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STIFFNESS CONTROL FOR SOFT SURGICAL MANIPULATORS

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Tunable stiffness control is critical for undertaking surgical procedures using soft manipulators. However, active stiffness control in soft continuum manipulators is very challenging and has been rarely realized for real-time surgical applications. Low stiffness at the tip is much preferred for safe navigation of the robot in restricted spaces inside the human body. On the other hand, high stiffness at the tip is demanded for efficiently operating surgical instruments. In this paper, the manipulability and characteristics of a class of soft hyper-redundant manipulator, fabricated using Ecoflex-0050TM silicone, is discussed and a new methodology is introduced to actively tune the stiffness matrix, in real-time, for disturbance rejection and stiffness control. Experimental results are used to derive a more accurate description of the characteristics of the soft manipulator, capture the varying stiffness effects of the actuated arm and consequently offer a more accurate response using closed loop feedback control in real-time. The novel results presented in this paper advances the state-of-the-art of tunable stiffness control in soft continuum

manipulators for real-time applications.

Keywords: Soft robots; stiffness control; force control; soft pneumatic manipulator; medical robots; flexible continuum robot.

1. Introduction

The robot-assisted Minimally Invasive Surgery (MIS) is gaining popularity due to a faster recovery period and the shorter time for undertaking complex procedures¹. However, the main drawback of commercially available rigid surgical robots is the difficulty associated with navigating these bulky manipulators through a confined space without damaging the surrounding delicate organs. Further, these non-flexible large manipulators also have limited degrees of freedom to reach confined spaces. These constraints with rigid medical robots led to the evolution of soft robots. Today, the field of soft robotics is fast emerging and there are various research papers on continuum robots for minimally invasive surgery.^{1–8} The inherent compliance of a soft continuum robot enables access into confined spaces and thus, performing complex tasks in a more efficient and safe way compared to their rigid counterparts. This emerging technology exhibits a high level of dexterity and enables safe navigation in unstructured environment.^{9,10} However, the state-of-the-art of soft flexible robots reveal that soft continuum manipulators lack the desired distal stiffness to perform any meaningful surgical task, such as tissue manipulation or incision as the structure itself offers limited backbone stiffness.

As the demand for soft surgical manipulators increases, the engineering requirements and functionalities necessary for safe human-robot interaction are becoming more challenging to realize.^{4,5} A fully operational soft surgical manipulator should be capable of safely navigating through complex anatomical pathways, whilst maintaining the stability of the distal tip in the presence of unknown perturbations and obstacles. The ability to control the stiffness of the soft manipulator in real-time is indispensable for its adaptation to a variety of mechanisms and devices in MIS.^{11,12}

Often, due to safety reasons, reduced stiffness at the tip of the soft manipulator is preferred whilst navigating but greater stiffness is essential to undertake useful tissue manipulation with surgical tools. Furthermore, the information on the forces exerted at the distal end of the soft manipulator and an appropriate closed-loop feedback control will enable precise manipulation, thus improving the robustness of the system, as well as safety for the patients. Stiffness control in soft continuum robots is challenging because the mapping of the kinematics and force between the embedded actuator and the tip is coupled. Also, due to the difficulty in sensing the stiffness of continuum robots, active stiffness control can only be achieved partly for methods implying deformation via controlling the deflection using tip position control, without any force or stiffness sensors.¹³ Invariably, the methods of stiffness control for a soft manipulator discussed in the literature are based on an approximation of the robot's coupled kinematics and force mapping, which are used in continuum robots such as the concentric tube robots and tendon-driven.^{14–16} A survey

of literature has revealed that most studies have focused on developing accurate position control^{15,17,18} and to the best knowledge of the authors, apart from,^{1,13} there is no solid research on the analyses and control of the stiffness of a continuum manipulator. Furthermore, it has been shown that this type of manipulator exhibits a high degree of non-linearity due to the high frictional effect that complicates the controller design.^{19,20}

To date, the methods proposed to vary stiffness of soft continuum manipulators are mostly through passive compliance control such as tendon-driven,^{21–23} shape memory alloy actuated,^{24,25} and granular jamming.^{26,27} Although these systems are capable of providing the necessary stiffness, they require additional actuation and stiffness mechanisms to be incorporated along or within the robot manipulator and thus complicate the mechanical design of the manipulator. Moreover, complexities in design will result in undesirable non-linear behavior that will degrade the steerability of the manipulator. Active compliance methods for continuum robots, whereby the stiffness or compliance characteristic is commanded through an intelligent control algorithm, have been investigated in the literature.^{1,13,28,29,30} The work by Mahvash and Dupont¹³ introduces active stiffness control through approximation by a Cosserat rod and the algorithm has been successfully implemented into a single segment flexible robot.

Similarly, other published work has proposed and tested active compliance control strategies on a single module²⁸ or a single joint²⁹. Tonietti and Bicchi³⁰ demonstrated adaptive position and stiffness control on two joints of a discrete rigid-link robot arm. But thus far, the only work that has investigated compliance or stiffness control for a multi-segment continuum arm is presented by Goldman et al.¹, who modelled the mapping of the environment wrenches to a generalized force in the configuration space of a continuum segment to realize the compliant motion control and used the support vector regression to model the uncertainties. While the work done in the literature, demonstrates good experimental results, the stiffness control is achieved without explicit knowledge of the interaction forces.

