ANALYSING DESIGN MODIFICATIONS EFFECTS ON THE COMPLIANCE OF DEFORMABLE HYBRID SERIAL-PARALLEL MANIPULATORS

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ABSTRACT

This paper presents a quantitative study on the effects of angle variation-disposition of actuators on the compliance of a class of Deformable Hybrid Serial-Parallel Manipulators (DHSPM). Although compliance is desired to achieve a secure and stable maneuverability, high stiffness is good to provide precision and reject perturbations. Thus, the compromises between compliance and stiffness can have different profiles along the degrees of freedom of deformable robots. The study is based on the simulation of the model of the robot derived from computational mechanics (Finite Element Method) and is conducted on a DHSPM with antagonistic actuation. We show that antagonistic actuation predominantly increases stiffness in torsion when activated and that by changing the orientation of the actuator it is possible to increase compliance in one direction while decreasing it in another. Finally, we provide guidelines for the design of soft robots having a parallel structure such as deformable hybrid serial-parallel manipulators.

Keywords: Soft Robotics; Design Theory; Simulation.

ANALYSE DES EFFETS DE CHANGEMENTS DE DESIGN SUR LA COMPLIANCE DE ROBOTS DÉFORMABLE HYBRIDE SÉRIE-PARALLEL

RÉSUMÉ

Cet article présente une étude quantitative sur l'effet qu'apportent des variations de l'orientation des actionneurs de manipulateur hybride série-parallèles déformables (DHSPM) sur leur compliance. Même si la compliance est désirée afin d'obtenir une maniabilité stable et sécuritaire, la rigidité permet d'obtenir de la précision ainsi que de rejeter les perturbations. De ce fait, les compromis qui sont fait entre la rigidité et la compliance peuvent avoir différents profils dépendamment du degré de liberté observé. L'étude est effectuée par simulation d'un modèle en élément fini du DHSPM ayant de l'actionnement antagoniste. Il est démontré que l'actionnement antagoniste augmente principalement la rigidité en torsion alors que le changement d'orientation des actionneurs peut entrainer une augmentation de rigidité dans certains degrés de liberté tout en la réduisant sur d'autres. Finalement, nous proposons des lignes directrices afin d'aider à concevoir des robots déformables ayant une structure parallèle tel les manipulateur hybride série-parallèle.

Mots-clés : Robotique Déformable; Théorie de Conception; Simulation.

1 INTRODUCTION

Compliance is an increasingly desired property in many robotic applications. Indeed, compliance is usually desired whenever there are robot-human interactions involved such as in minimally invasive surgery [1–3] or human-machine material handling [4]. Multiple research works have thus been carried out to achieve compliance in traditional robotics such as using active compliance where the controller is used to reduce the stiffness when the robot interacts with its environment [5] or to develop mechanisms that would allow passive compliance at the manipulator joints as proposed by [6–8]. Although these methods can reduce the stiffness, they are still based on traditional robots which were designed for rigidity and precision while performing repetitive tasks in controlled environments. These robots are thus not completely suited for use in a highly changing environment with human presence. An alternative to adding mechanisms on manipulators or to use the controller to increase the compliance is to use soft robots. Indeed, soft robotics is an increasingly popular field due to the intrinsic ability for deformation of the system and it is believed that soft robots could replace their rigid counterparts whenever they are involved in a working environment with human presence.

Design of soft robots is still in its infancy, and has mainly focused on prototype actuators and grippers [9–13]. Although some of the designs are functional, they remain not fully suited for commercialization. Promising designs are soft continuum manipulators, which are robots often inspired by biological agents such as elephant trunks and octopus tentacles [14–16] and tendrils [17], and offer a suitable alternative to their rigid counterparts for robot-human interactions applications due to their compliant nature. Indeed, robots such as the FeTCh [18] are hybrid serial-parallel manipulators that use soft actuators instead of the typical hydraulic rigid ones. Although multiple prototypes exist, the design of such devices is still an open topic in the robotics community since there are no formal design guidelines to follow.

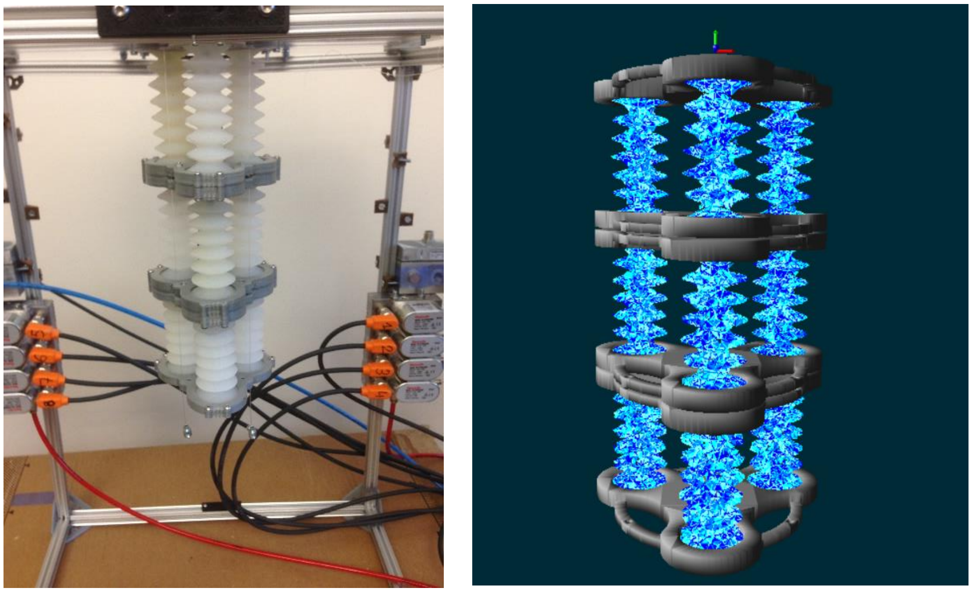
This lack of formal guidelines can be related to the difficulty of extracting the properties of such manipulators as there are no analytical models that can be employed due to the nonlinear behavior of the deformable parts. Indeed, analysis, modelling and control of soft robots is usually achieved through using finite element method (FEM) [19,20]. Furthermore, the design process of soft robots, being mobile robots, grippers, or manipulators is still highly a trial and error process to obtain the desired properties as almost no studies have been carried out to analyze the behavior of these systems under various working conditions. Thus, to improve the design process of soft robots, it is required to better understand how the compliance, which is the principal desired characteristic for soft robots, is affected when making design changes. This will help in relying less on multiple trial-error loops and thus accelerate the development of soft robots for their use in tangible applications.

