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Programmable multistable soft grippers

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Abstract— **Soft robots have attracted significant interest due to their capability to interact, adapt and reconfigure in response to external stimuli. Due to their low modulus constitutive materials, intrinsic safety is embedded in softrobots, allowing them to perform tasks that are nearly impossible with rigid counterparts. Nevertheless, the resulting highly nonlinear response of such materials renders the kinematical prediction and control of soft robots challenging, ofter requiring sophisticated sensing and processing state processing algorithms. Leveraging multistability offers exciting opportunities to encode several stable states of soft robots, ultimately simplifying the actuation and control problems. We present a pneumatically actuated soft gripper with encoded multiple stable states that provide a route to shape reconfiguration without closed-loop control. Informed by the mechanics of hierarchically multistable metastructures, we design coexisting states resembling different actuation modes in soft manipulators, including grasping and twisting. This is achieved by leveraging distinct path-dependent inversion sequences to access desired coexisting states on-demand. Our strategy offers a new route for controlling soft multistable robots exploiting their strong nonlinear mechanics to the designer's advantage.**

I. INTRODUCTION

Soft robotics is concerned with the implementation of soft and compliant structures into robotic design [1], largely motivated by the success of biological systems in using compliance to facilitate complex interactions [2]. Soft robots have been developed for a multitude of applications including minimally invasive surgery [3], physical rehabilitation [4, 5], locomotion in different media [6], and industrial parts handling [7]. In particular, soft robotic grippers attain their functionality by leveraging, mainly, global bending-based deflections resulting from local material stretching. This global bending results from the interaction between straining and strain-limiting layers [3, 8, 9]. Pneumatics and hydraulics are the most common means of actuation for soft robots [5, 10, 11]; however, alternative technologies driving kinematic reconfiguration include electroactive polymers [12], thermally responsive materials [13], magnetically responsive infills [14], and variable-extension driven cables [15, 16]. Many of these actuation methods maintain an actuated or deformed state via a constant energy input or by storing energy at a system level. Constant energy inputs take the form of applied voltage and applied magnetic field. [11, 12, 14]. Energy storage is often achieved using storage mechanisms that are separate from the robot itself, e.g., fluidic valves, locking motors, which may increase the complexity and reduce the robustness soft robots [5, 17].

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The use of body compliance is a defining characteristic of soft robotics. This dramatically increases the number of degrees of freedom for the soft robots—effectively rendering them infinite. The infinite dimensionality of soft robots both facilitates complex interactions with the environment and other agents, but also increases their complexity in terms of actuation and control [6, 7]. This trade-off implies that soft robots are inherently underactuated, and underactuation thus constitutes an obstacle to simplified and reliable implementations of control. These problems can be improved upon by introducing multistable structures into soft robots [18–21]. The existence of multiple global states allows for simplified control wherein predictable kinematical configurations are naturally attained, offering a route to reduced control effort..

In light of the aforementioned challenges and the benefits of leveraging multistability in soft robotics, bistable shells have become an increasingly popular feature in soft technology. Bistable shells are a key component in soft pneumatic oscillators [22], soft digital logic gates [23], and soft binary memory storage devices [24]. Furthermore, these structures have been shown to offer possible means of soft robotic locomotion [25] and fast motion in soft devices [26].

This work presents the design, numerical simulation, and testing of a pneumatic soft gripper with path dependent global stable states. We build from dome patterned metastructures described in our previous work [20], which exhibit multiple strain energy minima due to interactions between neighboring dome-shaped bistable shells. We utilized bistable domes as our building block to construct a multistable soft gripper that retains the mechanical response of the original structure but can be pneumatically actuated to achieve its different global coexisting stable states. To obtain a satisfactory gripper topology, the Finite Element Method (FEM) is used to analyze the influence of specific geometric parameters on gripper behavior. We optimize these parameters for grasping, local finger-twisting, and global gripper rotation. Finally, we qualitatively validate our results by 3D printing the final topology using thermoplastic polyurethane (TPU) and comparing the path-dependent multiple stable states and their associated grasping capabilities.