This paper addresses the challenges in characterizing the dynamic stiffness properties of a class of soft hyper-redundant continuum surgical robots made of Ecoflex-0050TM silicone and presents a new methodology for designing a real-time tunable stiffness controller. The method presented here can be applied to soft continuum robots, with and without in-built stiffening, to achieve better robustness against disturbances at the tip of the robot using force feedback. Active stiffness control is achieved through exploiting the natural compliance of the manipulator, in providing the variable stiffness along the length of the manipulator to reject the disturbances. An empirical approach is employed in formulating the tunable stiffness matrix for the purpose of real-time control. This method provides a precise description of the characteristics of the manipulator, captures the varying stiffness effect of the actuated arm and consequently offers a more accurate response to closed loop feedback control. The algorithm was verified experimentally by first formulating and validating the stiffness matrix for a single segment soft manipulator and then extending

the method to a two-segment manipulator.

Initially this paper introduces the design mechanism of the STIFF-FLOP (www.stiff-flop.eu) soft manipulator used in this study, followed by the local stiffness analysis of the soft manipulator. Thereafter, the formulation of the new dynamic stiffness matrix and real-time implementation of the stiffness controller are presented. Conclusions based on the results of experimental validation and recommendations for future research are given.

2. Mechanism Design

The soft robot prototype used for this research is based on the STIFF-FLOP manipulator design described by Wang et al.¹⁹ and Ranzani et al.³¹ and is shown in Fig. 1. The module is fabricated with Ecoflex-0050TM silicone using the process described by Fras et al.³² Each module is composed of three identical pneumatic chambers, which are parallel to the central longitudinal axis of the actuator and uniformly displaced at 120 degrees apart and aligned with a central longitudinal axis of the actuator. This design concept was also used by Chen et al.³³

The module also has a central chamber running along the length which is used to pass tubing and wires when several modules are connected together. The pressure chambers are reinforced with nylon fiber to constrain the silicone's radial expansion and maximize the bending. For this study, two segments are connected together by connectors constructed from polyactic acid (PLA) thermoplastic material.

The deformation of each individual chamber collectively drives the actuation of the entire manipulator. This deformation can be characterized by bending, steering, and elongation. The individual module of the manipulator is capable of elongating up to 50% of its original length and able to bend up to 90 degrees. The operational input pressure for each actuation chamber of the module ranges from 60 to 140 *kPa*, independently controlled through individual pressure regulation valves fed by a constant pressure air inlet.

3. Stiffness Characterization

This section aims at analyzing the stiffness characteristics of each module of the soft manipulator. The method developed is inspired by studies on manipulability, which is one of the standard tools for analyzing manipulator characteristics and numerous studies have discussed and applied these tools. A representative sample of the methods appear in the literature.^{23,34,35} These approaches give the geometric interpretation of the manipulator's capability in executing a specific task and can serve as a quantitative measure of force transmission capability of a system. The manipulating ability of a system is usually represented by a manipulability index and a plot of the manipulability ellipse/ellipsoid. This research takes inspiration from the manipulability study, presented in the literature,³⁵ to analyze the stiffness of the manipulator by generating ellipsoids based on the actual force-distance relationship at several local points within the workspace. The ellipsoid generated

Fig. 1: Single module prototype of STIFF-FLOP soft manipulator³² (a) at resting position, (b) elongated, (c) bending and (d) cross-sectional view.

in this section is a precise measure of flexibility of the soft manipulator at a local point. Based on this rigorous experimental study, the local stiffness of the soft manipulator can be accurately deduced as the ellipsoid is generated directly based on the displacement of the manipulator under a known exerted force. This graphical local representation of stiffness is used to compare the stiffness performance along and about different directions and also to find the best stiffness performance in a given direction.

The local stiffness of a single module manipulator is studied at thirteen different points in space on four selected frames. These thirteen points encompass all of the reachable regions of the manipulator, from the minimum to the maximum bending angle that can be achieved. Out of the four selected frames, three frames, which are at an orientation angle (Φ_i) of 10, 120, 200 and 340 degrees, are located within each defined tri-sector as in Fig. 2. The fourth frame, at an orientation angle of 120 degrees, is located in between the tri-sectors. For each frame, the stiffness is analyzed at three different bending angles (θ_j), which are at 30, 60 and 90 degrees.

Fig. 2: Coordinate frames of reference and symmetrical actuation of the module (alternating chambers using the same pressure will not correspond to a “symmetrical” force distribution on the force sensor at the tip). (a) Trisectors around the axial centre and (b) frames of reference for the force sensor.

A single module is used in the characterization to properly evaluate the degree of resistance to deformation caused by external forces. An industrial six degree of freedom robotic arm, Mitsubishi MELFA RV-1A, fitted with an aluminum probe attached to the end-effector, was programmed to apply a small force between 0.2 N to 0.8 N, at a constant speed. The distal end of the soft manipulator is fitted with a 3-axis OptoforceTM force sensor, to measure the force applied at the tip. The NDI Aurora electromagnetic tracking system³⁶ is used to calculate the position and orientation. Six hollow cylinders are designed to be fixed around the perimeter of the force sensor’s dome at equal distances as illustrated in Fig. 3.

