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Development of Novel Three-Dimensional Soft Parallel Robot

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***Abstract*—Soft robotics is an emerging area of research with great potential to revolutionize the safe interaction of humans and robots. Typically, soft robots are made of serial elastomeric arms. However, the application of a parallel structure in the design of a soft robot would be of great interest since it can provide more control on the overall stiffness and the payload of the robot. This paper reports on the design and manufacturing of a novel three-dimensional (3D) soft parallel robot. The robot consists of three closed kinematic chains that connect the moving platform to the fixed base and provide 3 DOF in x, y, and z directions. Each single pieced designed kinematic chain integrates active soft links along with passive links incorporating flexure hinges to create relative motion. The robot prototype is 3D printed using thermoplastic polyurethane (TPU) and actuated with three tendon driven soft actuators. The kinematic model of the robot is derived and simulated in different trajectories in Matlab Simulink. The Matlab Simscape model is created to obtain the dynamical response of the mechanism for various inputs. Both the kinematic model and dynamical model are validated through the experimental setup. The proposed soft robot is lightweight and efficient and can be used safely in close contact with humans in different industries such as the packaging and medical industry.**

Keywords—soft robotics, soft parallel mechanism, 3D printing, kinematics, Matlab Simscape. Compliant flexure

I. INTRODUCTION (*HEADING 1*)

Soft robotics has the potential to revolutionize the safe interaction of human and robotic systems due to the application of soft and compliant materials in the structure of the robot [1], [2]. This emerging technology has been utilized in different robotic systems including medical [3], [4], assistive [5], and search and rescue robots [6]. There is an increasing demand for safe collaborative robotic systems that can work in close proximity to humans [7]. While collaborative medical robots [3], [4] and industrial robots can have a positive impact on our daily life, safety is a major concern in the application of such robotic systems. The application of external force sensor and monitoring systems can improve the safety of robotic systems. However, these systems cannot guarantee the safety of collaborative robots. Thus, the application of soft, compliant, and lightweight materials in the structure of the robot would be critical to minimize the impact forces due to collision [7]. Compliance in robotic systems can be achieved through active or passive compliance. The active compliance in the rigid robotic systems is based on the application of sensory force and torque data to control the position of the end-effector [7]. Thus, this method is complex, expensive, and requires a fast real-time response which is hard to achieve. Alternatively, passive compliance can be realized by integrating soft and compliance joints and links in the structure of the robot [7]. Therefore, a passive compliance system can naturally deform in response to external loads without requiring any sensory data or control system. As a result, these systems can be designed properly to safely interact with humans. However, the passive compliance systems generally have lower accuracy and complex dynamics [7]. Typically soft and compliant robots have the serial or hybrid structure [8]. This limits the output force and accuracy of the soft robots. Application of parallel structure in the design of soft robots can enhance these characteristics [7]–[10]. The research area of soft parallel robot is relatively unexplored. One way to categorize the existing soft parallel robots is based on the application of soft links or soft joints in the structure of the robot. Amiri Moghadam et al. have proposed the application of both soft links and soft joints in a planar soft parallel robot [2]. Initially, Bryson et al. have utilized the soft links in a 6 DOF soft parallel robot [8]. Afterward, other research groups have used soft links in soft parallel robots [7], [10]–[12]. Yang et al. have proposed the application of soft joints for soft parallel robots. In the current work, we are proposing a novel 3D soft parallel robot that has 3DOF and can move in x, y, and z directions. The proposed soft robot is analogous to the rigid Delta robot and consists of three soft active links which are connected to passive links and the robot platforms employing soft joints. Figure 1 compares the proposed soft parallel robot with the existing ones which only have soft links or soft joints.