II. MULTISTABLE SOFT ROBOT CONCEPT

Soft grippers are generally designed to adapt to objects of different shapes, textures, and various external stimuli, by exploiting their compliant capabilities and their capability for large morphology reconfiguration. Conventional pressurized soft actuators/grippers are mainly designed such that bending motion is generated upon chamber pressurization [17, 27–29]. Deformation is caused by the incompatibility between

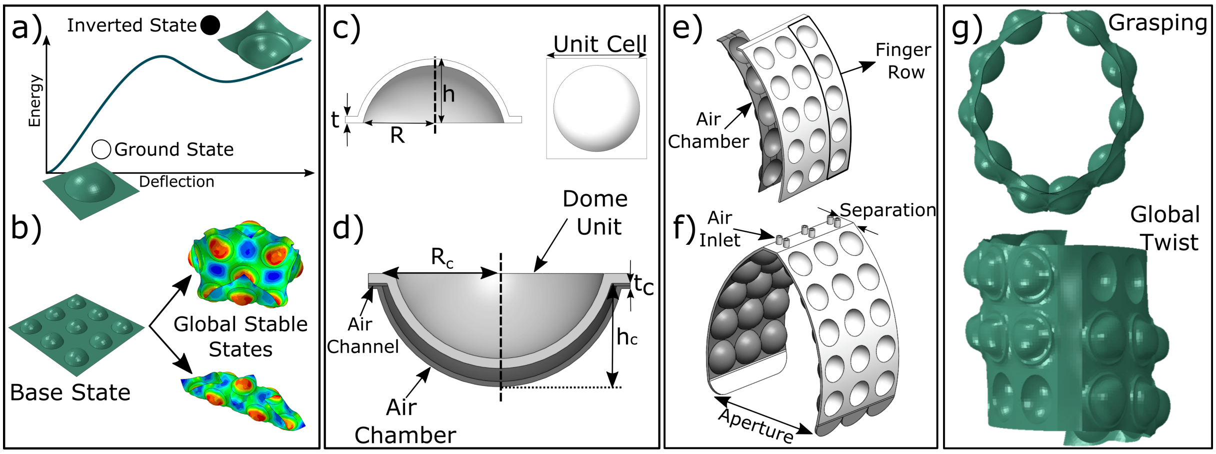

Fig. 1. Multistable softrobot concept, gripper topology, and the integration of bistable dome unit cells to soft gripper topology. a) Schematic representation of the Bistable behavior of dome unit cell. b) Dome patterned metasheet and its global coexisting stable states when all unit cells are inverted. c) Dome unit cell geometry and most relevant parameters for bistability. d) Actuation pressurized air chamber for a single unit cell and its geometric parameters. e) Soft finger geometry based on dome patterned metastructure and individual air chamber. f) Soft gripper topology composed of two soft fingers. g) Expected grasping and global twisting behavior for the soft gripper topology when different number of units are inverted.

the actuated chambers and a strain-limiting layer, which results in large gripper curvatures, highly limiting the robot response to one type of deformation. Furthermore, the material nonlinearities inherent to the soft constitutive materials used in soft robots renders the actuated state kinematic estimation challenging to predict, measure and control [30].