This arrangement allows for the probing of the force sensor at the same point for all experiments that are conducted with different bending angles and orientations of the module. This way, the repeatability in test results is assured. Further, this arrangement allows the end-effector of the MELFA robot to be in the normal direction to the distal end of the soft manipulator.

In this experiment, the STIFF-FLOP manipulator is first actuated to achieve the desired pose within the chosen frame. This is achieved by manually adjusting the input pressure for each of the three actuation chambers, with values within the operational range defined in section 2, i.e. 60 to 140 *kPa*. Then, the MELFA robot is actuated to approach and make contact with the pressurized module and the Aurora sensor calculates the displacement of the tip subjected to the applied force. This procedure is repeated for all six points around the circumference of the OptoforceTM sensor dome.

Based on the displacement of the tip at a local point, subject to 0.6 N normal force, the principal axes of the ellipsoid are deduced for each of the local points

Fig. 3: Experimental setup for local stiffness analysis. MELFA robot is used to apply force on the tip of the STIFF-FLOP soft manipulator.

and are plotted as shown in Fig. 4. These ellipsoids are defined as the flexibility ellipsoid whereby it provides the measure of flexibility of the manipulator at the given location. The bigger the displacement of the manipulator due to the applied force, the bigger the volume of the ellipsoid hence the more flexible the manipulator is at that particular point.

Comparison of the stiffness performance, at local points within the workspace, can also be accomplished by analysing Fig. 4. The positions in which the manipulator is stiffer and therefore can exert/withstand the greatest forces are when it is the most sensitive to the applied load. This is the position where the manipulator is capable of sustaining the loads without a large displacement. Based on the results in Fig. 4, it was observed that the ellipsoid has a larger principal axes and therefore, high flexibility when it is closer to the central axis (small bending angle). This information is used to calculate the flexibility and stiffness index and to analyze the stiffness performances over the entire workspace.

The flexibility index was normalized to simplify the analysis where 0 and 1 represents the highest and lowest flexibility respectively. These values were analyzed, plotted and extrapolated over the entire Cartesian workspace as in Fig. 5(a), using GRIDFIT surface plotting tool in MATLAB³⁷. Similarly, the stiffness index was also normalized such that 1 and 0 represents the highest and lowest stiffness index respectively. The stiffness index is plotted against the configuration space variables

Fig. 4: Flexibility ellipsoid generated based on applying constant forces along the perimeter of the STIFF-FLOP soft manipulator.

(orientation and bending angle) as illustrated in Fig. 5(b). The plots of flexibility and stiffness index (Fig. 5) indicate that the soft manipulator has a higher capability in rejecting disturbances as it is pressurized at a higher bending angle, across its entire orientation span. From Fig. 5(b), it is shown that the manipulator has a stiffness index of 0.85 to 0.9 when it is bent at a 90 degrees angle and a stiffness index of about 0.2 when the manipulator is at a 30 degrees angle. Symmetrical behavior can also be observed for each tri-sector i.e. 120 degrees around the module axial length, based on the anatomy and construction of the manipulator. It is inferred from this analysis that the ability of the soft robot to reject disturbances varies throughout its workspace and proves that its inherent stiffness is dynamic in nature. Therefore, there is a need to develop a new methodology to formulate the tunable stiffness matrix, which will capture the varying stiffness characteristics of the soft manipulator, for the purpose of designing the real-time controller.

Fig. 5: (a) Surface plot of tip position showing flexibility index extrapolated over the entire Cartesian workspace and (b) surface plot of the stiffness index extrapolated over the entire configuration space. The bar represents the normalized index value.

4. Tunable Stiffness Matrix Formulation

This section explains the new method to determine the tunable stiffness matrix of the soft STIFF-FLOP module without an in-built stiffness control mechanism, such as the granular jamming. The methodology presented here can also be generalized to soft robots with an in-built granular jamming mechanism for enhanced stiffening.

4.1. Background

This approach takes into account the following advantages of the STIFF-FLOP manipulator, such as: (1) the availability of a compact moment/force sensor developed by Noh et al.³⁸ that can be easily mounted at the tip, at the base as well as in between segments of the multi-segmented soft manipulator; (2) the ability to control chamber pressure accurately which is critical for stiffness and force control.

Therefore, a preliminary investigation was conducted on how to exploit these features to control the stiffness/force at the tip of the STIFF-FLOP manipulator, in order to resist external disturbances. Both the tip element and inter-module connection elements are rigid themselves, and since they are mounted in series with the soft modules their influence on the global stiffness of the soft arm can be neglected. The stiffness matrix derived is based on the Euler Bernoulli beam theory³⁹ and Hooke's Law. The elongation at any point along the module can be described as,

$$\Delta dl = \frac{F_p}{EA} dl. \quad (1)$$

where dl is the length of small fragment of the chamber in (m), Δdl is the change in the length of the chamber due to pressure in (m), F_p is the force generated by

actuating the pressure chambers in (N), A is the cross-sectional area of the silicone module in (m^2), and E is the material Young's modulus in (N/m^2). The Euler-Bernoulli beam equation as shown in Eq. (2) is used to determine the bending (θ_j) along the module after the application of the external forces.⁴⁰

$$\theta_j = \int_0^L \frac{d\theta}{ds} ds = \int_0^L \frac{M_0}{EI} ds = \frac{M_0 L}{EI} \quad (2)$$

where M_0 is the bending moment of the manipulator in (Nm), I is the second moment of inertia of the module in (m^4) and L is the length of the module at any instance in (m).

