Development of a Novel Six DOF Soft Parallel Robot

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***Abstract*— While soft robotics is an emerging field of research, soft parallel robots are among the latest advancements in this field. Usually, soft robots consist of serial soft arms and structure which provides high degrees of freedom and maneuverability. However, soft serial arms suffer from issues such as low stiffness and limited payload which limits their application. On the other hand, soft parallel robots can address these issues by providing more control on the overall stiffness and the payload of the robot. This paper reports on the design, modeling, and fabrication of a novel six degrees of freedom (DOF) soft parallel robot. The robot consists of six soft closed kinematic chains that connect the moving platform to the fixed base and provide six DOF (x, y, z, roll, pitch, yaw). Each kinematic chain incorporates an active soft link and a passive link which are integrated to the platform through soft spherical. The robot prototype is 3D printed using NINJA flex and PLA and actuated with six tendon driven soft actuators. The nonlinear kinematics of the robot is derived and simulated for different trajectories using Matlab. Moreover, the Matlab Simscape model is created to obtain the dynamical response of the mechanism for various inputs. The robot model is validated through the experimental setup using a six DOF electromagnetic position sensor. The proposed soft robot is lightweight and efficient and can be used safely as a cooperative robot in different industries such as the packaging and medical industry.**

Keywords—soft robotics, soft parallel mechanism, 3D printing, kinematics, Matlab Simscape, Soft joint.

I. Introduction

Soft robotics is an emerging interdisciplinary field of research which facilitates safe interaction of human and robotic systems due to application of soft and compliant materials in robot structure [1], [2]. Soft robots have wide range of application including medical [3]–[5] assistive [6], and search and rescue robots [7]. Human robot collaboration is an important topic which can revolutionize the future of robotic systems [8]. Demand for safe collaborative robotic systems grows rapidly [9]. The structure of conventional rigid robots comprises of rigid metallic parts and heavily rely on application of external force sensors and monitoring systems to improve the safety of system. However, failure of these safety systems when a rigid robot is in direct contact with the human can be catastrophic. On the other hand, structure of soft robots is made of soft, compliant, and lightweight materials which can facilitate the safe human robot interaction and minimize the impact forces due to collision [9]. There are two types of compliance in robotic systems namely active and passive compliance. The active compliance in rigid robots can be defined as application of sensory force and torque data to control the position of the end-effector [9]. Therefore, this technique is complicated, and requires a fast real-time response which limits its application. On the other hand, passive compliance can be achieved by integrating soft and compliance joints and links in the structure of the robot [9]. Thus, passive compliance systems can deform under external forces without requiring any sensory data, and control system. Therefore, the passive compliance in the structure of soft robots can be designed for safe human robot interaction. However, the passive compliance systems suffers from issues such as low accuracy and complex dynamics [9]. Most soft robotic systems comprises from serial or hybrid structure [10] which limits their blocking force, and accuracy. Soft parallel robots can address these shortcomings [9]–[12]. The research area of soft parallel robot is relatively unexplored. Amiri Moghadam et al. for the first time in 2015 used the term "soft parallel robot" in his work on development of a 2 DOF soft parallel robot equipped with electroactive polymer actuators [2]. One way to classify the soft parallel robots is based on the application of soft links, and joints. Amiri Moghadam et al. have utilized both soft links, joints in 2 and 3 DOF soft parallel robots [2], [13] Bryson et al. have proposed the soft links in a soft parallel robot [10]. Subsequently, other research teams have utilized soft links [9], [12], [14], [15]. Yang et al. have demonstrated