Incorporating multistable structures into soft robotics provides new advantages to overcome some of the limitations of the conventional designs by encoding multiple stable states [20, 21, 31]. We base our design on metasheets with units that can be reversibly inverted (Fig. 1a). This results in programmable multistable shapes and tunable mechanical responses [21] at the global scale generated due to the local prestress (Fig. 1b). We adapt this metasheet structure to a gripper topology, incorporating a 2D array that allows for interactions and stabilities beyond those demonstrated in our previous work [20]. Specifically, the design presented here departs from our previous work which maps a single row of domes to a bistable gripper architecture. Here we introduce an encapsulation comprising two connected metasheets that yields multiple stable states Figs. 1g), including some featuring the hierarchical multistable characteristic entailing different global morphology for the same pattern of inverted local units. Furthermore, hierarchically multistable configurations (i.e., coexisting states) are accessed depending on the order of unit inversion, thus showing a loading path-dependence that enables encoding many more than 2^N stable states (see Ref. [20] for details). This robotic morphology amplifies the utility of both metasheets and grippers by expanding the number of programmed inherently stable states and associating each configuration to a functional gripping morphology. We create a chamber per row of domes to facilitate pneumatic actuation (Fig. 1d and Fig. 1e) to individually invert each row of the patterned metasheet, while retaining the hierarchical multistability and order dependency of the metastructure. With our novel soft gripper topology we can encode different levels of grasping and grasping+twisting stable configurations (see Fig. 1g). By combining the robot's mechanical response and actuation system, we create an underactuated soft gripper that can achieve different stable configurations dictated by order of actuation and the number of actuated rows, thus encoding in the topology both the programmed shape and control.

III. SOFT GRIPPER TOPOLOGY

Gripper topology was motivated by our previous works [20, 31], and the objective to encode different coexisting stable states accessible by specific dome inversion sequences. We selected a five-by-three dome arrangement (Fig. 1e), as it can achieve both twisting and bending stable configurations. Every finger row comprises five concave bistable domes (Fig. 1c) that can be inverted by applying constant pneumatic actuation, while retaining their inversion state once the pressure is removed. To exploit the order-dependentce, we isolated each finger row by adding individual pressurized chambers (Fig. 1e) that can be actuated separately and promote different stable states of the gripper. Each finger row features an air chamber (Fig. 1e) based on a dome-like geometry with a 0.2 mm $\times$ 6 mm air channel that allows pressure to reach all domes. Each finger (dome array + air chambers) is 3D printed as a single piece to avoid leakage upon dome actuation (See Movie 1 [32] for details). To optimize our topology, the gripper was analyzed by dividing it into different sub-systems that can be decoupled and optimized without compromising its overall behavior. We started by analyzing one soft finger with multiple chambers to maximize grasping and twisting capabilities (see subsection III-B). By decoupling the system, we can reduce the total computation time and gain insight towards expanding this topology into more complex systems that uses the soft finger as its building block. After the best finger is found, we utilize this as our base to construct a two-finger soft gripper morphology retaining the building block's capabilities. Furthermore, the two-finger design promotes interaction between each half to generate more complex global morphologies, such as to achieve global twist. Every topology was analyzed using FEM (subsection III-A) and optimized to deliver different gripping configurations.

A. FINITE ELEMENT SIMULATIONS

FEM simulations of the soft finger and gripper were performed using commercial software ABAQUS. Different surface bodies are used to consider the gripper and the air chambers as separate entities, which are meshed using S4R shell elements with constant thickness. Frictionless surface-to-surface contact condition between all chambers and the dome array is implemented to avoid overlap. Bounding between the chambers and the dome array was simulated using tie interaction boundary conditions to couple the degrees of freedom of the chamber boundary to its corresponding finger row.

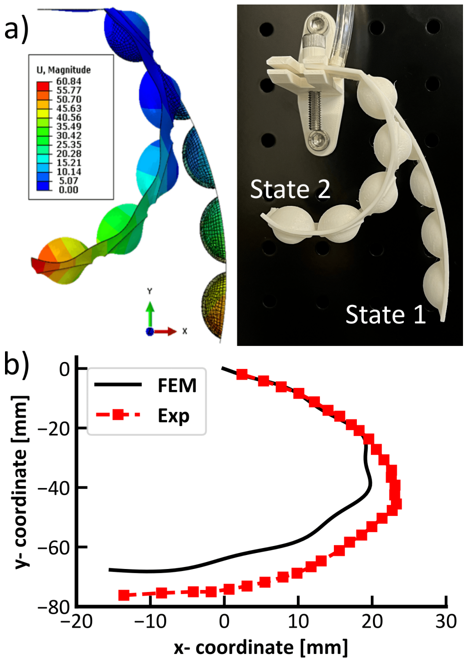

Fig. 2. Quantitative comparison between the experimental bistable strip and finite element simulations with a linear elastic model. a) Numerical and experimental stable shapes obtained after inverting all the domes in the strip. b) Final shape comparison between simulated and experimental data.