Therefore, in this paper we focus on providing insights about the compliance of deformable hybrid serial-parallel manipulators (DHSPM) when subject to design modifications. We first provide a larger background on the general characteristics of DHSPM. Then we provide the methodology that was employed to analyze the compliance of the manipulators. Finally, we present the results of the analysis and we provide insights on how to attain desired properties.

2 DEFORMABLE HYBRID SERIAL-PARALLEL MANIPULATORS

2.1 Pressure Actuated Sections

This paper mainly focuses on the design of a deformable hybrid manipulator similar to the FeTChMK1 which is shown in Fig. 1. These robots are composed of three (or more) deformable pressure actuators (either air or liquid) rigidly connected in parallel and similar to a Stewart platform, which are then combined to form a serial-parallel manipulator. Such a manipulator benefits from some of the typical properties of rigid hybrid manipulators such as increased workspace compared to parallel robots, better control/accurate motion, and improved rigidity compared to serial robots [21].

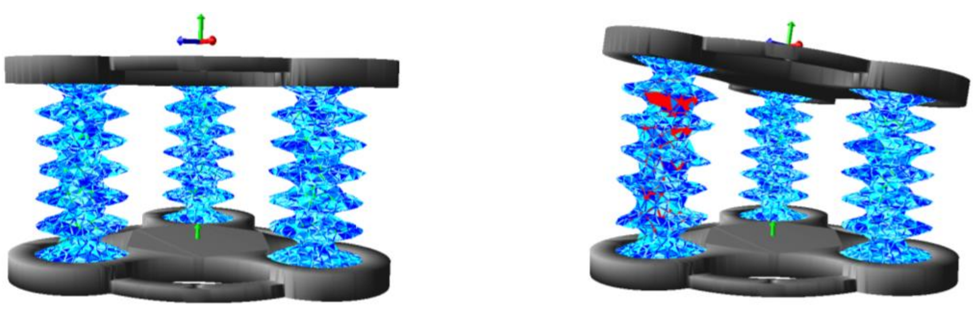


(a) (b)

Fig. 1. FeTCh Deformable Hybrid Serial-Parallel Manipulator (a) Real Implementation (b) FEM Simulation

Motion of the deformable robot is induced by silicon accordion-like pressure actuator. The accordion shape allows for the elongation of the cavity when pressurized; this type of behavior is called extensor. This behavior is in contrast with the Mckibben actuator (artificial muscle) [22,23] which shortens when actuated.

As mentionned earlier, the soft actuators are rigidly connected in parallel. This has many benefits such as easing the fabrication process or by allowing a more accurate FEM to be created for the control of the robot. Moreover, deformable manipulators are simple structures with few components compared to their rigid counterparts as there is no need for mechanical joints (such as spherical joints) that would allow the effector to rotate since the deformable components allow for such motion. Indeed, it is shown in Fig.2 (a) and (b) how a section (parallel robot) deforms from its orginal position when pressure is applied in the cavity of an actuator.



(a) (b)

Fig. 2. FEM of a manipulator section (a) unactuated (b) with left inflated actuator.

2.2 Antagonistic Actuation

Another way of actuating soft robots other than pressure is by using cables. By combining both cable actuation and pressure actuation it is possible to obtain antagonistic actuation. This has many advantages such as increasing the number of controllable degree of freedom of the manipulator, and potentially controlling the stiffness of the robot. Indeed, the pneumatic actuator works only in extension while the cable works in compression. Thus, combining these two actuations can help increasing the robot's stiffness (as it will be shown in section 5.2) as they are working against each other. In the case of the DHSPM, antagonistic actuation can be achieved by adding cables to each individual section from the robot's base to the section's end, or to the whole robot by only connecting the base to the end-effector, which is shown in Fig. 3. Although both methods for connecting the cables have the same controllable degree of freedom, a manipulator like the one in Fig.3-(a) would have more degree of actuation and potentially a larger workspace.