4.2. Formulation

The stiffness matrix $\mathbf{K}$ that relates the force at the tip to the displacements of all joints is⁴¹

$$\mathbf{F} = \mathbf{K}\mathbf{d}. \quad (3)$$

where $\mathbf{F} \in \mathbf{R}^3$ is the force at the tip in (N), $\mathbf{d} \in \mathbf{R}^3$ is the displacements of the joints in (m) and $\mathbf{K} \in \mathbf{R}^{3 \times 3}$ is stiffness matrix in (Nm^{-1}). However, a constant stiffness matrix is not suitable for use in the case of the soft manipulator as explained in stiffness characterization. This paper presents a new methodology for modelling the dynamic stiffness matrix by finding out the force exerted by the manipulator in a particular configuration and direction.

The workspace of the manipulator is categorized into four possible configurations which are the three tri-sectors of operation and elongation. Each sector occupies a space of 120 degrees around the module's axial length, as shown in Fig. 2(a), which is determined by the pressures in opposing chambers. The stiffness matrix derived from this approach maps the forces in the Cartesian coordinate, which has symmetry of a 90 degrees as in Fig. 2(b), to length of the module that is symmetrical around each tri-sector i.e., a 120 degrees coordinate system, as seen in Fig. 2(a).

As illustrated in Fig. 6(a) the process of determining the empirical relationship between change in pressure and the resulting force/moment of the tip of the module involves constraining the tip of the soft manipulator as the pressure within the chamber is incrementally increased. A small change in pressure dP , as shown in Fig. 6(b) is applied within chamber i and the forces or moment generated at the tip of the module is measured. Repeating the experiment for different pressure levels and for all the workspaces defined above, allows for the estimation of the trends between the applied force and the pressure for the four configurations. The complete operational pressure range of the manipulator as defined in section 2, i.e. between 60 and 140 kPa , is covered in determining this empirical relationship.

Figure 7 illustrates the variation in moment ($M_{x,y}$) and force (F_z) acting on the tip of the soft manipulator due to incremental changes in pressure for each of the

(a) Single STIFF-FLOP module³² with constrained tip

(b) Pressure in the three internal chambers

Fig. 6: Experimental setup used to evaluate the relationship between pressure and force.

three chambers. As evident from Fig. 7, the relationship can be approximated to be linear in this operational range given by Eq. (4), where dM_x and dM_y are the moments at each axis in (Nm), dF_z is the force along the z-axis in (N), B is a constant in (m^2), dP is the change in pressure of each individual chamber in (Pa), C is a constant in (N) and $i \in \{1, 2, 3\}$ is an index to the chambers' number.

$$\begin{aligned} dM_{x,y} &= B_{i,x,y} dP_i + C_{i,x,y} \\ dF_z &= B_{i,z} dP_i + C_{i,z} \end{aligned} \quad (4)$$

The chamber pressure can be used to calculate the force applied by each chamber on the module as in Eq. (5).

$$F_i = P_i A_{ch} \quad (5)$$

where F_i is force exerted onto each chamber cross-section in (N), P_i is pressure in (N/m^2) and A_{ch} is the cross sectional area of the chamber in (m^2), and based on Eq. (1), the change in length of the individual chamber is as in Eq. (6).

$$\Delta dl_i = \frac{F_T}{EA} dl_i = \frac{dP_i A_{ch}}{EA} dl_i \quad (6)$$

where l_i is the length of the i^{th} chamber and A is the area of the silicone module (i.e., cross section area minus the area of the three chambers) in (m^2).

Rewriting Eq. (4) in terms of pressure, yields

$$dP_i = \frac{dM_{x,y}/dF_z - C_{i,xyz}}{B_{i,xyz}}. \quad (7)$$

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Fig. 7: Linear fitting between the change in moment (primary Y-axis, on the left) and force (secondary Y-axis, on the right) and the applied pressure.

Substituting Eq. (7) into Eq. (6) yields the following relationship:

$$\Delta dl_i = \frac{dM_{x,y}/dF_z - C_{i,xyz}}{B_{i,xyz}} \frac{A_{ch}}{EA} dl_i \quad (8)$$

thus establishing a dynamic relationship between length and the stiffness as

$$K_{i,xyz} = \frac{B_{i,xyz}}{dl_i} \frac{EA}{A_{ch}}. \quad (9)$$

The change in length is defined as the compliance matrix multiplied by the force vector measured by the force sensor

$$\Delta dl = \mathbf{K}^{-1} \mathbf{F} \quad (10)$$

where $\mathbf{l} = [l_1 \quad l_2 \quad l_3]^T$ and each element of $\mathbf{F}$ is a calibrated force/moment value defined as $F = dM(x, y)/dF_z - C_{i,x,y,z}$. The inverse of the stiffness matrix, i.e. the compliance matrix, is

$$\mathbf{K}^{-1} = \begin{bmatrix} K_{x1}(dl_1) & K_{y2}(dl_1) & K_{z3}(dl_1) \\ K_{x1}(dl_2) & K_{y2}(dl_2) & K_{z3}(dl_2) \\ K_{x1}(dl_3) & K_{y2}(dl_3) & K_{z3}(dl_3) \end{bmatrix}^{-1}. \quad (11)$$

where each element of $\mathbf{K}^{-1}$ is the reciprocal of Eq. (9).