A quasi-static dynamic implicit analysis with geometric nonlinearities is utilized to consider the snap-through instability of each dome and help the overall convergence of the model. Every dome row is actuated to the inverted state by applying constant pressure in each unit and adding different relaxing steps to gradually release boundary conditions. Ultimaker TPU 95A [33] is simulated as a linearly elastic, isotropic material with a Young's modulus of $E = 26$ MPa. Typically, soft robots are designed and numerically tested using hyperelastic models [34]. However, the behavior of our multistable gripper, is fundamentally dictated by the shell geometry (i.e., geometrically nonlinear), which dominates over the material nonlinearity. Indeed, hierarchical multistability is a purely elastic phenomenon requiring no material nonlinearity (Refs. [20] and [31]). Therefore, we obtain good agreement between the experimental cases and the linear elastic FE simulations.

To further examine the accuracy of our numerical analysis, a simulation of one dome strip to an air chamber was performed using a linear elastic model and compared with experimental data obtained from a 3D printed sample. The obtained tip displacement and strip curvature compared well with simulations, thus validating our model (see Fig. 2b). An 8.1% and 8.05% difference was obtained for the tip displacement and deformed arc length, respectively.

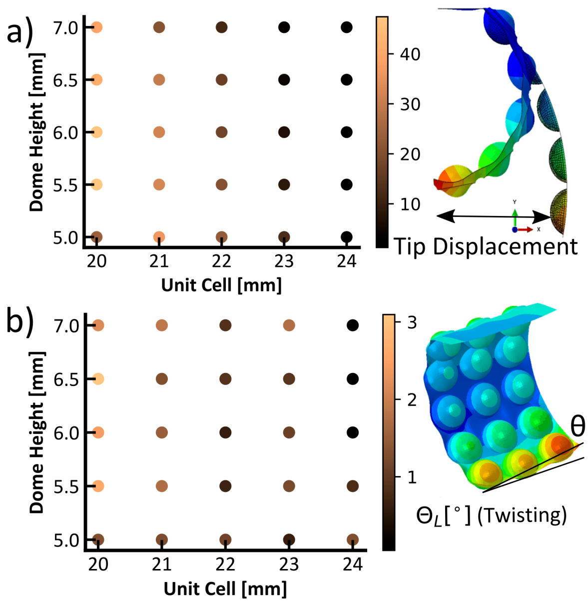

Fig. 3. Dome height and unit cell size parameter sweep for the soft finger topology optimization using FEM. a) Tip displacement to maximize finger grasping. b) Tip rotation angle to maximize finger twist.

B. GRIPPER CHARACTERIZATION

To characterize our gripper, we consider the most relevant parameters that affect the metasheet behavior. As described in previous works [20], multiple stable states and hierarchical multistability are generated due to the proximity between dome units. By fixing the dome base radius (R), we can control the proximity of our units by changing the unit cell size, which would modify the flat region dimension surrounding the dome. Furthermore, we control the prestress and bistability of the units by considering the domes' geometrical form factors and the unit cells' dimensions. We evaluate the gripper's overall response as a function of dome height (h), base radius (R), unit cell size (UC), and thickness (t). We performed a parameter sweep over the soft finger topology by changing h and UC while fixing R and t to understand the relation between the unit cell and the resulting global stable states. Concretely, we focused on determining the best parameter combination that maximizes grasping and finger rotation.