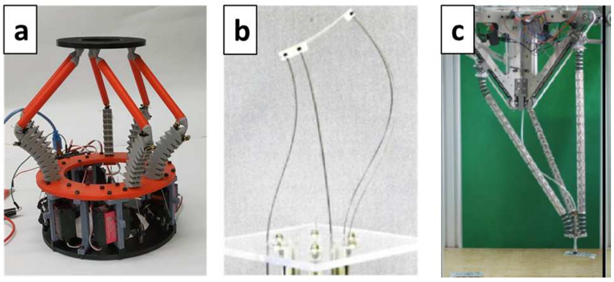

Fig. 1. Soft parallel robots: (a) the proposed 6 DOF soft link and joint soft parallel robot. (b) the flexible link parallel robot [10], and (c) the flexible joint soft parallel robot [11].

the application of soft joints for soft parallel robots. In the current work, we are proposing a novel six DOF soft parallel robot which can move in x, y, and z directions and rotate in roll, pitch, and yaw. The proposed soft robot is analogous to the rigid Stewart [16] mechanism and consists of six soft active links which are connected to passive links and the robot platforms through soft joints. Figure 1 compares the proposed soft parallel robot with the existing ones which only have soft links or joints.

The rest of the paper is organized as follows. In section II the design and fabrication 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 discusses the modeling, design, and fabrication of the soft robot and presents the experimental results.

The design of the soft robot is inspired from the structure of a rigid Stewart mechanism. To transform this mechanism to its analogous soft parallel robot we replace the linear actuators and rigid joints with soft bending actuators and soft joints. This design consists of the following: six soft links, six servo motors and mounts, six wire wheels, a mobile platform and modular base assembly.

Each of the soft closed kinematic chains consists of one soft link, one compliant link, and two soft joints (Fig. 2). The links are attached to the base with a 4 mm bolt through a hole in the end of the soft link, and the top flexure link is attached permanently to the underside of the top plate. The six links are grouped in pairs and orientated 120 degrees from the other paired links; within the pairs, the links are 30 degrees apart.

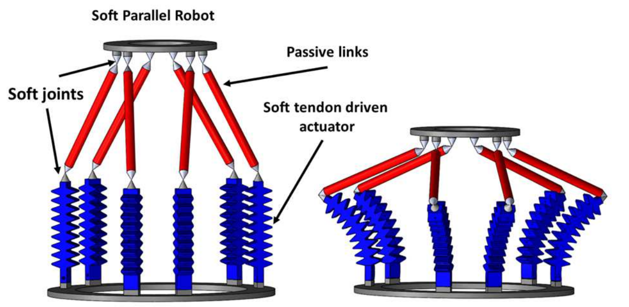

Fig. 2. Cad model and the prototype of the soft 3d-printed in TPU.

The initial soft joint design was chosen over a standard ball and socket because the latter would have to be made with a rigid material and would wear over time. Of the many joint designs considered, the hyperbolic profile has been shown to provide the most stable point of rotation. After 3D printing and testing several diameters, the current diameter of 2.8 mm was the dimension that showed to be effectively durable and flexible.

Additionally, the soft tendon driven actuators are designed to have thread run along the length of the part. This thread is responsible for the link's motion (CW and CCW rotations); when the thread is pulled on side, the link will flex towards that pull. This actuation is controlled with the rotational motion a wire wheel that is connected the threads to an Arduino that is by changes in programming.

This forward and backward actuation is achieved by the rotation of a servo motor that is connected to a wire wheel where the threads tie in. The servo's motion is controlled via computer is an Arduino IDE.

To make the design modular and simpler to 3D print, the base assembly is split into a base top, base bottom, and connecting legs that are bolted together with metric screws and bolts. The soft link and compliant flexure links are printed with Ninjaflex using 100% infill. This material was chosen for its shore hardness (85A) and stretch/elongation (660%) which allowed for maximum flexibility while retaining enough stiffness for the build to remain upright independently. The entire base assembly, top plate, all wire wheels, and complient links are printed in polylactic acid (PLA).

In the original assembly, the thread that actuated the soft links was secured with a nut and bolt to allow for retightening after each experiment. However, the nut and bolt did not hold well after more than a couple of experiments and would occasionally shoot off the threads when the link was actuated aggressively enough. As a solution, we created and 3D-printed a design based on a boat cleat that held firmly through more experimental runs while still allowing for easy disassembly.