The methodology for dynamic stiffness characterization presented here can be applied to any pneumatically actuated soft robots. This proposed method can be extended to a two-segment soft robot. Equations (4) to (11) for each segment need to be determined to effectively reject normal (during elongation) and lateral (when the manipulator is bending) external disturbances. Similar to the single segment system, the force/moment and change in pressure relationship were first established by constraining the tip of the module and incrementally increasing the pressure within the chamber from 60 *kPa* to 140 *kPa*. The corresponding chambers are actuated together e.g. Chamber 1 of Segment 1 and Chamber 1 of Segment 2 are actuated in tandem, Chamber 2 of Segment 1 and Chamber 2 of Segment 2 are actuated together and so forth, while the tip of the manipulator is constrained. Following these tests, the force/moment-pressure relationships are obtained and are used to derive the stiffness matrix for each segment as previously described.

5. Robustness of Tunable Stiffness Controller

In this section, the closed-loop stiffness control architecture is presented, and the efficacy of the tunable stiffness controller in rejecting external perturbations is verified experimentally.

5.1. Tunable Stiffness Control

Figure 8 illustrates the closed-loop control architecture to reject disturbances for *n*-segmented soft robots. To effectively reject disturbances, a weighting factor is assigned to each segment based on the current configuration or the available chamber pressure for each chamber. For the case of a single module, W_1 will be equal to 1 as the duty of rejecting the disturbances relies solely on a single module. For the case of a soft manipulator with *n* segments, the task of disturbance rejection is distributed among the other segments. The weight assignment determines the segment that would have more contribution range to reject disturbance compared to the others, by applying the following equation to each segment and chamber:

$$W_{i,j} = \frac{(P_{max} - P_{i,j})}{\sum_{j=1}^n (P_{max} - P_{i,j})} \quad (12)$$

where P_{max} is the maximum pressure for each individual pressure chamber, $P_{i,j}$ is the current actuation pressure within the pressure chamber, $i \in [1, 3]$ is the index

Fig. 8: STIFF-FLOP soft manipulator control architecture.

of chamber number, $j \in [1, n]$ is the index of segment number and n is the number of segments combined in series.

For example, consider the case of a two-segment soft STIFF-FLOP manipulator. If the base module is more actuated compared to the tip module, i.e. its chambers are closer to the upper actuation limit of 140 kPa , the base module has less available pressure to actuate the chamber in order to correct the displacement due to perturbations. Therefore, it would have a lower capacity than the tip module in rejecting the disturbances. Giving the segments that are less actuated, i.e. the ones that are further away and have a higher range to react, higher weight factors improves the effectiveness of disturbance rejection and prevents the segments that are more actuated from saturating to the upper 140 kPa limit.

Initially, the STIFF-FLOP soft manipulator is set to reach a desired tip position (X_d, Y_d, Z_d) whereby the position controller will calculate the length for each chamber $(l_{1,d}, l_{2,d}, \dots, l_{n,d})$ required to achieve the desired tip position based on constant curvature inverse kinematics model.⁴⁴ The moment/force sensor by Noh et al.³⁸ measures any presence of disturbances, $dM_{x,y}/dF_z$ which are used by the stiffness controller to calculate $K_{i,xyz}$ as in Eq. (9) and the change in length, Δdl , using Eq. (10) to correct the positional error cause by these forces. The overall goal is to maintain the desired position despite the presence of any external disturbances. Hence, the position controller is always operational throughout the experiment.

In the presence of any disturbances, the algorithm generates the compliance matrix as in Eq. (11) based on the force/moment generated by the application

of external forces, measured by the force sensor mounted at the base of the manipulator. This matrix is generated in real-time to persistently resist any external disturbances. This dynamic stiffness matrix will be used by the stiffness controller to identify the necessary changes in length, Δdl , to compensate for the disturbances and to continuously update the position controller to maintain the desired value in real-time. This change in length is used to re-evaluate the total chamber lengths set by the position controller. The tip position is continuously monitored to ensure the correct tri-sector is activated. In these experiments, all the constant parameters, E , A and A_{ch} , are first initialized to the values shown in Table 1.

Table 1: Initialization parameters.

Parameter	Description	Value	Units
E	Young's modulus	35000	N/m^2
A	Manipulator cross-sectional area	$1.96 \cdot 10^{-5}$	m^2
A_{ch}	Chamber cross-sectional area	$2.01 \cdot 10^{-6}$	m^2

The robustness of the dynamic stiffness controller was verified and validated through demonstrating disturbance rejection for the following two scenarios:

- (i) *Lateral disturbance rejection*: To reject the impact of disturbance when the external force is applied laterally along the body of the soft manipulator while it is in the bending configuration.
- (ii) *Normal disturbance rejection*: To reject the impact of disturbance when external forces are applied normal to the tip of soft manipulator, when it is in the elongation mode, i.e., all three chambers have roughly equal pressures (tip disturbance rejection).