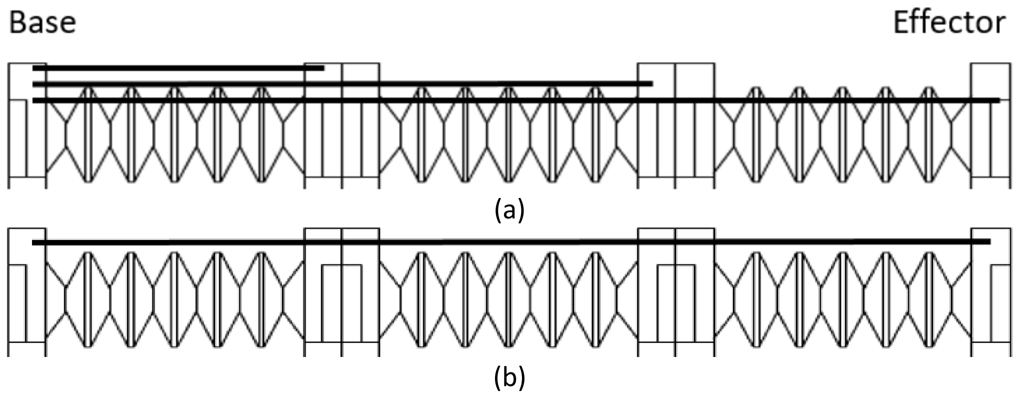


Fig. 3. Connection of cables for antagonistic actuation (a) for each sections (b) single cable from base to effector

3 DESIGN MODIFICATIONS FOR DHSPM

3.1 Orientation of the Actuators

There are multiple factors that can influence the compliance of soft robots. Changing the material or thickness of the membrane (as in the case of pressure actuators as shown in Fig.4) would necessarily modify the properties of the manipulator. However, there are certain limitations that should be accounted for when doing so. First, the fabrication of these robots is still a highly artisanal process (silicon casting, 3D printing) and thus limitations exist regarding the usable materials and the maximum/minimum dimensions. Furthermore, because finite elements are usually used to model the robots, there are also limitations regarding the dimensions as the meshing process for the FEM might result in an inaccurate model, or a too computationally heavy one. Therefore, in this paper we explore design variations of the DHSPM section by changing the orientation of the actuators and analyze the effect on the compliance. This analysis is based upon the assumption that a functional and realizable actuator has first been designed for the desired robot size. By using a standard actuator during the analysis, we are also trying to solve one of the problem raised by [24] which states that soft robotics lack standardized components such as in rigid robotics, which leads to difficult knowledge transfer between finalized projects and new designs. Therefore, throughout the analysis of different section designs, the same actuator, shown in Fig. 4, is used. Furthermore, it is worth noting that the actuators used in this paper are made of Dragon Skin 10 Silicon [25].

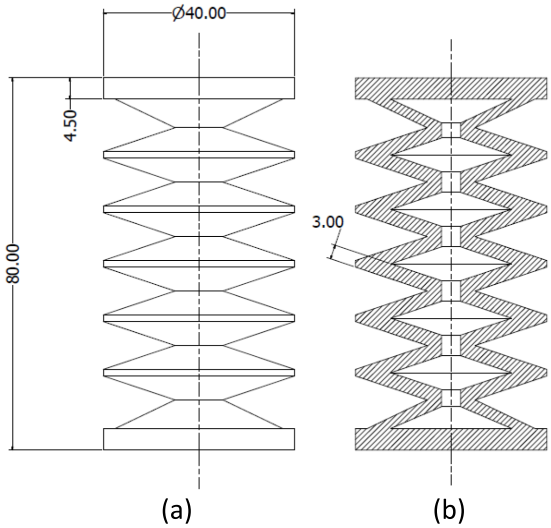


Fig. 4. (a) pressure actuator dimensions, (b) cross section of the actuator, dimensions are in mm.

We analyze the effect of changing the orientation for both inward (degree-In) and outward position (degree-Out) where we define the degree-*In* orientation of the actuator being oriented towards the center of the DHSPM section. Models of sections with different orientation are shown in Fig.5 . We will refer to the design variations as follows: *value*-Deg-*orientation*. Thus, a section having 10 degrees inwards orientation will be referred as "10DegIn" and the one with 10 degrees outwards as "10DegOut".

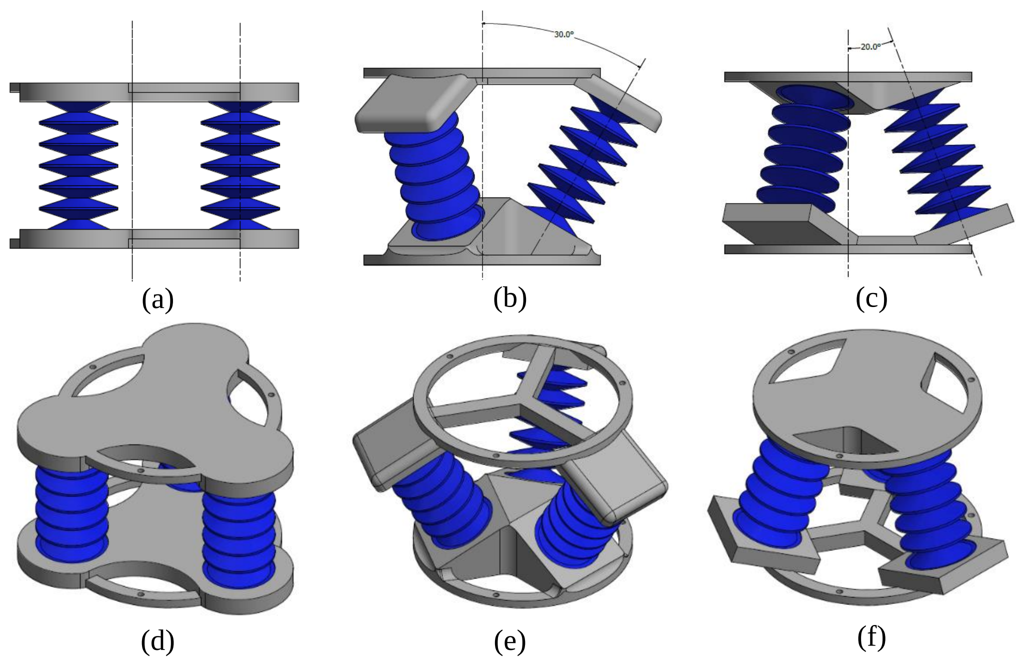


Fig. 5. (a)-(c) side view of a 0Deg, 30DegOut, 20DegIn manipulator section (d)-(f) isotropic view of 0Deg, 30DegOut, 20DegIn manipulator section

Furthermore, each of the sections were designed such that the centroid of the actuators laid on a circle of 55mm radius around the y axis as it shown in Fig. 6.