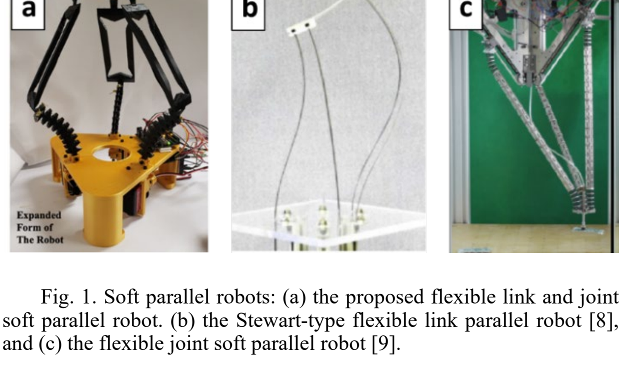

Fig. 1. Soft parallel robots: (a) the proposed flexible link and joint soft parallel robot. (b) the Stewart-type flexible link parallel robot [8], and (c) the flexible joint soft parallel robot [9].

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The rest of the paper is organized as follows. In section II the design and manufacturing of the robot will be discussed. The modeling of the robot including kinematics and dynamics is presented in section III. Finally, section IV is the conclusion.

II. DESIGN

This section briefly discusses the design and development of the soft robot along with the experimental results.

The initial soft robot was designed with three flexible links 3D printed using thermoplastic polyurethane (TPU) which consists of an active soft link and a compliant four-bar linkage connected with flexure as depicted in Fig. 2a. The fin-like soft link with the strings allowed the link to deform in either direction once the string was actuated as shown in Fig. 2b. If the string running on both sides of the soft link was pulled/ actuated thereby releasing the right string, the link deformed to the left. Likewise once the right string was actuated and the left string was released, the soft link deformed to the right as expected. Besides, the fins on the soft link prevented the pulling of the soft link more than a certain degree. The soft link consisted of 8 fins with a length of 110 mm and an overall width of 26 mm.

Furthermore, the compliant four-bar link enabled the tip of the soft link-compliant four-bar arm to move side to side without bending the soft link. The soft link and the compliant link were connected through a compliant flexure with 10mm thickness to create relative motion between each.

The initial soft delta robot consisted of 3 flexible links, three servo motors with strings, a top platform, a bottom platform that houses the servo motors, and the Arduino as shown in Fig. 3a. The soft links were 3D-printed using TPU and the top and bottom platforms housing the servos were 3D-printed out of polylactic acid (PLA). The three soft links were attached on the bottom platform by 120° apart from each other as well as 60.3 mm apart from the center of the bottom platform. Also, the soft links were connected to the top platform which was kept parallel to the bottom platform in its initial configuration. Each of the flexible links had embedded strings that were actuated by a pulley wheel connected to a servo motor. The servo motors were connected to an Arduino and can be controlled independently via the joysticks or computer.

If all the links are actuated in the same direction, then the top plate follows a straight up and down motion while the top plate remains parallel to the ground. Even though the top platform was lowered due to the outward deflection of the soft links, the displacement wasn't significant since the string got loose after a couple of cycles due to the connections at the top end of the fin-like structure and the lack of tension. In addition, the compliant four-bar linkage was too stiff

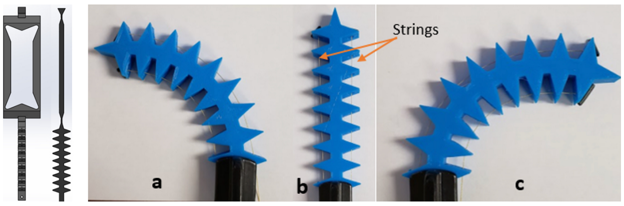

Fig. 2. Cad model and the prototype of the soft 3d-printed in TPU.

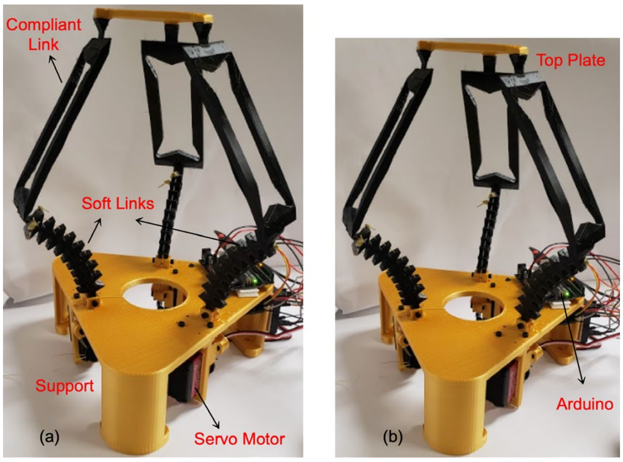

Fig. 3. (a) Initial configuration and (b) deflected position when pulled down through the servo motors.

preventing the required side to side motion. Consequently, the soft links bent side-to-side as opposed to bending along the direction in which the strings are actuated.