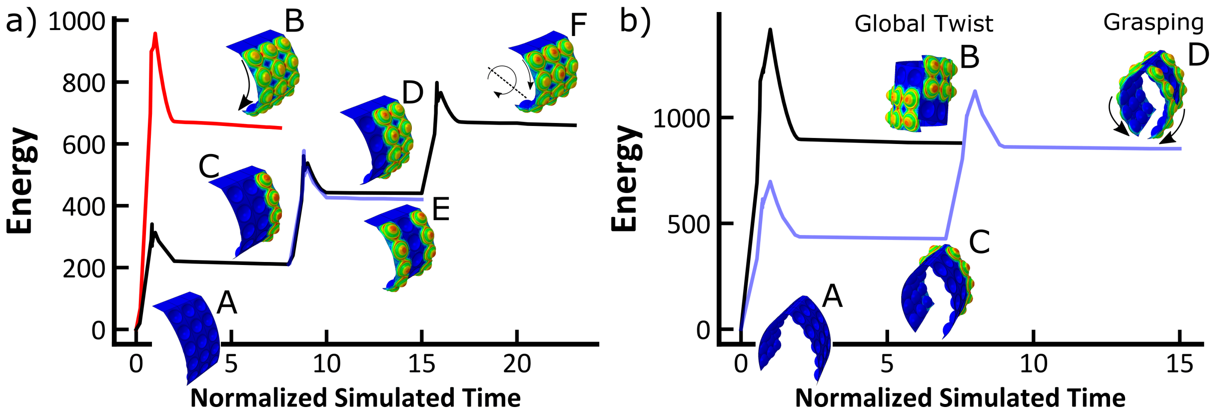

Fig. 4. Effect of order inversion in the strain energy and final shape. a) Soft finger final energy and shape after different row inversion patterns. b) Soft gripper grasping and global twisting states.

1) SOFT FINGER DESIGN: To constrain our analysis within the best ranges, results from previous works [21] were considered. Based on observation and experience, we bounded the dome height (h) between 5 and 7 mm, as taller domes require higher actuation pressures. The dome radius (R) and thickness (t) were fixed to 8 mm and 0.75 mm, respectively, as results indicated good gripper deformation for this type of unit cells. Most importantly, the unit cell size (UC) was bounded between 20 and 24 mm. Given that the domes' R fixes its size, reducing UC below 20 mm causes the interaction between neighboring units to become relatively strong. This undesirably changes the unit stability from bistable to metastable. In contrast, the interaction between units weakens above 24 mm affecting the onset of hierarchical multistability and reducing the number of possible global stable states of the system. The effect of the chamber height (h_c) and chamber thickness (t_c) was evaluated using FE simulations, revealing that the height of the chamber does not influence the metasheet's behavior. Therefore, this was set to be 1 mm higher than the dome height ($h_c = h+1$ mm) to allow airflow. In contrast, chamber thickness strongly affects the finger's overall stiffness and can potentially eliminate the coexisting stable states. Considering this, we set a value of $t_c = 0.6$ mm, to preserve several coexisting global states and maintain path-dependent actuation as means for kinematic control. The remaining air chamber geometrical was set as a function of the dome unit cell to guarantee the actuation of the dome units. The selected parameters were $t_c = t+1$ mm, $h_c = h+1mm$, $R_c = R+0.5$ mm and the same UC size.