The effectiveness of the stiffness control algorithm is evaluated by calculating the error between the actual position of the tip of the soft manipulator and its desired position, which quantifies its ability to maintain the desired position and limit position error while undergoing external disturbances. Its performance is compared with the position error attained by applying position control only, without stiffness control. For this comparison to be meaningful, and to grant repeatability for all experiments, it is important that the application point and magnitude of the disturbance forces exerted on the soft manipulator are rigorously controlled. An industrial rigid-link robotic arm equipped with a contact force sensor mounted at the tip of its end-effector is well fitted for this purpose, due to its capability to apply consistent forces at the desired locations with high precision. Therefore, such a rigid-link robotic arm will be used for experimental validation of the stiffness control algorithm proposed.

Figure 9 illustrates the spatial configuration of the rigid-link robot arm applying the disturbance force and the soft manipulator executing the stiffness control

Fig. 9: Diagrams of the different stiffness control experiments with soft manipulator and rigid-link robot arm (not to scale): (a) lateral disturbance on single-segment manipulator, (b) normal disturbance on single-segment manipulator and (c) lateral disturbance on 2-segment manipulator.

algorithm for the different experimental scenarios analyzed in this section, i.e. (a) lateral disturbance on single-element manipulator (Section 5.3), (b) normal disturbance on single-element configuration (Section 5.4) and (c) lateral disturbance on two-segment manipulator (Section 5.5).

5.2. Hardware and Software Framework

Figure 10(a) is the schematic diagram showing the interface between the hardware and software building blocks. The test setup in Fig. 10(b) is used to implement the real-time tunable stiffness control of the multi-segment STIFF-FLOP arm. The system operates using the Robot Operating Software (ROS) environment and the RoNeX board by Shadow Robot Company⁴² is used as the central interface between the host PC and hardware component.

The software is executed in a 1 kHz loop extracting signals from the different sensors and publishes commands to the relevant actuators. The pneumatic circuit of this hardware system is supplied by a stable 150 kPa compressed air supply and the actuation is controlled by a valve system.

Each of the three actuation chambers are connected to a pressure sensor and pair of two-way solenoid valves, which work as a unit to inject and dispense the

(a) Schematic of the software and hardware interface

(b) Testbed using MELFA robot for exerting lateral and normal disturbances

Fig. 10: Experimental setup using two modules of the STIFF-FLOP soft manipulator³² for validating the disturbance rejection controller.

pressure within chamber. A low-level closed-loop pressure controller is designed, within the software framework, to maintain the actuation pressure at a desired value. The deflection (θ) and tip position of the STIFF-FLOP manipulator (X_c, Y_c, Z_c) is measured using the NDI Aurora sensor.³⁶ In this setup, three Aurora sensors are used, two of which are located at the base of tip module and base module, as well as one at the distal tip of the tip module. The NDI Aurora position sensor is used to measure the position of the STIFF-FLOP manipulator within its 3D workspace, identify the operational tri-sector, which in turn allows the choice of appropriate stiffness matrix.

The Mitsubishi MELFA RV-1A industrial robot is used to verify the performance of the formulated stiffness matrix. It is programmed to exert forces on the STIFF-FLOP arm to simulate disturbances in the range 0 to 1.2 N . The MELFA robot is a rigid-link manipulator with six revolute joints, each with different motion range limits, enabling it to accurately position its end-effector at any pose in a workspace of approximately 0.1 m^3 . Real-time feedback of MELFA robot's end-effector's six-dimensional pose, in joint coordinates, is obtained from the servomotor absolute angular encoders through an Ethernet connection between the MELFA robot's controller box and the computer terminal running the experiments.

The inverse kinematics model of MELFA is applied to control the position in the Cartesian workspace reference frame, using the ROS framework and MoveIt mobile manipulation package.⁴³ In addition, an OptoforceTM sensor is attached to the end-effector of MELFA, providing real-time measurements of the normal force applied by it. These readings are acquired via-USB by the computer terminal and used for active through-the-arm force control, controlling the normal force applied by correcting the position of the end-effector along its x-axis.

5.3. *Lateral Disturbance Rejection*

The scenario under investigation is when a single STIFF-FLOP soft module in a bending configuration within one of the three tri-sectors of operation, demonstrates rejection of external forces in the lateral direction. Equations (4) to (10) generate every element of compliance matrix $\mathbf{K}^{-1}$, but it is more effective to reject occurrences of lateral disturbance using only two out of the three chambers. The direction of the external forces is used to determine which two corresponding chambers should be activated to counteract the disturbance. Therefore, some of the elements of the compliance matrix will have a zero entry once the corresponding chambers to be activated are determined. However, the chamber that is not activated through the matrix may still be actuated since the position controller is always operational throughout the whole experiment.

In this experiment, the manipulator was initialized to bend 75 degrees towards sector 3 with internal pressures as shown in Fig. 11(a) and (b). An external force as in Fig. 11(c) and (d) was exerted onto the manipulator after $t=2.2$ s. The MELFA robot is aligned to exert the external force laterally, perpendicular to the circum-

ference of the tip module, as in Fig. 10(b), from orientation angle of approximately 250 degrees. The frame convention used in defining the orientation angle throughout the experiment can be found in⁴⁵.

Fig. 11: Demonstration of disturbance rejection for single STIFF-FLOP module against lateral force, whilst bending along tri-sectors: (a), (c) and (e) with only position controller; (b), (d) and (f) with both position and stiffness controllers.