Individually, the soft links are capable of 1 DOF motion as described earlier. However, when the model is completely assembled, the soft link and joint design allows for complete 6 DOF motion.

As shown in Fig. 3, when the soft links are actuated outward, the top platform is moved vertically. Vertical displacement can be achieved by flexing the links toward the center of the model, but displacement is more significant with outward actuation. Horizontal motion is achieved by flexing a single pair of links at a time, while roll, pitch, and yaw are achieved through various combinations of soft link flexures.

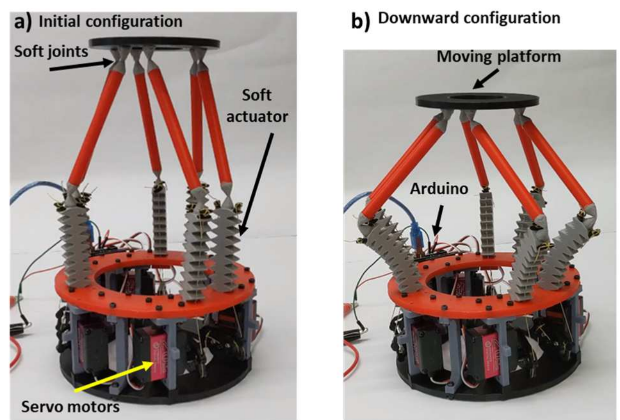

Fig. 3. (a) Initial configuration and (b) downward configuration (all soft actuators bend outwards).

As shown in Fig. 4 the soft robot experiment setup consisted of the soft parallel robot, power supply, a laptop with MATLAB and Arduino IDE, and a 6 DOF electromagnetic motion sensor. To experimentally validate that the robot has 6 DOF and is capable of moving in arbitrary points within its workspace, the position and orientation of the robot will be sensed by an electromagnetic (EM) trackers [17] attached to the robot end-effector. EM trackers have been successfully used in several studies to measure the 6 DOF motion [17], [18]. The system consists of two main components: sensors, and EM transmitter. The sensors are arrays of small coils which will be placed at the catheter tip and the transmitter will generates a small EM filed to track the sensors. The system is capable of measuring 6 DOF motion (x, y, z, roll,

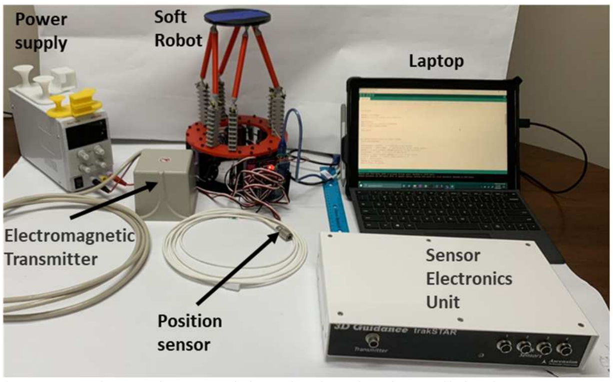

Fig 4. Experimental setup of the 3d-printed soft parallel robot.

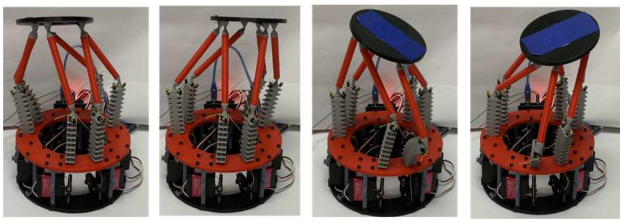

Fig 5. Different configurations of the parallel soft robot.

pitch, yaw). Fig. 5 shows several configurations of the soft robot.

III. Modeling

In this section, the kinematic and dynamic model of the soft parallel robot will be presented using Matlab Simscape. 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.