Fig. 4, shows the behavior of the soft finger as a function of the selected parameters. One simulation per geometric configuration was performed, and the tip displacement (Grasping) and tip rotation (θ_L) were measured after convergence. The best configuration was selected based on the amount of finger twisting as this behavior is more difficult to achieve with the chosen finger aspect ratio (length/width). Results show that taller domes do not result in higher finger bending; on the contrary, the gripper's preferred deformation mode changes from bending to torsion along the finger's long axis, which is an undesired behavior. Unit cell size shows similar behavior to the previous analysis, as increasing the unit cell size reduces the interaction between domes and the stress within the flat region surrounding the unit cell. Using the results shown in Fig. 3, we determine the best geometric configuration to be: $h = 6.5$ mm, UC = 20 mm, $R = 8$ mm and $t = 0.75$ mm. The selected geometric parameters are used to build a soft finger that is capable of fingertip bending deflections of up to 110% from 35 to -5 mm, taking the finger's base as origin. In terms of finger twist, our results show angular deflection of up to 3.1°, which can be further exploited if the gripper length is increased. The chosen finger topology also exhibits order dependency observed in the original metasheet, enabling path-dependence as a control strategy to access to desired stable states. Fig. 4a shows two different grasping modes, a high energy mode, which is achieved by inverting all domes at the same time following path A→B (red line in Fig. 4a), and a low energy one with less grasping capabilities, achieved by following the path A→ C→ E (blue line in Fig. 4a). These two different grasping configurations have a strain energy difference of 35%. Finger twist stable state can be achieved by following the path A→C→D→F (black line in Fig. 4a)) show a stable state with a strain energy at least 1% higher than the full grasping mode. Furthermore, it was observed that despite the addition of the chamber, unit cells can still interact with one another, as the strain energy generated due to the inversion of two adjacent rows (D in Fig. 4a) is 5% higher than the case where the two outer rows are activated (E in Fig. 4a).

2) SOFT GRIPPER DESIGN AND PERFORMANCE: The soft gripper was designed by combining two soft fingers connected via a flat shell of the same material (see Finger separation in Fig. 1f). This separation region promotes interaction between the dome generated prestress leading to more stable shapes. As local prestress produced by the domes decays over short lengths [21], finger separation was set to the minimum possible distance. This results in the chambers air inlets be to be positioned on the top gripper's flat section. This design aims to maximize the number of possible encoded states, either by inverting a specific combination of rows or by exploiting the metasheet's inherent nonlinear

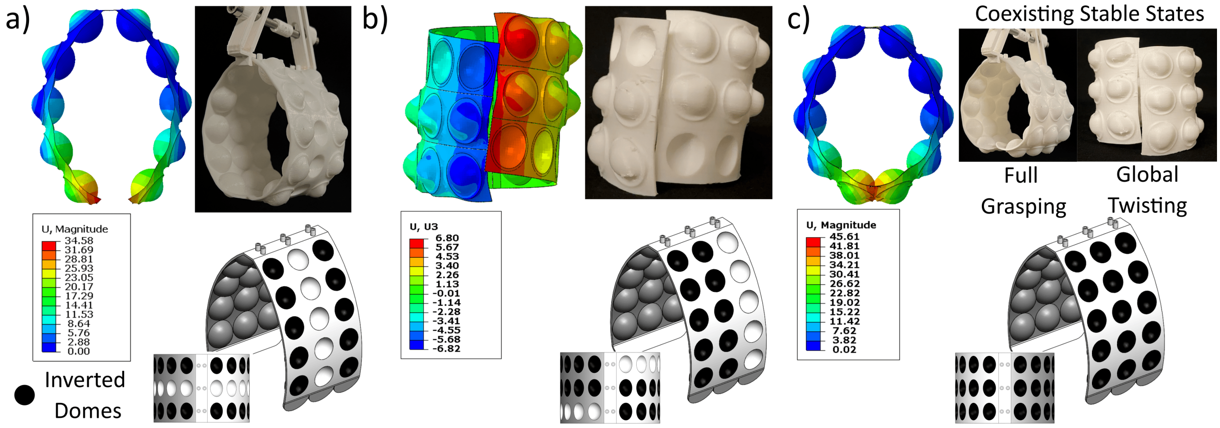

Fig. 5. Qualitative comparison between the soft gripper stable states found experimentally and numerically (FEM). a) Grasping state with four inverted rows. b) Global twisting state with four inverted rows. c) Global coexisting stable states (Full Grasping and Twisting) with all rows inverted.

mechanics, such as geometric frustration [31]. Fig. 4b shows the grippers' capability to access new stable states based on the interaction between the two soft fingers. By following path A→B (black line in Fig. 4b), we can get a global twist of gripper topology generated by combining both finger twists. Moreover, we can access regular grasping by activating the external rows of each finger (path A→C→D). The order dependency of the gripper can lead to up to 6! stable states corresponding to every possible combination of activated rows.

