shell remains relatively deep, the eccentricity is much smaller and closer to a symmetric configuration. As a result, the geometric difference between the left and right sides is insufficient to fully dominate the snapping direction. During the snapping process, the elastic energy alternates between the two sides of the shell, leading to oscillatory left–right motion in the trajectory. Despite this instability, the remaining eccentricity still introduces an overall asymmetric tendency.

In **Figure 3**(e), the parameter combination **4.0&3.0** results in a non-converged simulation. Under this configuration, the shell is both very deep and highly eccentric. Although such geometry would theoretically enhance asymmetric snapping, severe local buckling occurs during deformation. Specifically, the left side of the shell becomes nearly perpendicular to the boundary. As the right side rises during inflation, the left side can no longer deform smoothly and instead undergoes local buckling until the snapping threshold is reached, after which it rapidly jumps upward. This behavior produces the sharp discontinuity observed in the

trajectory. During deflation, the right side collapses first, while the left side buckles again under compression. Because the right side simultaneously pushes the structure laterally, the buckled left side bends further toward the left, causing excessive deformation and ultimately leading to numerical instability in the simulation.

4 Conclusion

In this work, an asymmetric inflatable snapping actuator (AISA) was proposed to investigate asymmetric snapping behavior in soft pneumatic structures. By introducing an eccentric dome geometry into a conventional snapping shell, controllable asymmetric motion was successfully achieved during the inflation–deflation cycle. Unlike conventional symmetric snapping structures, the proposed design exhibited asymmetric snapping trajectory.

Finite element simulations based on a fluid–structure interaction framework were conducted to analyze the influence of geometric parameters on the snapping behavior. The results demonstrated that both shell depth and eccentricity play critical roles in determining the trajectory characteristics. Shallow shells limited the available deformation space and suppressed asymmetric motion, while insufficient eccentricity led to unstable oscillatory behavior. In contrast, an appropriate combination of shell depth and eccentric offset enabled stable and repeatable asymmetric snapping trajectories. Excessive depth and eccentricity, however, introduced severe local buckling and numerical instability during deformation.

The study shows that geometric asymmetry can effectively guide snapping direction and deformation evolution in inflatable soft actuators. The proposed actuator provides a simple and fully mechanical approach for generating directional motion without relying on additional control systems or electronics. These findings offer a potential strategy for developing physically intelligent soft robotic systems with programmable motion behaviors, and may inspire future applications in soft locomotion, adaptive structures, and mechanically encoded control systems.

5 Acknowledgment

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