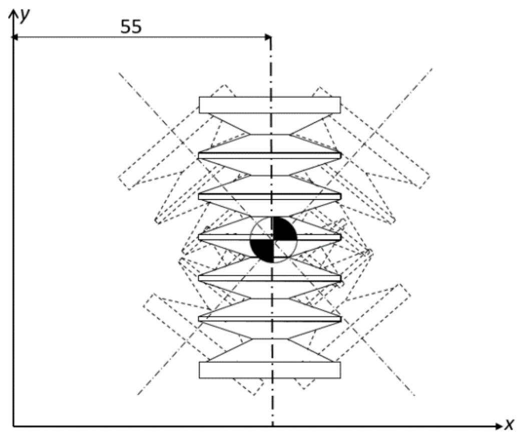


Fig. 6. Actuator positioning around the y axis

3.2 Number of Cables in Antagonistic Actuation

Antagonistic actuation can be used to control the stiffness of the manipulator, making it stiffer or more compliant by having the cables act against the pneumatic actuators. The intuitive design would be to use the same number of cables as pressure actuators to have a complete antagonistic effect. However, there is not any increase in controllable degree of freedom from adding one or three cables for the sections of the currently studied DHSPM. Indeed, the pressure actuators allow for positive translation along the vertical axis (y-axis in this case) and rotation around the other two (x/z) while the cables only enable negative translation along y. It is not possible to achieve x/z translation if the actuators/cables are not inclined from the y-axis. Furthermore, it would not be possible to achieve rotation around the y axis if only three pressure actuators and cables are used in configurations similar to the ones in Fig. 5. However, having three cables increases the workspace of the robot as well as improves its control compared to zero or one cables, as shown in Fig. 7. In the case of the FeTCh manipulator, the cables are located opposite to each actuator and apply a moment to the rigid vertebrae, which in turn, allows for greater bending angles. Nevertheless, because of the disposition and width of the actuators, the force applied by the cables also introduces undesired behaviors such as on the shearing of the section (i.e there could be displacement of the effector along the x/z axes, but this motion would be a result of the robot's deformation and would not be controllable). Thus, we investigate if increasing the number of cables is beneficial for increasing the stiffness of a DHSPM, even if this, in turn, increases the complexity of the design.

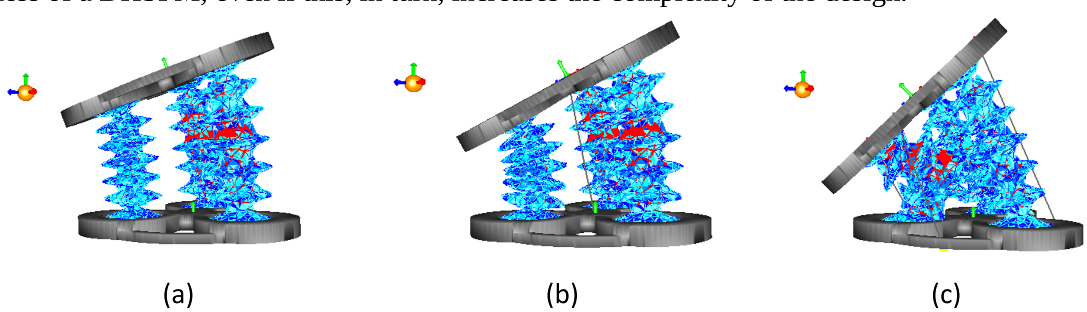


Fig. 7. Tracking of an object (sphere) for (a) cable-less section, (b) section with center cable, (c) three cable section

4 MEASURING THE COMPLIANCE OF A SECTION

Behavior of the DHSPM is dictated by the behavior of the sections it is composed of. Although soft robots are non-linear entities, it is possible to assume linear behavior in the deformation of soft actuators that are comprised between two rigid section as it is shown in [26]. Thus, we focus on the analysis of a single section of the manipulator. As mentioned previously, analysis of soft robots is achieved numerically and in this paper, we use the SOFA framework [27] with its Soft Robots plugin [28] for simulating the deformable robots. The FEM of an actuator is created using CGAL [29] and each of the actuators are constituted of 3550 tetrahedra. Furthermore, during the simulation the cables (when antagonistic actuation is used) are considered rigid in tension.

The compliance, which is defined as the inverse of the stiffness and denoted by $\mathbf{K}^{-1}$, is measured through simulation. The FEM initially results in a sparse stiffness matrix being built. We inverse and condense the sparse matrix to a 6x6 compliance matrix by applying a wrench at the effector of the robot's model and retrieving the displacement to build the condensed matrix. This process is similar to methods that have been substantially used for analysis of rigid serial, parallel and hybrid manipulators where an exact model is difficult to obtain [30–32]. However, in this paper we use the FEM instead of the real robot.

As mentioned earlier, we assume that there is a linear behavior for small displacement/force between two rigid sections. This assumption allows for the comparison of the condensed compliance matrices, $\mathbf{K}^{-1}$, of the various designs, which will be used to better understand the effect of actuator orientation and antagonistic actuation in the compliance of these systems around home configuration. In fact, Eq. (1) is equivalent to the result of simulation, where an example of simulation measurement is shown in Fig. 8.