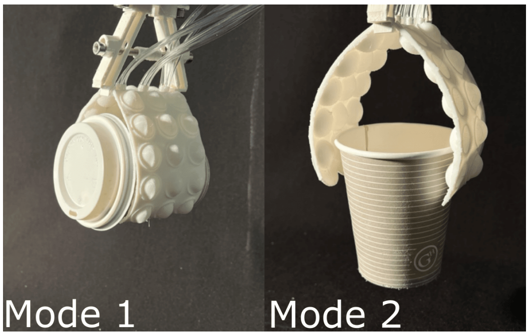

Fig. 6. Soft Gripper carrying capabilities under two different carrying modes.

A qualitative comparison between the stable states found numerically and experimentally was performed for the final gripper design. As shown in Fig. 5, both grasping and global twisting are achieved with a full gripper closure showing good agreement with FE simulations. It is worth mentioning that a quantitative comparison was not performed as when the two-finger contact each other, the trajectory becomes challenging to predict.

To further explore the performance of our gripper, payload capacity tests were conducted to determine the maximum the system's maximum carrying weight. The designed global states allow for adjusting the output force depending on the number of inverted domes. This is characterized by the increased payload capacity as more dome columns are inverted. Thus, we can modulate our gripper's shapes and output forces. The test was performed under two different carrying modes (see Fig. 6), which show that the gripper is able to carry up two 8 (Mode 1) and 14.6 (Mode 2) times its own weight on each mode.

3) LIMITATIONS AND DESIGN IMPROVEMENTS: The presented design demonstrates a multistable gripper with coexisting global stable shapes and strategy to access them exploiting path-dependence. However, a quantitative comparison was not performed as we do not modeled contact between fingers, which renders trajectory predictions challenging. Our experimental validation relied on stable states being reached by pressure inversion of dome rows in the same order as the numerical simulation and measurements were taken using image analysis and a grid-scale on the background. Results show that our design can rotate up to 1.04 rad or 60° (Measured from the base) and can fully close when all domes are inverted, allowing the structure to wrap around non-uniform objects with unknown geometries. The observed twisting behavior is small, however improvements in the separation region provide significant improvement margins. Larger deflections can also be attainable by using a less rigid material; TPU has a higher modulus than many polymers used in soft robotics, thus using slighly lower modulus materials offers an alternative route to achieving higher deformations. The high deformations and order dependency exhibited within this design open a new avenue for compliant robots to be reconfigured to different use cases while still maintaining an adaptability to external inputs, reacting based on objects' shapes and characteristics.

IV. CONCLUSIONS AND FUTURE WORK

This paper implements dome-patterned multistable structures in a soft gripper geometry that can reach different energy minima and, therefore, different functional programmed stable shapes, upon a simple actuation protocol. We leveraged the concept of hierarchical multistability to expand the capabilities of previous generations of multistable soft robots. Concretely, we exploit the coexisting global configurations (programmed stable states) and local prestress from the dome inversion to program and access different stable shapes into the system. We show the influence of the unit cell geometric parameters in the total grasping and finger twisting. This revealed the crucial role of the unit cells' mechanical interactions for exploiting the hierarchical multistability of the gripper. A reliable, yet straightforward actuation mechanism was utilized by incorporating separate chambers into each dome row to enable pneumatic actuation of unit cell groups. This allows control over inversion order, while maintaining the ability to access different and coexisting stable states with a minimum number of actuators. The topology found using numerical analysis was printed to test the actuation mechanism, corroborate the existence of the stable states, and perform a qualitative comparison between the final shapes obtained from numerical simulations. By consistently accessing the different stable configurations and leveraging the actuation path revealed by the metastructures' mechanics [20, 31], we can predict the gripper's final kinematic configurations. This opens a new route to underactuated, open-loop controlled soft robots attaining precisely defined kinematic configurations. Although the proposed methodology offers insight on a novel multistable gripper topology, future work will focus on improving the gripper's global twist to add more dexterity to the system.

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