**Proceedings of the Canadian Society for Mechanical Engineering International Congress**
**32nd Annual Conference of the Computational Fluid Dynamics Society of Canada**
**Canadian Society of Rheology Symposium**
**CSME-CFDSC-CSR 2025**
**May 25–28, 2025, Montréal, Québec, Canada**

# Semi-continuum Robot with Discrete Quantized Deformation of Bistable Metastructure

Hasti Jahanara[1], Hang Xu[1*]
[1] Department of Mechanical, Industrial and Aerospace Engineering, Concordia University, Montreal, Canada
*e-mail address: hang.xu@concordia.ca

***Abstract***—Continuum robots are widely used in surgical applications. However, the non-linear motion system of continuum robots has a number of kinematic degrees of freedom approaching infinity. Even with a complex control system, continuum robots cannot achieve repeatable and accurate deformation that is comparable to that of conventional robots, e.g. puma robots. This study aims to develop a semi-continuum robot with discrete quantized deformation to improve the repeatability and accuracy of continuum robots. We integrate bistable metastructures with designable discrete deformations into continuum robots, making the degrees of freedom tailorable. The deformation performance of the proposed bistable metastructures is obtained via numerical simulation. The combinations of the achievable deformations are then estimated. The triggering mechanism is also developed and integrated into the 3D-printed prototypes.

***Keywords-continuum robot; metastructure; bistable structure; discrete deformation***

## I. INTRODUCTION

A continuum robot is an actuatable structure, whose constitutive material forms curves with continuous tangent vectors. Continuum robots can realize bend, extend/contract, and twist. Concentric tube continuum robots with a diameter of only 0.5 to 3 mm have been widely used in interventional/surgical applications, where complex deformation combinations are achieved with soft, human-friendly materials. Complex control and actuation systems have been developed for continuum robots to overcome tortuous paths under anatomical constraints.

Depending on the application and objectives of the system, the robots need to offer desired characteristics, such as high repeatability, accuracy, payload, and speed. However, compared to conventional robots, e.g. puma robots, the continuum robot falls short of providing repeatability and accuracy due to its structure, actuation, and control complexity. Figure 1 represents a continuum robot arm developed by Clark et al. [1]. The arm consists of three sections, each controlled by four servo motors moving the section. The proposed continuum robot arm is light, flexible, and affordable, however, it is susceptible to input errors. This is primarily due to the fact that continuum robots move through the continuous deformation of compliant mechanisms or soft materials. Since small variations in external forces or internal actuation can cause unintended deviations, the flexibility in components makes it difficult to achieve precise re-positioning.

In contrast to continuous deformation, discrete deformations can be achieved by the snap-through buckling of the bistable structures, which can only stay at two discrete mechanical stable stages. Each stable stage of the bistable structure can resist external disturbances and autonomously recover its deformation at the stable stage. Bistable structures are thus suitable for providing repeatable and accurate deformations.

Integrating bistable structures as building cells into robot arms exists in literature. Osele et al. [2] utilized bistable tape structures (obtained from a tape measure) as light, flexible, and one-degree-of-freedom manipulators to build a robot arm. The developed robot arm can access far and hard-to-reach locations in aerial applications where space and weight impose limitations. While the research provides insight into the lightweight, low-cost, compact, and relatively reliable arms, the solution falls short on the precise positioning of the robot due to the limitation in the designability of the selected bistable tape structures. Furthermore, the proposed solution is not stiff and robust enough to grab and carry heavy objects, thus imposing strict payload limitations. Moreover, the arm relies on friction and the bending configuration of the tape to reach desired angles, making the structure susceptible to external disturbance, i.e. gust. In another study, Kaufmann et al. [3] propose a continuum robot arm made of Kresling origami, a bistable cylindrical origami structure. The developed lightweight robot is actuated by tendons to realize a relatively accurate positioning. However, the number of reachable positions is quite limited.