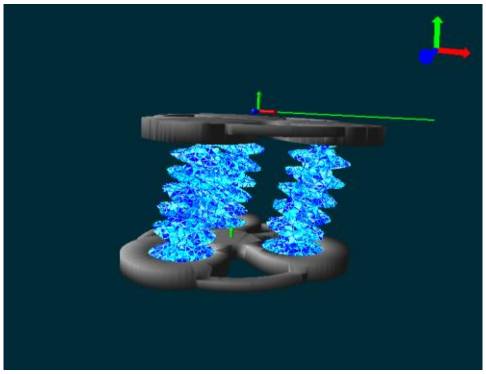


Fig. 8. Simulation of the compliance measurement in SOFA

$$\left[\delta p_x\ \delta p_y\ \delta p_z\ \ \delta\phi\ \ \delta\theta\ \ \delta\psi\right]^T = \mathbf{K}^{-1}\left[F_x\ \ F_y\ \ F_z\ \ M_x\ M_y\ M_z\right]^T \tag{1}$$

with $\left[\delta p_x\ \delta p_y\ \delta p_z\right] = \Delta\mathbf{p}$ being the change in position along the principal axis and $\left[\delta\phi\ \delta\theta\ \delta\psi\right] = \Delta\mathbf{r}$ being the change in orientation. However, it is not possible to extract the full compliance matrix from the simulation if a single wrench is applied. Thus, to build the compliance matrix, we apply multiple wrenches to the FEM in order to compute each column i of the compliance matrix by measuring the resulting displacement vector $\left[\Delta\mathbf{p}\ \Delta\mathbf{r}\right]^T$ such as shown in Eq. (2).

$$\left[\Delta\mathbf{p}_i^*\ \Delta\mathbf{r}_i^*\right]^T = \mathbf{K}^{-1}\cdot(\text{onehot}_6(i)\cdot a_i)^T \tag{2}$$

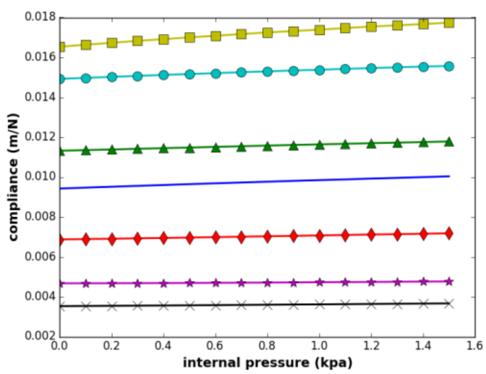
where $\text{onehot}_6(i)$ is the function that return a vector with 1 at the element i and 0 otherwise (ex: $\text{onehot}_6(2) = [0\,1\,0\,0\,0\,0]$), and a_i is a scaling factor for the wrench which value should be chosen to ensure linear behaviour. It is to note that in this paper, a_i was chosen after trial-error through the simulation and resulted in $a_1 = a_2 = a_3 = 1\,[\text{N}]$ and $a_4 = a_5 = a_6 = 0.05\ [\text{Nm}]$. The resulting vectors $\left[\Delta\mathbf{p}_i^*\ \Delta\mathbf{r}_i^*\right]^T$ are temporary values directly extracted from the simulation which need to be descaled, as shown in Eq. (3), in order to be used to fill the compliance matrix. These steps are similar to multiplying $\mathbf{K}^{-1}$ by the identity matrix.

$$\left[\Delta\mathbf{p}_i\ \Delta\mathbf{r}_i\right]^T = \left[\Delta\mathbf{p}_i^*\ \Delta\mathbf{r}_i^*\right]^T / a_i \tag{3}$$

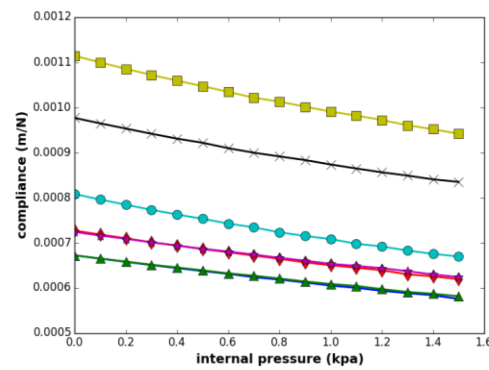
5 RESULTS

5.1 Effect of Actuator Orientation on the Compliance

Different methods can be used to analyze the compliance of a system through the compliance/stiffness matrix such as using the trace, by computing the determinant, or by finding the eigenvalues [33]. However, in this paper we carry out a more detailed analysis by providing the diagonal elements of the compliance matrix. Using these results better help in understanding the effect of the design modification as some modifications might result in an increased stiffness in a specific direction and reduced it in another. Furthermore, we also provide results of the compliance with different internal pressure values as it would necessarily affect the results, especially if antagonistic actuation is used. The results from the simulation for different internal pressures of the actuators are shown in Fig. 9.