To address these issues, the initial design was modified. Taking into consideration the lack of tension in the strings as well as the flexibility and stiffness, the compliant four-bar linkage was revised from having sharp corners to curve corners with a smaller thickness. Besides, the soft link thicknesses were increased from 10mm to 14mm to prevent excessive bending. Also, in order to resolve the lack of tension in the strings, a pulley wheel was designed to tighten the string to the servo motor as well as incorporating a spring attached to both strings as shown in Fig. 3a. This allowed the servo to pull the string more effectively while adding more tension. In addition, the connection of the strings at the top ends of the soft robot was changed from a permanent connection to an adjustable connection via a bolt and a nut as depicted in Fig. 3b. The bolt and the nut wrapped by the string kept added more tension to the string while allowing it to be adjusted if it becomes loose under actuation. After making the necessary adjustment to the soft delta robot, it was reassembled with the modified soft links and the pulley wheels as shown in Fig. 4. Additionally, the mechanism was controlled by programming via the computer instead of the joysticks.

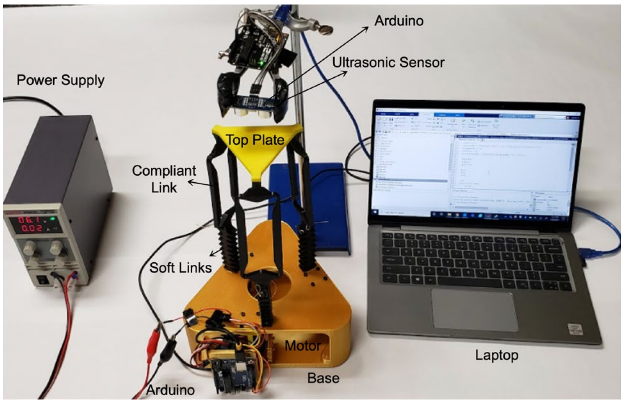

Fig 4. Experimental setup of the 3d-printed soft parallel robot.

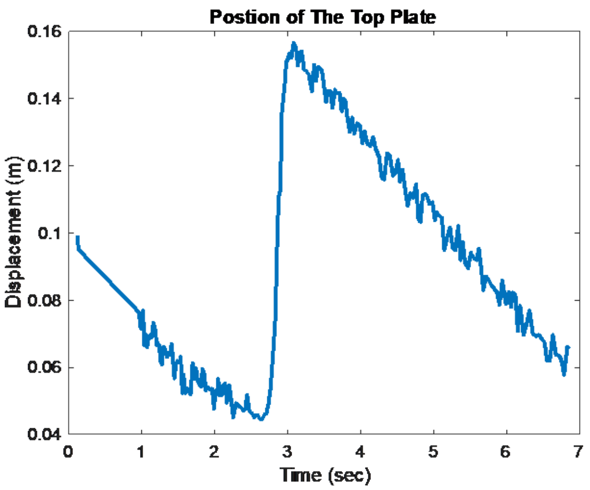

Fig 5. Position of the top plate in the z direction.

The soft delta robot experiment setup consisted of the soft delta robot, power supply, a laptop with MATLAB and Arduino IDE, and an ultrasonic sensor with an Arduino. The soft delta robot was tested for up and down and side to side motion to ensure that the top plate remains parallel to the bottom platform as well as testing the performance and behavior of the soft link. An ultrasonic sensor was used to measure the distance at which the top platform moves down. It was observed that the top platform, as the soft link moved outward, was displaced 12 cm in z direction as seen in Fig. 5 while the several configurations of the mechanism are provided in Fig.6.

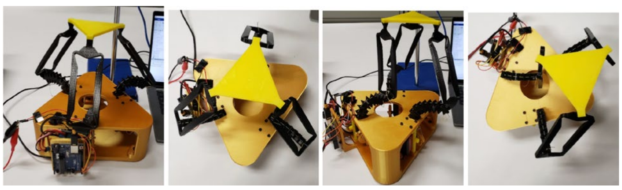

Fig 6. Different configurations of the parallel soft robot.