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], [19]. Next, proper frames will be

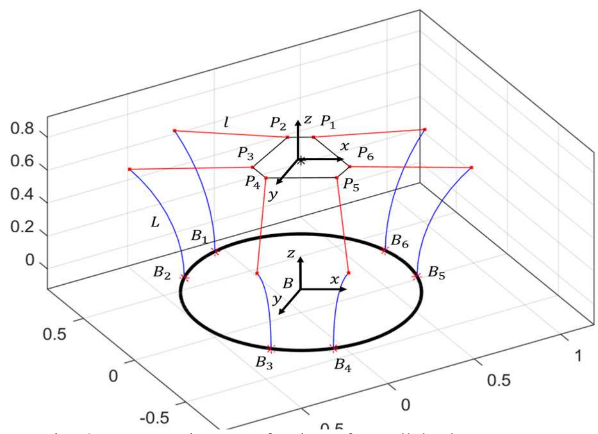

Fig. 6. Frame assignment for the soft parallel robot.

assigned to the soft robot platforms. Based on Fig. 6, the kinematics model of the soft robot can be defined as follows:

$$\{B_i^B\} + \{L_i^B\} + \{l_i^B\} = \{P_P^B\} + [R_P^B]\{P_i^P\} \quad (1)$$
$$i = 1 \; to \; 6.$$

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

$$l_i = \|l_i^B\| = \|\{P_P^B\} + [R_P^B]\{P_i^P\} - \{B_i^B\} - \{L_i^B\}\ \| \quad (2)$$
$$i = 1 \; to \; 6.$$

Eequation (2) 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, several trajectories have been simulated. Figure 7 shows the simulation results of the kinematics model for yaw 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. 8. While Fig. 9 demonstrates a vertical trajectory.

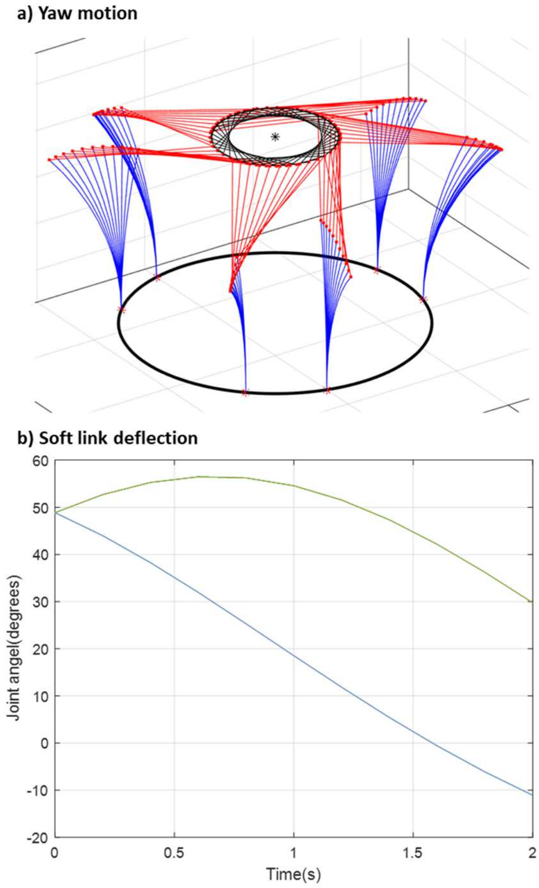

Fig. 7. Simulation of the kinematics model. a) Yaw trajectory, and b) associated bending angels of the soft links.

