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Induced Vibrations of Soft Robotic Manipulators for Controller Design and Stiffness Estimation

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Abstract— **Soft robotic systems are primarily characterized by their low stiffness properties. However, for these high dimension nonlinear systems, it becomes increasingly difficult to define and estimate stiffness properties. This paper presents a methodology to estimate the dominant compliance of a soft robotic manipulator using only motion information. We show how this information can be used for input shaping to suppress unwanted vibrations during point to point motion. Furthermore the methodology can be used to assess manipulator design and stiffening mechanisms.**

I. Introduction

Stiffness is defined by the extent to which a body deforms in response to an applied force. Traditional robotic systems were characterized by isotropic and linear stiffness properties. In most cases their stiffness was very high that they could be ignored. For delicate interactive tasks, force control strategies for perceived stiffness modulation were used [1]. With the advent of soft robotic systems, this could be achieved intrinsically using soft materials [2]. Although they provide numerous advantages in terms of adaptability, safety and dexterity, modeling their dynamic properties still pose a challenge.

Typical soft robot designs undergo deformation by storing and releasing elastic energy. The kinematics of these systems are coupled with their quasi-static forces. Therefore with accurate kinematic and force mapping models, tip forces can be estimated and controlled using only deformation information [3]. With the addition of intrinsic force sensors, external wrench minimization at unknown contact locations was also shown in [4]. However forming a stiffness/force mapping becomes difficult for complex manipulators without well developed analytical models. For model-less control approaches, estimation of forces/stiffness are done by using force sensors at the tip [5] or externally [6]. Diversely, we propose a motion tracking based approach for stiffness estimation. The idea is based on excitation of normal modes of a soft manipulator.

Vibration analysis is a common practice in industrial applications [7], [8]. Typically they use high resolution accelerometers for this purpose due to the high frequencies involved with rigid materials. Soft materials, on the other do not not need specialized sensors for vibration analysis due to their low stiffness. Tracking devices based on vision and magnetism can be used for both motion tracking and vibration analysis.

Undesired vibratory motions are common with soft robots while executing fast point to point motions. Therefore typical kinematic controllers employ long control cycles or slow actuator space motions to dissipate/avoid excitation of the normal modes [9]. However this reduces the speed and accuracy of the controller. Although with the help of dynamic models, vibration free control strategies could be formulated, they are very difficult to develop [10]. Even if comprehensive dynamic models could be developed, their applicability has been limited due to their computational time [11], [12]. Our work takes advantage of the fact that there exists dominating normal modes which are easily observable and controllable. This is attributed to relatively low stiffness components in the whole structure. This allows us to model equivalent stiffness estimates along the direction of actuation using only low resolution tracking systems.

This paper presents a data driven methodology for developing relative stiffness estimate models for a soft robotic manipulator using vibration analysis. The proposed approach facilitates development of a relative stiffness mapping for the corresponding manipulator configuration based on information about the frequency and damping of primary vibration modes. This numerical model can then be used for manipulator analysis and controller design. Experimental results indicate that the proposed methodology suit soft manipulators in particular for developing fast stiffness models due to their lower frequency of vibration. Validation of the approach is done by evaluating stiffness modulation mechanism using a hybrid actuation mechanism. Further, we demonstrate vibration suppression for point to point motion using the stiffness estimates. A single motion tracking device was sufficient to develop a kinematic model and the stiffness model without any prior information about the system.

The organization of this paper is as follows: Section II describes the I-Support platform and its hybrid actuation mechanism. Section III presents the theoretical background and assumptions behind the proposed

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approach. Experimental results are given in Section IV followed by a concluding Section V.

II. Experimental Setup

The overall concept of the I-Support manipulator has been extensively presented in a previous work [13], where the focus was on the exploitation of the hybrid actuation strategy for a dexterous soft system able to interact with people in an assistive task. In particular, authors combined two different actuation technologies, as follows:

- Mc-Kibben based flexible fluidic actuators, that enable elongation and omni-directional bending and provide high strength, but low accuracy
- Tendon-driven mechanisms, that can implement shortening and (redundant) omni-directional bending with high movement resolution, and high accuracy.

As a result, the system is capable of elongation/contraction and bending movements while, specific antagonistic activation sequences enhance variable stiffness ability (Figure 1).In the previous version of the manipulator, there were three identical interconnected modules; each constitutive segment, 150 mm in length and 60 mm in diameter, was based on the combination of three cables and three flexible fluidic actuators equally spaced at 60 degrees[14].

Authors, taking inspiration from the outcomes achieved in the framework of the I-Support manipulator, propose a simplified version of the system, as a platform for further investigations and advancements on control strategies for soft manipulators based on stiffness estimation.

With respect to the original design, authors refer to a different manipulator that counts on two interconnected modules: (i) the proximal one is hybrid and made of three flexible fluidic actuators and three cables equally spaced; (ii) the distal part has only three flexible fluidic actuators equally spaced at 120.