III. Modeling

In this section, the kinematic and dynamic model of the soft parallel robot will be presented using Matlab Simscape. Although soft robots provide more advantages compared to rigid mechanisms, their modeling is much more complex since soft link deformations yield nonlinear equations. Several approaches have been adopted in the literature. While the Cosserat rod theory is used for the modeling of tendon-driven soft robots [13]–[15] modeling through finite element analysis is the most common method among many since it provides an accurate solution considering the material nonlinearity.

In our design, each kinematic chain connecting the top plate to the support base is designed as a soft link connected to a compliant four-bar linkage through soft joints. The deformation of the links is obtained from the kinematic model. Dynamical modeling through the Simscape model is the very first soft robot modeling to the best of our knowledge.

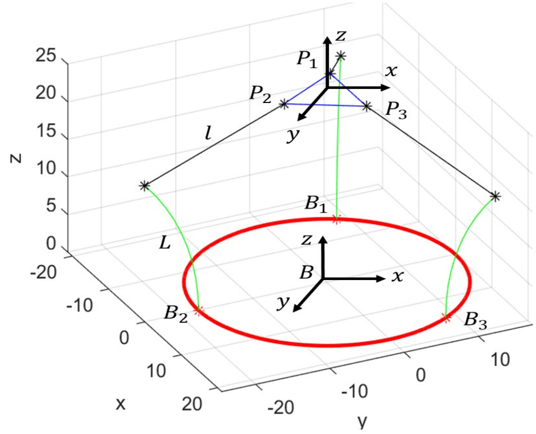

Fig. 7. Frame assignment for the soft parallel robot.

A. Kinematic Model

To develop the kinematics model of the soft robot we assume constant curvature for the motion of the 3D printed tendon-driven actuators [2], [16]. Next, proper frames will be assigned to the soft robot platforms. Based on Fig. 7, the kinematics model of the soft robot can be defined as follows:

$$\{B_i^B\} + \{L_i^B\} + \{l_i^B\} = \{P_P^B\} + [R_P^B]\{P_i^P\} \qquad (1)$$

$$i = 1, 2, 3.$$

where $\{B_i^B\}$ is the position of the vertex of robot fixed platform, $\{L_i^B\}$ is the position of the soft actuators, $\{l_i^B\}$ is the position of the passive links, $\{P_P^B\}$ is the position of the end-effector, $[R_P^B]$ is the rotation matrix, and $\{P_i^P\}$ is the position of the vertex of moving platform. Equation (2) states that the length of the passive links must be constant and equal to l such that

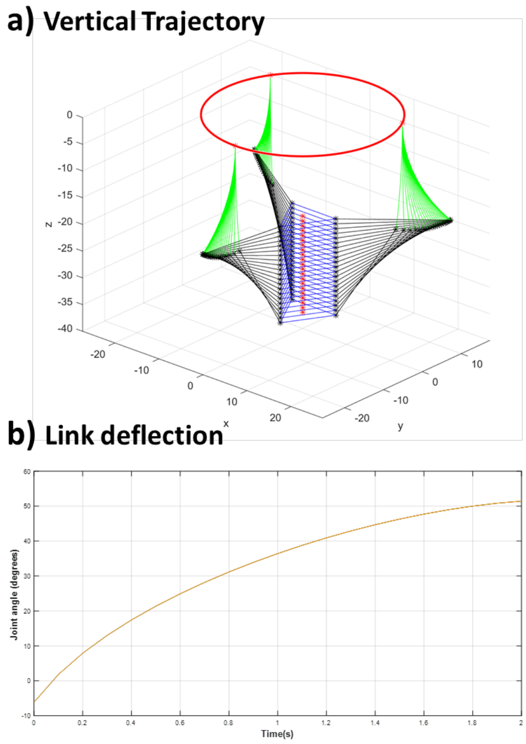

Fig. 8. Simulation of the kinematics model. a) Vertical trajectory, and b) associated bending angles of the soft links.