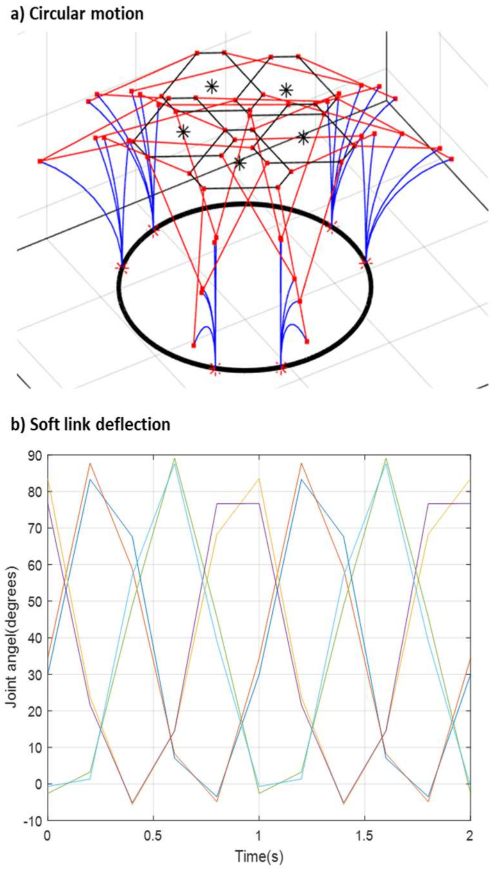

Fig. 8. Simulation of the kinematics model. a) Circular trajectory, and b) associated bending angels of the soft links.

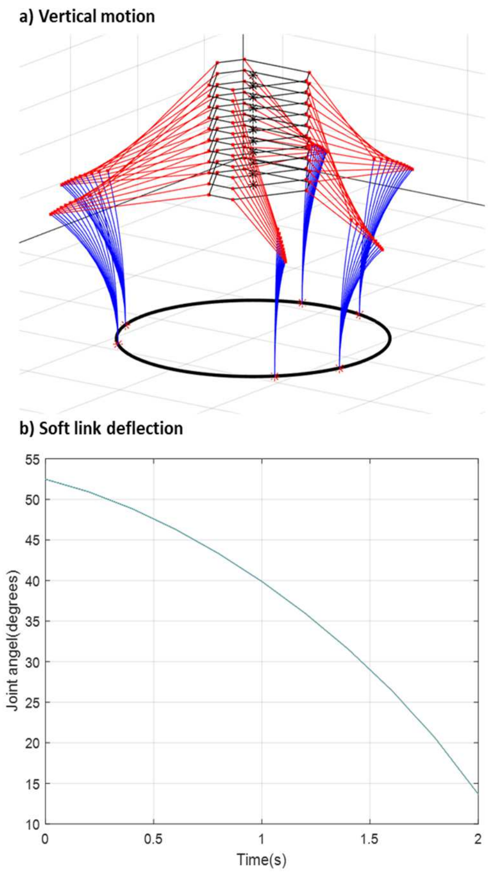

Fig. 9. Simulation of the kinematics model. a) Vertical trajectory, and b) associated bending angels of the soft links.

B. *Simscape Model of The Soft Robot*

Despite the motion capabilities and superiorities of the compliant joints/mechanisms and soft robots, derivation of the mathematical model of complex designs including their dynamics is a very challenging task [20-24]. In this section we designed a graphical user interface (GUI) for our proposed 6 DOF soft robot comprised of soft links, compliant spherical and large deflecting flexure hinges in Matlab Simscape. Matlab Simscape enables to analyze systems either by importing the CAD model or generating the models using the Simulink library. One of the salient features of Simscape modeling is that the simulation results can be exported to the workspace while 3D visualizing the motion through the mechanics explorer. In our previous work, we designed and developed compliant mechanisms by 3D printing and modeled the same systems in Simscape to test how accurately Simscape models simulate a physical system [25].