Figure 11(e) shows larger tip displacement with only position feedback and without any force feedback for stiffness regulation. On the other hand, Fig. 11(f) shows minimal displacement of the tip with both stiffness control and position control activated. In both cases, when no force feedback activation and with activation of the tunable stiffness controller, the dominant pressure is in chamber 1, starting at just over 80 kPa , and chamber 2 starting at approximately 73 kPa (Fig. 11(a) and (b)). After 2.2 seconds, the forces in the z-direction reached a maximum value of -1.05 N for the case where only the position controller is operational and -0.98 N for the case when the tunable stiffness controller is activated. The moment reached maximum value of approximately -0.005 Nm in the x and 0.011 Nm in the y-directions (Fig. 11(c) and (d)) for both cases.

The displacement of the tip position for the experiment that does not use the tunable stiffness controller is found to be 14 mm in the x, -18 mm in the y, and 9.5 mm in the z-directions as seen after 2.2 seconds (Fig. 11(e)). The change in the pressure for the case where the tunable stiffness controller is not activated (Fig. 11(a)) is caused by the position controller trying to correct the displacement of the tip, which, without the disturbance controller, is not sufficient in maintaining the tip position at its desired value. On the contrary, when the tunable stiffness controller is activated, the pressure in the three chambers is corrected accordingly, to compensate for the change in the length caused by the disturbances. This action is seen after 2.2 seconds where the pressure increases in chamber 1 from 81 kPa to 140 kPa (Fig. 11(b)). Similarly the pressure in chamber 2 increases from 70 kPa to 120 kPa . This correction in pressure allows the module to resist the applied disturbance force/moments as seen in Fig. 11(d). As a result, a much smaller displacement is observed for the tip position where it moves 3.5 mm in the x, 4.9 mm in y, and 6.65 mm in the z- directions, as seen after 2.2 seconds from the start of the experiment, (see Fig. 11(f)). The controller in this case was shown to improve the accuracy of the tip position, during a disturbance, by reducing the error in displacement by approximately 88%.

The results presented here are for demonstrating disturbance rejection by the tunable stiffness controller operating in the second tri-sector. Similar results were observed for the first and third tri-sectors. Overall, the error in the tip displacement was well within 3.37 mm , for all three tri- sectors, corresponding to disturbance forces under 2 N using the new tunable stiffness controller.

5.4. Normal Disturbance Rejection

The results presented in this section correspond to the scenario when a single STIFF-FLOP module under elongation mode, encounters an external disturbances at the tip, normal to the cross-section of the soft manipulator. The pressure in all three chambers is approximately 60 kPa . Ideally, the bending angle for the manipulator under elongation mode should be zero, however, in the algorithm, the manipulator is considered to be under elongation if the bending angle is below 5

degrees. This definition provides more stability and reduces the oscillation in rejecting the unwanted forces. The tunable stiffness controller activates the matrix for elongation configuration when the bending angle is below 5 degrees. Furthermore, at any point, if the bending angle increases due to high external disturbances, the stiffness controller will activate the appropriate tri-sector matrix based on the current location of the manipulator.

In this experiment, a normal force of 0 to 3.9 N in the z-direction is applied to the tip of the STIFF-FLOP manipulator (Fig. 12(a) and (b)). Although this force is normal to the cross-section, the point of application is not exactly at the central axis of the manipulator, generating a small moment (and a slight bending of the manipulator), at a magnitude of approximately 0.0035 Nm in x and between -0.0013 to -0.0026 Nm in y-direction as shown in Fig. 12(a) and (b). The tunable stiffness controller activated the appropriate matrix, as explained above, to maintain the tip position of the STIFF-FLOP robot as close to the central axis as possible.

Fig. 12: Demonstration of disturbance rejection for single STIFF-FLOP module against normal force, whilst the manipulator is in elongation mode: (a), and (c) with only position controller; (b) and (d) with both position and stiffness controllers.

(a) Without tunable stiffness controller (b) With tunable stiffness controller

Fig. 13: Disturbance rejection capability by the single STIFF-FLOP soft module: (a) without tunable stiffness controller, and (b) with tunable stiffness controller.

As illustrated in Fig. 12(c), the maximum tip displacement when the tunable stiffness controller is inactive is 18 mm in x, -10 mm in y and 9 mm in z-direction. The tip displacement is much less when the tunable stiffness controller is activated. As illustrated in Fig. 12(d), at $t = 5.9$ s, when the force/moment is at the lowest magnitude, with 1.15 N z-direction and 0.0013 and 0.0012 Nm in x and y-direction respectively, the tip displacement was observed to be 2 mm in x, 1.3 mm in y and -3.6 mm in z-direction. Overall, a maximum deviation of 7.8 mm in x, 6.3 mm in y and 5.7 mm in z-direction is recorded when an external force as in Fig. 12(b) is applied at the tip of the manipulator.