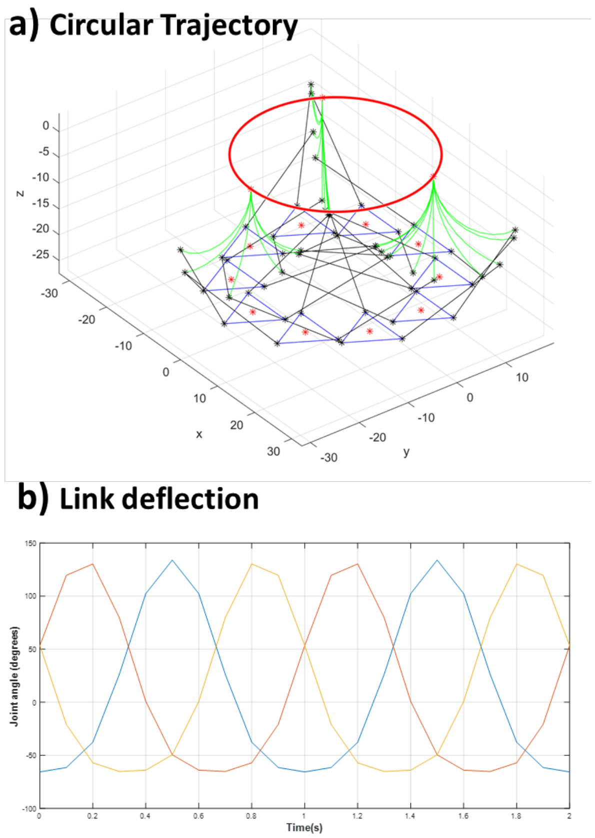

Fig. 9. Simulation of the kinematics model. a) Circular trajectory, and b) associated bending angels of the soft links.

$$l_i = \|l_i^B\| = \|\{P_P^B\} + [R_P^B]\{P_i^P\} - \{B_i^B\} - \{L_i^B\}\ \| \quad (2)$$

$$i = 1, 2, 3.$$

To avoid the square-root in the norms of the Eqn. 4, we can square it to get:

$$l_i^2 = \|l_i^B\|^2 = l_{ix}^2 + l_{iy}^2 + l_{iz}^2 \quad (3)$$

$$i = 1, 2, 3.$$

Equation (3) can be solved numerically to obtain the value of the required bending angle in the active links for a given position of the robot end-effector. To demonstrate the application of the kinematic model, both vertical and circular trajectories have been simulated. Figure 8 shows the simulation results of the kinematics model for vertical trajectory plus the required bending angels of the 3D printed soft actuators. The simulation results for a circular trajectory plus the required bending angles of the soft actuators are depicted in Fig. 9.

B. Simscape Model

The proposed design consists of three main parts: base, soft links, and top plate. Once a new Simscape model is created using the command smnew, the blank model opens default with the world frame, solver, and mechanism configuration blocks. The gravitational force can be modified using the mechanism configuration block depending on the configuration of the design. A general flexible block was selected from the Simulink library to connect these three blocks. There are four sections of the soft link arms. The bottom of the arm connected to the base is a compliant flexure with a height of 90.5mm and a thickness of 6mm. There are nine protruding triangular ridges on both sides of this section where the flexure will bend inwards and outwards. There is a small opening down the face of all ridges where a cable will pass through to deform the soft links. Two cables are connected to the top ridge to bend the soft links in two directions through the servo motors. This would allow both inward and outward movements depending on which cable is pulled down. The soft arm consists of soft and compliant links which have a height of 120mm and a width of 1.5mm possessing flexure hinges at the edges. The compliant flexures allow the links to bend and revolve depending on the actuation. For simplicity, the protruding triangular regions are omitted in the Simscape model. Rigid Transform blocks are used to position the placements of the cable while a brick solid block is connected to the top of the general flexible block that will be used to tie the ends of the cable. This brick solid block has the same distance across the small holes in the arm's first region ridges and to connect the cable to the brick solid ends, frames are introduced in the settings of the brick solid block. A belt-cable end block is used to attach the cable to this frame. For the first test, the top cable on both sides of the brick solid was pulled down. To model the pulley mechanism, the belt-cable end is connected to a pulley block located at the bottom of the general flexible block. The bottom pulley is located at a distance by using a rigid transform block. The rigid transform block is connected to a revolute joint to rotate the pulley along with a cylindrical solid that must be used for the pulley wheel. The revolute joint and the cylindrical solid are also connected to a belt-cable spool which represents the pulley. A torque is