The Simscape model of this robot consists of four main body parts: bottom plate for housing the motors, rigid arms, top plate, and soft links. Additional elements required to build the model include a subsystem of the spatial contact forces, transform sensors, and the to workspace blocks which collect the coordinates of the top plate. While the top and bottom

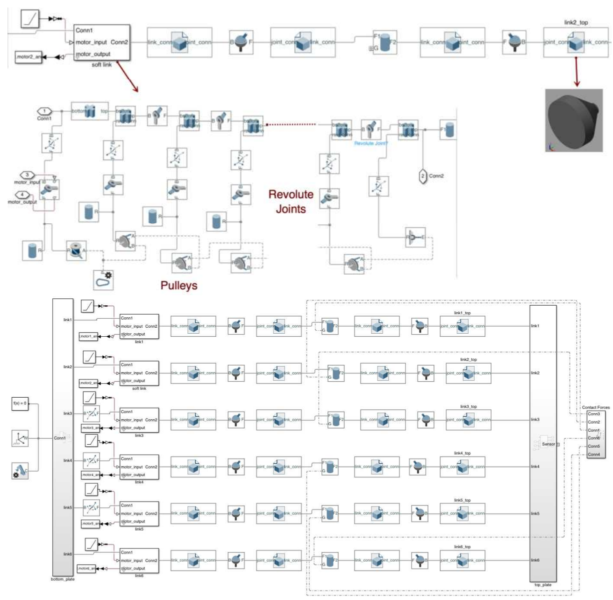

Fig. 10. Simscape model of single arm consisted of soft link, compliant spherical joint, and rigid arm.

plates are imported from Solidworks part files using two File solid blocks, soft links, flexure hinges connecting the rigid arms to the top plate and compliant spherical joint connecting the soft links to the rigid arms are created using Simscape library blocks. First, a single arm is built by modeling a soft link which is connected to a hinge with a spherical joint, and rigid arm with a spherical joint without top connection as illustrated in Fig 10. The soft link is generated by utilizing the alternating extruded solid blocks and revolute joints. The cross-sections for the extruded solids are created using the cross-section sketch of the SolidWorks part file. The stiffness of the soft link is adjusted through the spring stiffness and damping coefficient properties of the revolute joints. The tip of the soft link is connected to a conical hinge. Here, the physical hinge used in the experimental model resembles a spherical joint. In the Simscape model, the hinge is created by first splitting into two while connecting them together using a spherical joint block. The stiffness of these joints is tuned from the internal mechanics of the spherical joint block. A cylindrical solid with a radius of 5 mm and length of 96.3 mm is connected to the hinges. Free end of the soft link is connected to the bottom plate and the top of the second hinge is connected to the top plate.

Since the physical setup of the 6 DOF soft robot is tendon driven using the servo motors, we utilized pulleys to bend the soft links either inward or outward. In the model, the cylindrical solids connected to the belt-cable spool block simulates the motor. A smaller cylindrical solid is placed within each extruded solid element at the point where the string runs through the physical model. Each of these small cylindrical solids are connected to revolute joints and pulley blocks. This series of pulleys ends with a belt-cable end block at the last element of the link. It should be noted that belt-cable properties block must be connected to the pulley system. The revolute joint that is connected to the motor cylindrical solid is actuated using a motion input and a position sensor is set to collect the rotation data of the motor. This pulley system replicates the strings used to pull the links in the physical model. Spatial contact force blocks are applied between the rigid cylindrical solids of each arm to prevent penetration between the arms. There are a total of 15 spatial contact force blocks used to establish contact from arm to arm.

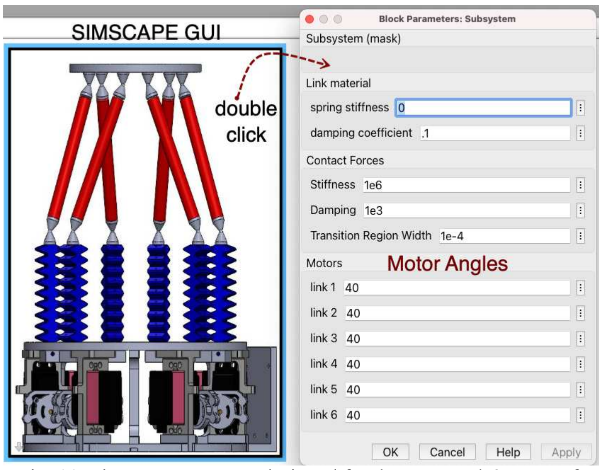

Fig. 11. Simscape GUI App designed for the proposed 6 DOF soft robot.