This research aims to propose a bistable metastructure for continuum robots to improve movement repeatability and accuracy. Metastructures are designable matters that can achieve superior performance than their base units, e.g. bistable structures, via a reasonable structural design. Bistable structures at the same dimensions provide precisely the same deformation under identical loading conditions. When periodically tessellate a number of bistable structures, triggering each bistable unit can generate a "quantum" of length/angle change, making the overall deformation quantitative. The quantized deformation can be programmed into the architecture of the bistable metastructures. The developed bistable metastructure can realize discrete quantized linear transformation, 2D bending, and 3D coiling. The number of kinematic degrees of freedom of continuum robots can be decreased by the discretization of deformation. The control system can thus be simplified. The deformation accuracy is guaranteed by the anti-interference ability of bistable structures at stable states. Moreover, employing bistable structures is an energy-efficient approach, as these structures do not need constant force to maintain a position. Such an arm robot is useful for repetitive tasks (e.g., high-precision manufacturing lines, devices or material inspection, material processing, etc.).

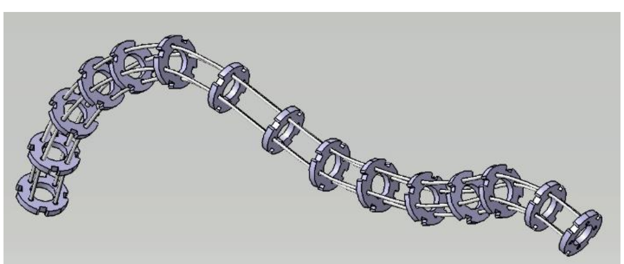


Figure 1. A representation of the continuum robot arm built inspired by the concept in litearture [1]

## II. METHODOLOGY

The proposed robot arm consists of a chain of unit cells, each having four bistable building blocks. The unit cell is additively manufactured via Thermoplastic Polyurethane (TPU), a hyperelastic material providing flexibility. The building block shape shown in Figure 2 is defined using the key parameters, e.g. skew angles, which are manipulated to attain different configurations with various levels of bistability. Bistability is assessed through the normalized values (Eq. (1)) with maximum/minimum strain energies obtained from numerical simulations. The higher the normalized bistability obtained from Eq. (1), the higher the energy threshold obtained via bistable structures at the second stable stage. Figure 2 represents strain energy curves for three building blocks of different $\alpha$ when they are triggered by forces to snap through from one stable stage to another. As depicted, there are a local minimum and a maximum referred to $E_{min}$ and $E_{max}$, respectively, or each curve. Moreover, the corresponding deformation modes of the building block at the beginning, the $E_{max}$, and the $E_{min}$ are also represented.

$$\frac{\Delta E}{E_{max}} = \frac{E_{max} - E_{min}}{E_{max}} \qquad (1)$$

According to numerical simulations, the skew angle (indicated as $\alpha$ in Figure 2) has the highest effect on the bistability. The higher the skew angle, the more bistable the structure. However, high skew angles impose limitations on other aspects of the design. High skew angles make the unit cell too tall, which causes large deflections of the unit cell when deformed. In other words, high skew angles result in more drastic movement of the arm, which further limits the number of reaching positions. Moreover, high bistability is not desired as it would demand a higher triggering force to move the structure back to its original stable stage, which makes it less responsive to the control mechanism.

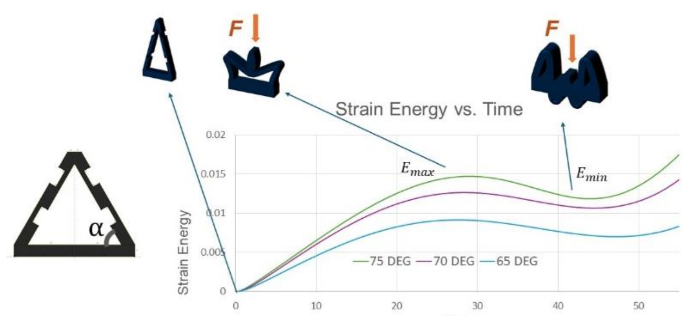



Figure 2. Strain energy diagram and the corresponding states of the building block. The $\frac{\Delta E}{E_{max}}$ for the building blocks with variable $\alpha$ of 75°, 70°, and 65° are 0.19, 0.15, and 0.11, respectively.