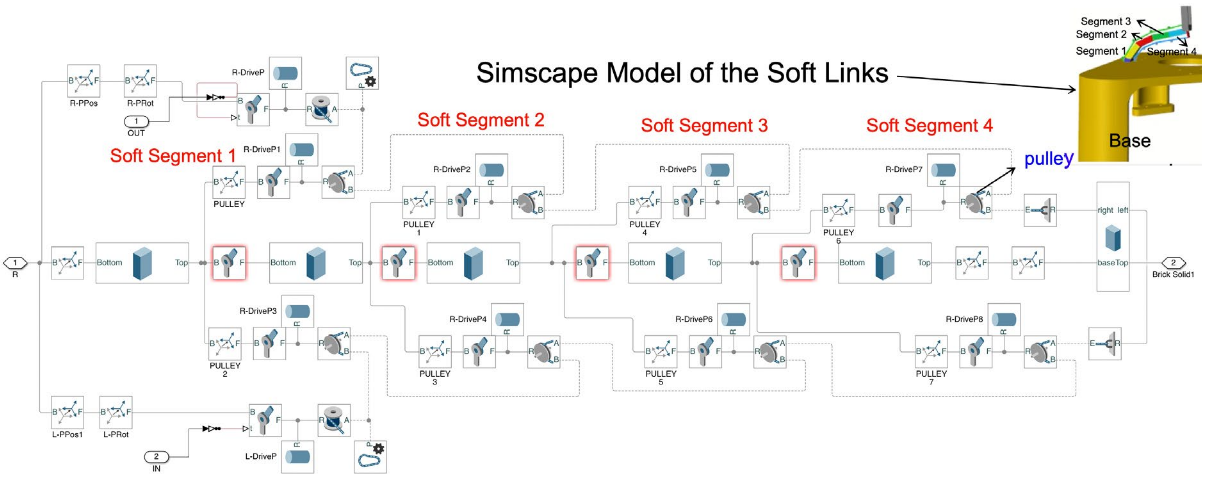

Fig. 10. Simscape model of the soft links.

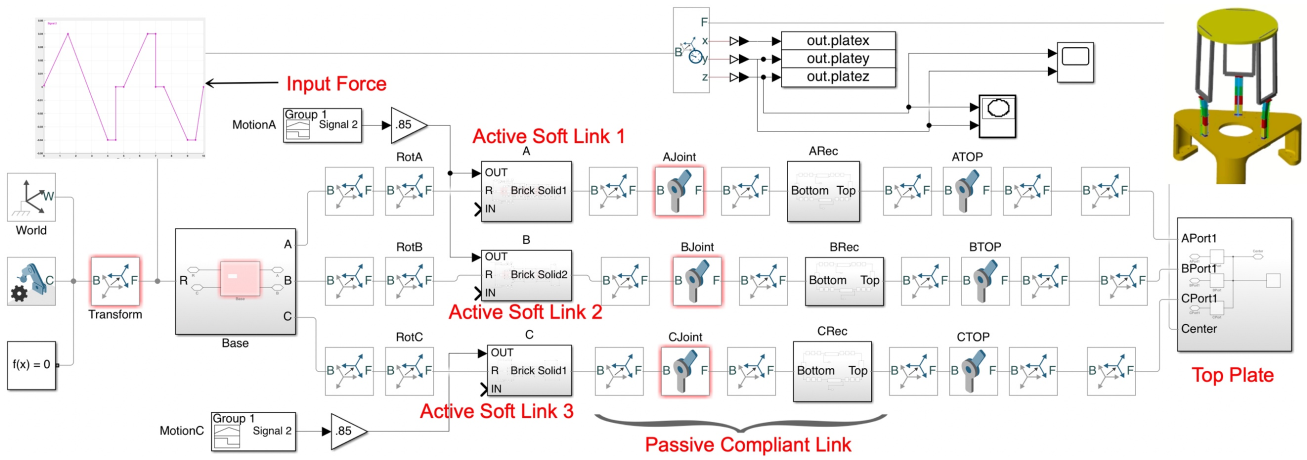

Fig. 11. Simscape model of the soft parallel robot.

applied to the revolute joint to pull the cable as shown in Fig. 10.