(a)



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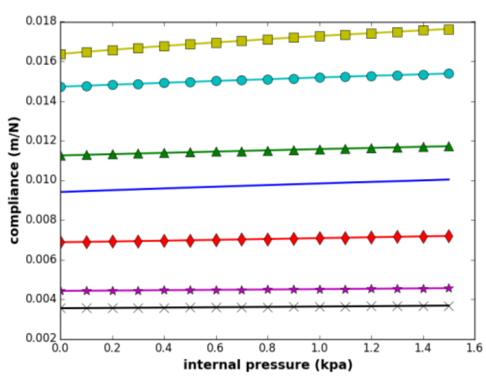
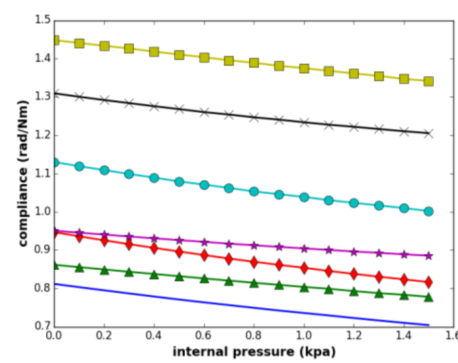


(c)



(d)

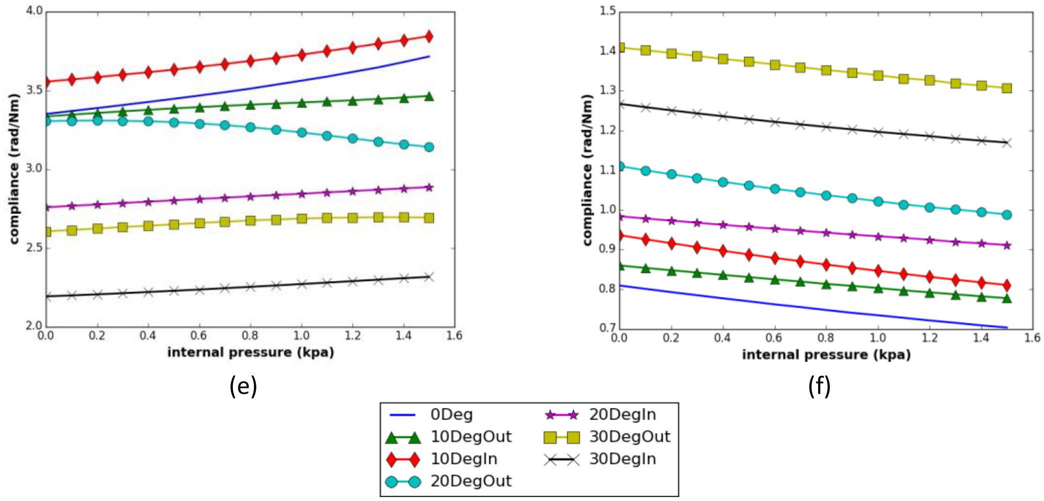


Fig. 9. (a)-(c) Compliance in displacement along x,y,z respectively. (d)-(f) Compliance in rotation around x,y,z respectively. In (b), 10DegOut overlaps 0Deg, and 20DegIn overlaps 10DegIn

As it can be seen in Fig. 9, the compliance is only slightly modified when the actuators are pressurized if no antagonistic actuation is used. Furthermore, the results also show that the main advantage of changing the orientation of the actuator is to gain stiffness in "shear", which is obtained by inward orientation. However, changing the orientation, both inward and outward increases the compliance in torsion along the non-vertical axes. These findings constitute interesting design guidelines for this type of actuators.

5.2 Effect of Antagonistic Actuation on the Compliance

As mentioned previously, antagonistic actuation has the potential to increase the stiffness of a soft robot. We use the same process as the analysis from the change in orientation to obtain the results regarding the effect of using one cable in the center or three cables (as it was shown in Fig.7). These results are shown in Fig. 10.

As it can be seen in Fig. 10, adding a single cable in the center of the actuator does not seem to have a positive effect on increasing the stiffness of the manipulator section as it might have been expected. This is the result of the center cable acting as a pivot point, especially for rotations around the y axis. However, adding 3 cables does significantly reduce the compliance (as seen in Fig. 10, specially 10*d* and 10*f*) and thus could be used whenever a stiffer section is desired, such as the base of the manipulator.

Furthermore, it is possible to significantly rigidify the structure of the robot by combining both change in orientation and antagonistic actuation. Indeed, by using a 30 degree-In section with three cables should increase both the "shear" stiffness, which was just slightly improved for the parallel section with antagonistic actuation, and the non-vertical axis torsion stiffness.