Figure 13 compares the resultant tip displacement of the single module of the STIFF-FLOP manipulator, under increasing disturbance forces up to 1.8 N in z-direction, with and without the tunable stiffness controller for the two operational conditions, i.e., elongation and bending. As shown in Fig. 13(a), the soft module is unable to maintain its tip position, in the absence of a tunable stiffness controller, when a normal disturbance force is applied to the module's tip and this results in significant deviation from the desired tip position. On the other hand, Fig. 13(b) illustrates that there is significant robustness against the same normal disturbance force by the tunable stiffness controller. For the bending and elongation scenarios presented, the tunable stiffness controller reduced the tip displacement by about 58% and 70% respectively.

5.5. Multi-Segment Soft Manipulator

The validation of the proposed control architecture illustrated in Fig. 8, for a two-segment soft manipulator, is presented in this section. Two scenarios have been tested to determine the efficacy of the proposed method for the two-segment STIFF-FLOP soft manipulator: 1) a lateral force is applied by the MELFA robot arm and maintained for 2 seconds before it was removed. 2) two consecutive impulses were

applied in the lateral direction. For both of these case studies, the initial configuration of the base module and the tip module is 35 degrees and 70 degrees respectively, bending toward the third tri-sector at orientation angle of approximately 300 degrees. The MELFA robot arm approaches the STIFF-FLOP manipulator and exerts a force laterally from the orientation angle of 120 degrees.

For scenario 1, a force of -1.3 N in z-direction, and moment 0.01 Nm in x- and y- directions are applied to tip module of the two-segment system as shown in Fig. 14(a). As can be seen in Fig. 14(c) and (d), the tip module is more actuated than the base module before the external forces were applied, hence, it has lesser contribution in rejecting the disturbances. The pressure in chamber 1 and 3 of the tip module increases from 40 kPa to approximately 110 kPa , whilst the pressure increase in chamber 1 and 3 of the base module has an amplitude of roughly 80 and 90 kPa respectively. As the force is exerted laterally to chamber 2, only chambers 1

Fig. 14: Tunable stiffness controller for two-segment STIFF-FLOP manipulator: (a) lateral force/moments applied at the tip, (b) tracking of tip displacement, and pressure within actuating chambers for the (c) base and (d) tip modules.

and 3 of both tip and base module, are activated to correct for any error in the tip position. However, there is a small change in pressure within chamber 2 for both of the modules caused by the position controller actively trying to maintain the tip position. A maximum displacement of 5 mm in the x, 5.6 mm in y and 4.7 mm in z-axis is observed.

A similar response was observed in the second scenario, when two consecutive impulses, each with a duration of 0.6 seconds, were applied at an interval of 6 seconds, as shown in Fig. 15. The tip displacement was approximately 6 mm when the first impulse (0.01 Nm in x, -0.01 Nm in y and -1.25 N in z-axis) was exerted. The second impulse is of a smaller magnitude (0.06 Nm in x, -0.01 Nm in y and -1 N in z-axis) which results in a smaller displacement pattern with an average of 4.5 mm maximum deviation in x, y and z-axis.

Fig. 15: Tunable stiffness control for two-segment manipulator when two consecutive impulses are applied: (a) force/moments applied at the tip, (b) tracking of tip displacement, and pressure within actuating chamber for the (c) base and (d) tip modules respectively.

The responses in both scenarios demonstrate the capability of the stiffness controller to correct in real-time errors due to sustained and dynamic external disturbances. The tip is maintained with position errors within the aforementioned $\simeq 5mm$ range at all times and settling the position of the tip within 0.5 seconds of the application and removal of the disturbance force/s. This gives more than enough time for the tip position to stabilize between the two consecutive impulse disturbances of scenario 2.

The results illustrated here for a two-segment soft manipulator is the verification and validation of the tunable stiffness controller in real-time. This methodology can be extended to n number of segments for any type of pneumatically actuated soft robots, thus illustrating its efficiency, modularity and robustness against disturbances.

6. Conclusion and Future Work

In this paper, a new methodology for characterizing the dynamic stiffness of a soft continuum robot for real-time control is presented. The tunable stiffness controller for disturbance rejection in soft continuum manipulator is implemented by regulating chamber pressures without the presence of any in-built stiffness mechanism. Experiments were conducted to derive the empirical relationship between chamber pressures and applied force as well as the relationship between the chamber length and the applied forces. Tunable stiffness matrices were derived for four configurations depending on the workspace of the manipulator, namely, the three tri-sectors and elongation. Each stiffness matrix operates dynamically based on the position and interaction forces of the manipulator. This method was first implemented and verified on a single segment soft manipulator, followed by validation using a two-segment soft manipulator.

Further improvement in the performance of this soft manipulator can be achieved by using an accurate material based dynamic model⁴⁶ and through introducing an in-built granular jamming mechanism to provide additional stiffening. These innovative results on material based dynamic modelling and *ex vivo* experimental validation of this soft continuum robot for safe diathermic tissue cutting procedure are now underway and will be published as separate articles. The next step will be to validate the stiffness control approach using miniaturised modules suitable for *in vivo* experimentation, to explore any unexpected scalability issues.

Although the case studies demonstrated here are specific to soft manipulators design using Ecoflex-0050TM silicone, this theory can be extended to other soft continuum robots as long as the Young's modulus of their constituent material is known and the tunable stiffness matrix of its modules is characterised. Another line for future work would be to validate this approach on multi-segment soft manipulators fabricated with a different material. It is envisaged that this methodology will become popular for a wider class of multi-segment soft continuum robots in future surgical applications.

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