The basic idea in modeling the active soft links is to consider the them as a discretized system which consists of rigid finite elements (RFEs) connected by spring–damping elements (SDEs) [17], [18]. Once the simulation results are confirmed with the experimental setup, the soft links are integrated into the rest of the mechanism. Four revolute joints are utilized to imitate the compliant flexures on each passive links. To this end, each of the active soft links is modeled using four segments connected through serial revolute joints and connected to the pulley. The passive soft links are also joined to the passive compliant links thereby increased the simulation time. To address this problem, a general flexible beam with TPU properties is replaced with a segmented link connected via revolute joints with the spring value K having the same load-deflection behavior as the general flexible block as the complete Simscape model is shown in Fig. 11. This method not only enabled faster simulation response but also increased the accuracy of the dynamic solution.

If the motor strings are actuated, then the top plate is displaced by 13 cm (see Fig. 12) validating the results from the experimental setup as depicted in Fig. 5. The strings are pulled as a function of time to obtain all possible configurations of the soft robot as illustrated in Fig. 13. The superiority of the Simscape modeling of soft robots is that any

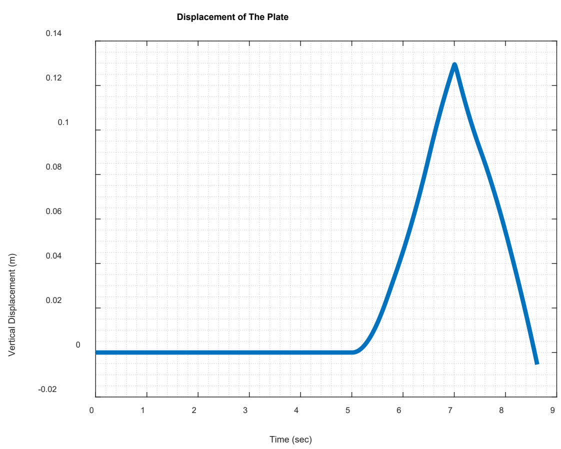

Fig. 12. Position of the top plate.

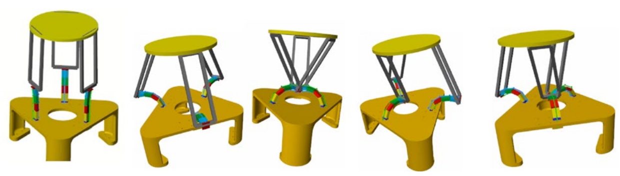

Figure 13. Different configurations of the robot depending on the input force

data can be exported if the corresponding sensors are utilized in the model.

Although the simulation time would significantly be affected, as an alternative to the creation of the design using the Simulink library blocks, the cad model of the mechanism can be imported into Simscape and the soft links and flexures can be replaced with the flexible beams and torsional springs. The compliant four-bar linkage can also be modeled using pseudo rigid body modeling by replacing each flexure with their equivalent torsional stiffnesses having the same load-deflection behavior [19, 20].

IV. CONCLUSION

This paper reports on the design, modeling, and manufacturing of a novel 3D soft parallel robot that is analogous to a rigid Delta robot. The robot consists of three closed kinematic chains that connect the top platform to the bottom platform through soft links and joints. The structure of the robot was 3D printed using TPU and actuated through three tendon driven soft links. The kinematics model of the robot is derived based on the constant curvature assumption and the simulation results showed that the robot can move in 3D trajectories. The dynamics of the soft robot is simulated using Simscape. To emulate the motion of the soft links, they have been molded using discrete sets of elements connected using rotary joints and springs. The comparison of the experimental data and simulation results indicates the effectiveness of the Simscape model. This paper can be considered as a step forward in the design and development of soft parallel robots that have both soft links and soft joints. The design procedure used in the current work can be used to develop other soft parallel robots with 6 DOF analogous to the Stewart mechanism.

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