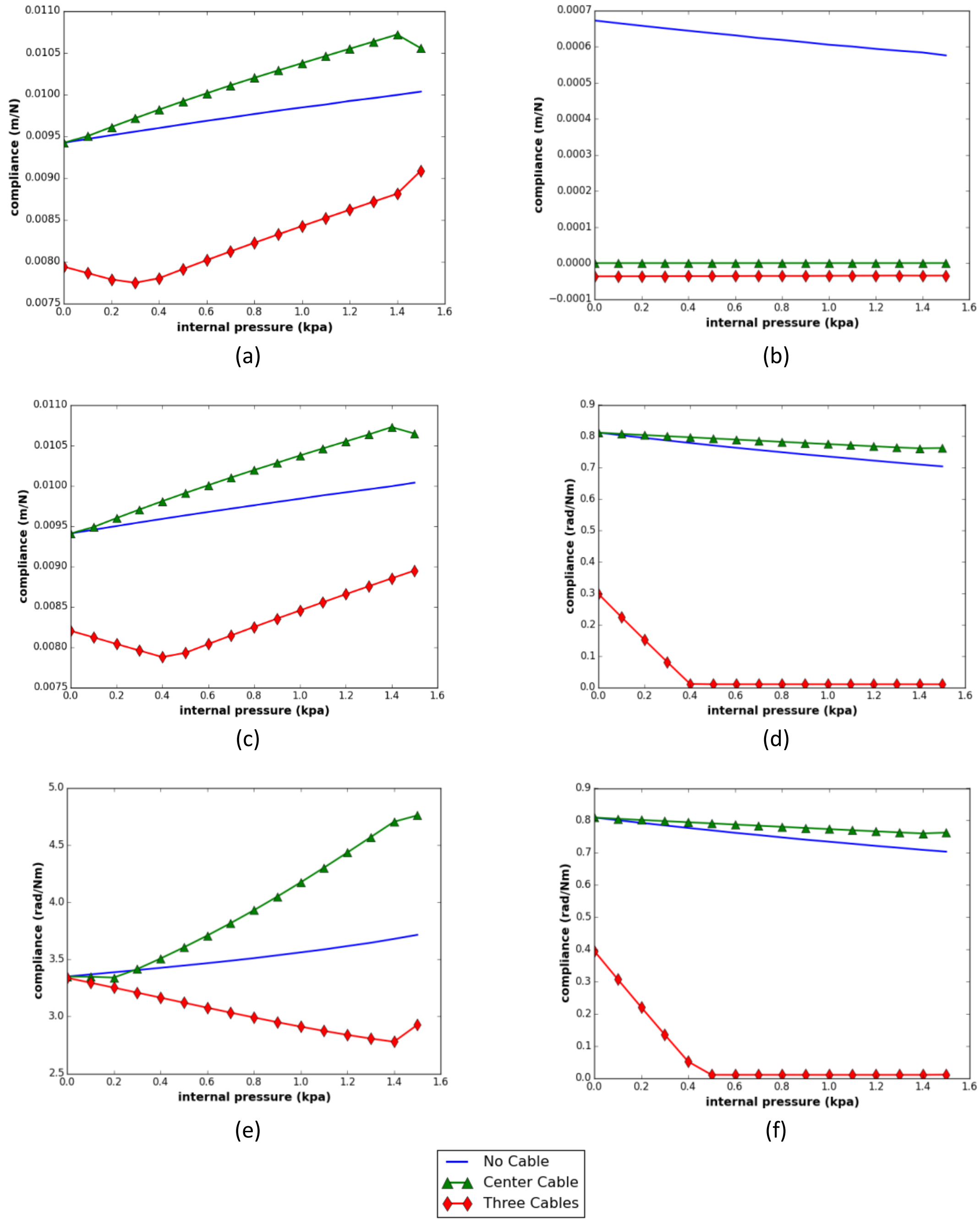


Fig. 10. (a)-(c) Compliance in displacement along x,y,z respectively. (d)-(f) Compliance in rotation around x,y,z respectively, for 0 degree section

6 DISCUSSION AND CONCLUSION

Soft robotics still lack standardized components to support faster development and to reduce the variability of trial-error based design process. In this paper, we demonstrated how it is possible to extract the properties, such as the compliance, of deformable robots through simulation. Moreover, we showed that it is possible to control the properties of deformable hybrid serial-parallel manipulators by changing the orientation of the soft actuators or through antagonistic actuation. Indeed, these design modifications can be used to obtain properties for the robot without necessarily designing multiple actuators. Furthermore, the result of the analysis could lead to new control algorithms for active stiffness, which would be similar to the rigid robots algorithms for active compliance. This would be achieved by having a minimum pressure in the actuator to rigidify the structure using antagonistic actuation. Moreover, the compliance analysis can be extended to design displaying similar patterns where multiple actuators are connected in parallel, such as in walking robots or soft grippers. Finally, some design guidelines can be drawn from the current analysis. If greater shearing stiffness is desired, it is required to orient the actuators inwards. Antagonistic actuation with 3 cables should be used whenever increased stiffness in torsion is desired. Finally, the only advantage of using antagonistic actuation with a central cable is if larger rotation angle is desired, such as in the case of a 6 actuators Stewart platform that allow rotation around the symmetry axis, as the central cable increases the compliance.

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REFERENCES

[1] Tzemanaki, A., Fracczak, L., Gillatt, D., Koupparis, A., Melhuish, C., Persad, R., Rowe, E., Pipe, A. G., and Dogramadzi, S., 2016, “Design of a Multi-DOF Cable-Driven Mechanism of a Miniature Serial Manipulator for Robot-Assisted Minimally Invasive Surgery,” pp. 55–60.

[2] Shi, C., Luo, X., Qi, P., Li, T., Song, S., Najdovski, Z., Ren, H., and Fukuda, T., 2016, “Shape Sensing Techniques for Continuum Robots in Minimally Invasive Surgery: A Survey,” IEEE Trans. Biomed. Eng., pp. 1–1.

[3] Chen, J., and Lau, H. Y. K., 2016, “Transferring Autonomous Reaching and Targeting Behaviors for Cable-Driven Robots in Minimally Invasive Surgery,” pp. 79–84.

[4] Bicchi, A., Rizzini, S. L., and Tonietti, G., 2001, “Compliant Design for Intrinsic Safety: General Issues and Preliminary Design,” pp. 1864–1869.

[5] Shetty, B. R., and Ang, M. H., 1996, “Active Compliance Control of a PUMA 560 Robot,” pp. 3720–3725.

[6] Cutkosky, M. R., and Kao, I., 1989, “Computing and Controlling Compliance of a Robotic Hand,” IEEE Trans. Robot. Autom., **5**(2), pp. 151–165.

[7] Albu-Schäffer, A., Haddadin, S., Ott, C., Stemmer, A., Wimböck, T., and Hirzinger, G., 2007, “The DLR Lightweight Robot: Design and Control Concepts for Robots in Human Environments,” Ind. Robot Int. J., **34**(5), pp. 376–385.

[8] Tsagarakis, N. G., Laffranchi, M., Vanderborght, B., and Caldwell, D. G., 2009, “A Compact Soft Actuator Unit for Small Scale Human Friendly Robots,” pp. 4356–4362.