Figure 3 shows one unit cell, which consists of four building blocks. Each building block has two stages, resulting in $2^4 = 16$ states for the unit cell.

Table 1 illustrates the 16 states that one unit cell with four building blocks of identical geometrical dimensions can obtain. Under identical triggering force exerted on different building blocks, the unit cell obtains identical deformation angles but in opposite orientations. However, it is possible to use non-identical building blocks in one unit cell which results in various deflection angles. This design step provides more design space for the arm. In other words, depending on the requirements of the arm, various configurations can be employed to realize the desired outcome.

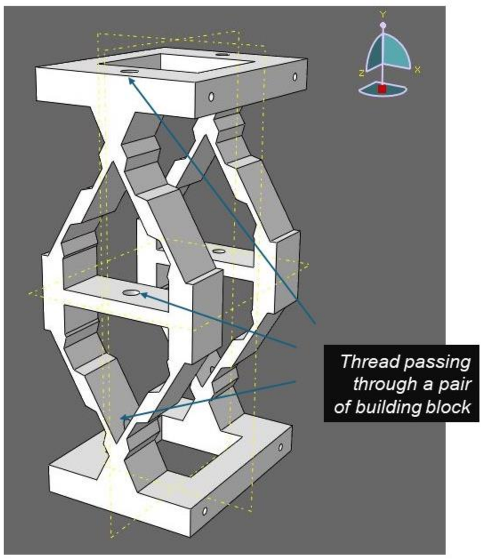
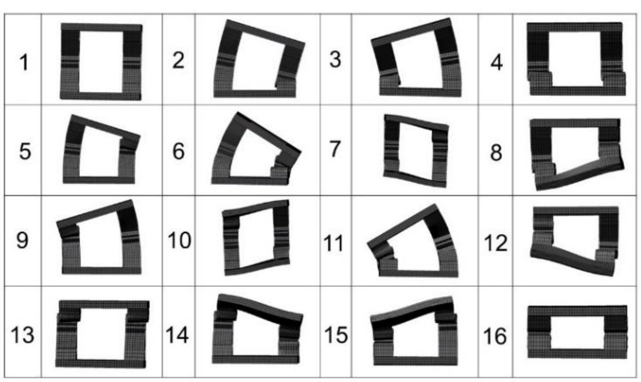



Figure 3. Unit cell consisting of four building block configurations

TABLE 1. THE 16 UNIQUE STATES OF A UNIT CELLS




Combining four building blocks to create a unit cell comes at a cost in bistability: once one side of the unit cell is deflected, the other side pulls it back to the original stable stage. A mechanism (Figure 4) was proposed to avoid this deterioration. This mechanism is employed to have the opposite force, moving the pair on the other side back to the original position, by causing momentum around a certain point resulting in the application of a force in the other direction of the other side. In other words, the attempt to deflect the other side would cause the deflected side to return to its original position (refer to Figure 4).

To ensure the precise motion of the arm, unwanted movements need to be restricted. The proposed mechanism prevents the unit cell from moving in *x-y* plane (Figure 3). Also, as aforementioned, the deformation angle of the unit cell is of great importance as it determines the positions that the robot can reach. The introduced mechanism addresses this issue by causing the unit cell to remain at a certain and known angle when deformed.

The triggering mechanism of the unit cell includes a thread passing through the middle of a pair of building blocks, as shown in Figure 3. The thread pulls one side of the unit cell causing the two building blocks on the side to fully deform gradually. To have the unit cell back to its original state, the thread on the other side is pulled, causing the unit to snap back to the undeformed state. By continuing the application of the pulling force the other side becomes fully deformed. Figure 5 depicts these steps.