A GUI App is created for the proposed 6 DOF soft robot as shown in Fig. 11. Once the user double clicks on the image, the App allows the user to enter the material properties of the soft link and change the input angles and can also open the Simscape model by simply clicking on the little arrow on the

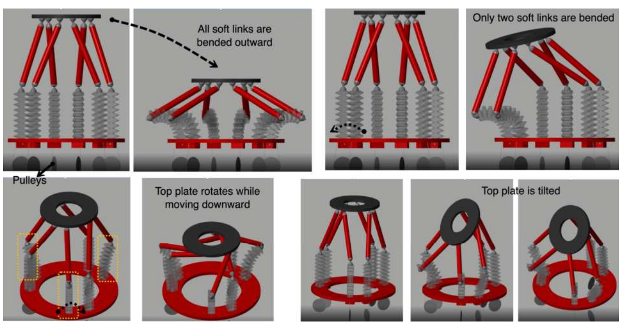

Fig. 12. Simulation of 6 DOF Soft Robot in Matlab Simscape.

bottom left corner of the image and change the geometry of the soft and rigid links. The top plate trajectory depends on how (inward/outward) and how many soft links are actuated as some of the possible trajectories are provided in Fig. 12. If all the soft links are bended outward, then the top plate is displaced in the vertical direction. If only three motors are actuated such that motors 1, 3 and 5, then the top plate moves along the vertical direction while rotated by 90°. If only two soft links are bended, then the top plate is tilted towards the bended links.

C. Validation of The Simscape Model

The coordinates of the top plate are recorded using the 6 DOF sensor from the experimental setup while bending all soft links through the pulleys and the servo motors by 35° in the outward direction. Same inputs are supplied to the Simscape model and results are compared as shown in Fig. 13. The small deviations are due to the delay in the actuation of the motors through Arduino and the adjustment of the string tension of each soft link but overall, the top moves about 5 cm. validating the Simscape model.

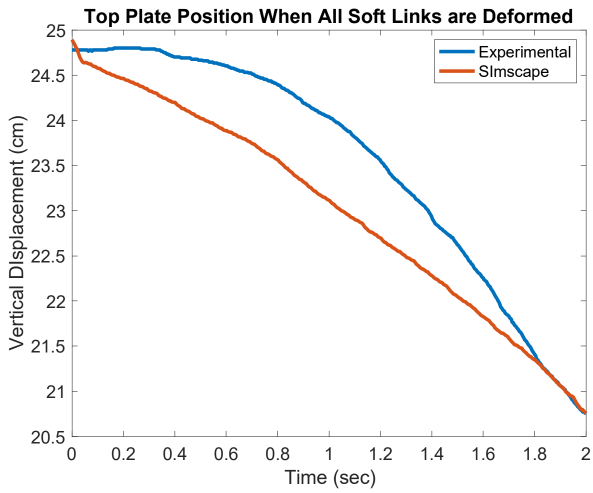

Fig. 13. Comparison of the experimental and simulated coordinate of the top plate when all the soft links are deflected outward.

IV. Conclusion

This paper reports on the design, modeling, and fabrication of a novel six DOF soft parallel robot which is analogous to a rigid Stewart mechanism. The robot consists of six 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 NINJA Flex and actuated through six 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 arbitrary 3D trajectories within its workspace. The dynamic model of the soft robot is simulated using Simscape. To simulate the motion of the soft links, they have been modeled 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. Future work includes robust position control of the soft robot and design of a 6 DOF joystick for the system.

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