[9] Bishop-Moser, J., Krishnan, G., Kim, C., and Kota, S., 2012, “Design of Soft Robotic Actuators Using Fluid-Filled Fiber-Reinforced Elastomeric Enclosures in Parallel Combinations,” pp. 4264–4269.

[10] Faudzi, A. A. M., Razif, M. R. M., Nordin, I. N. A. M., Suzumori, K., Wakimoto, S., and Hirooka, D., 2012, “Development of Bending Soft Actuator with Different Braided Angles,” pp. 1093–1098.

[11] Seok, S., Onal, C. D., Cho, K.-J., Wood, R. J., Rus, D., and Kim, S., 2013, “Meshworm: A Peristaltic Soft Robot With Antagonistic Nickel Titanium Coil Actuators,” IEEEASME Trans. Mechatron., **18**(5), pp. 1485–1497.

[12] Waynelovich, J., Frey, T., Baljon, A., and Salamon, P., 2016, “Versatile and Dexterous Soft Robotic Leg System for Untethered Operations,” Soft Robot., **3**(2), pp. 64–70.

[13] She, Y., Li, C., Cleary, J., and Su, H.-J., 2015, “Design and Fabrication of a Soft Robotic Hand With Embedded Actuators and Sensors,” J. Mech. Robot., **7**(2), p. 21007.
[14] McMahan, W., Chitrakaran, V., Csencsits, M., Dawson, D., Walker, I. D., Jones, B. A., Pritts, M., Dienno, D., Grissom, M., and Rahn, C. D., 2006, “Field Trials and Testing of the OctArm Continuum Manipulator,” pp. 2336–2341.
[15] McMahan, W., Jones, B. A., and Walker, I. D., 2005, “Design and Implementation of a Multi-Section Continuum Robot: Air-Octor,” pp. 2578–2585.
[16] Zheng, T., Yang, Y., Branson, D. T., Kang, R., Guglielmino, E., Cianchetti, M., Caldwell, D. G., and Yang, G., 2014, “Control Design of Shape Memory Alloy Based Multi-Arm Continuum Robot Inspired by Octopus,” pp. 1108–1113.
[17] Mehling, J. S., Diftler, M. A., Chu, M., and Valvo, M., 2006, “A Minimally Invasive Tendril Robot for In-Space Inspection,” pp. 690–695.
[18] “FeTCh Mark 1 Manipulator | Soft Robotics Toolkit” [Online]. Available: http://softroboticstoolkit.com/fetch. [Accessed: 03-Jan-2017].
[19] Duriez, C., 2013, “Control of Elastic Soft Robots Based on Real-Time Finite Element Method,” pp. 3982–3987.
[20] Largilliere, F., Verona, V., Coevoet, E., Sanz-Lopez, M., Dequidt, J., and Duriez, C., 2015, “Real-Time Control of Soft-Robots Using Asynchronous Finite Element Modeling,” pp. 2550–2555.
[21] Tanev, T. K., 2000, “Kinematics of a Hybrid (Parallel–serial) Robot Manipulator,” Mech. Mach. Theory, **35**(9), pp. 1183–1196.
[22] Tondu, B., and Lopez, P., 1997, “The McKibben Muscle and Its Use in Actuating Robot-arms Showing Similarities with Human Arm Behaviour,” Ind. Robot Int. J., **24**(6), pp. 432–439.
[23] Ching-Ping Chou, and Hannaford, B., 1996, “Measurement and Modeling of McKibben Pneumatic Artificial Muscles,” IEEE Trans. Robot. Autom., **12**(1), pp. 90–102.
[24] Lipson, H., 2014, “Challenges and Opportunities for Design, Simulation, and Fabrication of Soft Robots,” Soft Robot., **1**(1), pp. 21–27.
[25] “Dragon Skin® 10 VERY FAST Product Information | Smooth-On, Inc.” [Online]. Available: https://www.smooth-on.com/products/dragon-skin-10-very-fast/. [Accessed: 05-Apr-2017].
[26] Bosman, J., Bieze, T. M., Lakhal, O., Sanz, M., Merzouki, R., and Duriez, C., 2015, “Domain Decomposition Approach for FEM Quasistatic Modeling and Control of Continuum Robots with Rigid Vertebras,” pp. 4373–4378.
[27] “SOFA” [Online]. Available: https://www.sofa-framework.org/. [Accessed: 03-Jan-2017].
[28] “SOFT ROBOTS Plugin for SOFA – INRIA Lille – DEFROST Team” [Online]. Available: https://project.inria.fr/softrobot/. [Accessed: 03-Jan-2017].
[29] “The Computational Geometry Algorithms Library” [Online]. Available: http://www.cgal.org/. [Accessed: 03-Jan-2017].
[30] Dumas, C., Caro, S., Cherif, M., Garnier, S., and Furet, B., 2012, “Joint Stiffness Identification of Industrial Serial Robots,” Robotica, **30**(4), pp. 649–659.
[31] Tyapin, I., Hovland, G., and Brogardh, T., 2014, “Method for Estimating Combined Controller, Joint and Link Stiffnesses of an Industrial Robot,” pp. 1–6.
[32] Hu, B., Yu, J., Lu, Y., Sui, C., and Han, J., 2012, “Statics and Stiffness Model of Serial-Parallel Manipulator Formed by K Parallel Manipulators Connected in Series,” J. Mech. Robot., **4**(2), p. 21012.
[33] Carbone, G., and Ceccarelli, M., 2004, “A Stiffness Analysis for a Hybrid Parallel-Serial Manipulator,” Robotica, **22**(5), pp. 567–576.