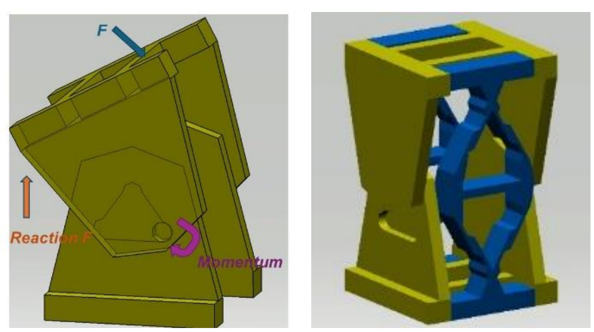



Figure 4. The designed mechanism on the two sides of the unit cell

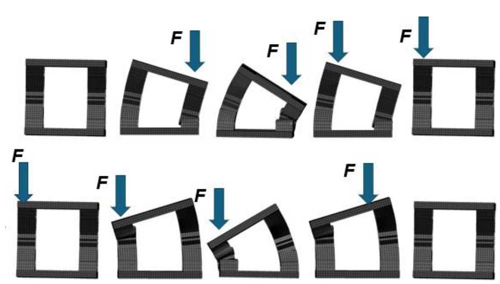



Figure 5. The process of transforming through five states and the corresponding triggering force

## III. RESULTS AND DISCUSSION

Figure 6 shows the robot arm built by a chain of unit cells in the original and deformed position respectively. As aforementioned, the state of each unit cell dictates the position and shape of the building block which derives the configuration of the robot arm accumulatively. Figure 7 shows the potential point to reach with a robot arm consisting of five unit cells. Each unit cell is oriented in the two following manners: (1) deflects in the XY plane and (2) deflects in the YZ plane. For each orientation, there are multiple states (for this figure only the three states are considered: (1), (6), and (11) of

TABLE 1), making the total states of each unit cell, five (disregarding one duplicate).

Figure 6. Original and deformed robot arm

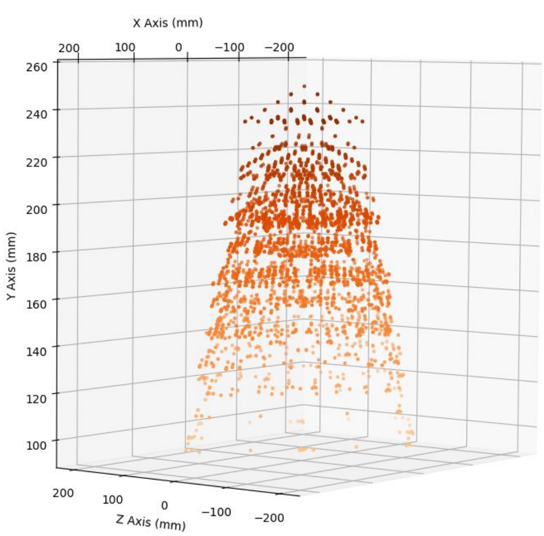



Figure 7. The points that a robot arm including five unit cells of length 50 mm can reach

## IV. CONCLUSION

In this study, we integrate bi-stable structures into continuum robots to realize a semi-continuum robot with discrete quantized deformation. The developed robots achieve designable deformations with up to $2.7\times10^3$ distinguished deformation via only five unit cells.

## V. FUTURE WORK

The study will continue to develop the control algorithms for the system. The challenges include having the control algorithm efficiently operate the arm by finding the quickest path from one position to another. Additionally, simulations and prototypes are used to validate and verify the design and control algorithm. The testing process involves employing the optical measurement method to verify the accuracy of the system.

## REFERENCES

[1] A. B. Clark, V. Mathivannan, and N. Rojas, “A Continuum Manipulator for Open-Source Surgical Robotics Research and Shared Development,” *IEEE Trans. Med. Robot. Bionics*, vol. 3, no. 1, pp. 277–280, 2021, doi: 10.1109/TMRB.2020.3041391.

[2] G. Osele, A. Okamura, and B. Do, “A Lightweight, High-Extension, Planar 3-Degree-of-Freedom Manipulator Using Pinched Bistable Tapes,” p. 1196, May 2022, doi: 10.1109/ICRA46639.2022.9811976.

[3] J. Kaufmann, P. Bhovad, and S. Li, “Harnessing the Multistability of Kresling Origami for Reconfigurable Articulation in Soft Robotic Arms,” *Soft Robot.*, vol. 9, Feb. 2021, doi: 10.1089/soro.2020.0075.