In order to amplify the effect provided by the fluidic actuation in the overall manipulator performances in combination with more stability during bending motions, chambers have been doubled in number without increasing the number of valves. Each pair of chambers is guided by a single proportional pressure micro-regulator. This reconfiguration of the system does not affect the electronic and control boards that remain the same as presented in [14].

Moreover, if the proximal module is an identical replica of the original version proposed in [13], in the distal one the total length has been slightly increased up to 23 cm, without changing the remaining elements. In this way, the dynamic effects of the vibrations in the distal section of the manipulator are amplified with a more effective bending. A magnetic tracker (trakSTAR, NDI Medical) is mounted at the end effector for capturing the motion and vibration information.

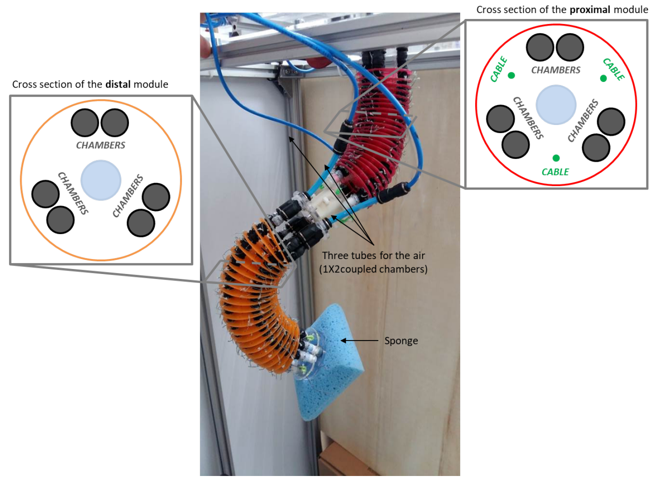


Fig. 1: The two-modules manipulator is represented with the cross-section of each segment showing the actuators arrangement. The proximal module is hybrid and counts on three flexible fluidic actuators and three cables equally spaced while the distal segment is only pneumatic-based. A sponge is mounted on the tip of the manipulator.

III. theory

The stiffness of a system is a mapping that relates force to displacement relationship. The stiffness tensor of a multi DoF system is location dependent and highly coupled. Even with assumptions of isotropic material properties, it becomes infeasible to form a complete estimate of the stiffness tensor. However by fixing the location of measurement and the direction of applied forces, the stiffness coefficient becomes a scalar quantity.

For the purpose of this paper, we are concerned only with the stiffness properties along the direction of actuation. This is mainly because unwanted vibrations due to excitation of the normal modes are due to the actuation impulses itself and would also be along the direction of actuation. Any induced vibrations due to external impulses are difficult to actively control. For simplifying the problem and to avoid coupling effect among sections, the actuation of the proximal module is kept fixed in between trials. Assuming Hookes law is valid, the stiffness coefficient would be a constant for each actuation configuration. Assuming high axial stiffness and neglecting extension of the distal arm, the internal actuation can be represented by a equivalent moment force at the tip. Therefore, our desired stiffness component would become a one dimensional constant that relates the bending of the arm to the applied moment.

$$k(q) = \frac{\delta M}{\delta \theta} \tag{1}$$

Note that the stiffness is also a function of the actuator configuration $q \in \mathbb{R}^n$, where n is the number of actuators (nine in our case). The manipulator shown in Figure 1 can be modeled as two 3-D flexible beams connected in series (see Figure 2). If the actuator configuration is defined by the fixed proximal actuators q_p and the variable distal actuators q_d, the equivalent stiffness coefficient can be written as the function:

$$k = F(q_p, q_d) \tag{2}$$

Where the equivalent stiffness k is in turn a combination of the individual stiffness matrices K_1 and K_2. The main idea behind this work is based on the fact that induced vibrations of a multi DoF system would lead it to oscillate in frequencies that are directly related to the stiffness elements K_1 and K_2 and consequently k. Cases where one of the stiffness elements (K_1 or K_2) is significantly lower than the other, unimodal vibrations can be observed. This lower component would in turn be directly proportional to the equivalent stiffness component k along the direction of actuation at the tip of the manipulator. This is because for beams in parallel, the lowest stiffness component affects the equivalent stiffness component the most.

The step response at the tip of the two section manipulator when the proximal section is underactuated is shown in Figure 3. The response is similar to spring-mass-damper system with a unimodal oscillation pattern. Since the two modules behave like a single beam, it can be ascertained that the one of the modules has significantly higher stiffness properties and therefore does not contribute much to the observed mode of vibration.

By observing the vibrations for each actuator configuration, a relative stiffness and damping map can be obtained. Note that we are only estimating a relative stiffness mapping based on the frequency of vibration which is sufficient for input shaping and design analysis. Nonetheless an absolute mapping can be formed by using force sensors for a single point and then extrapolating for the whole data. Since the frequency of oscillation is in the order of Hertz, low resolution sensors are enough to capture information about the natural frequency. This stiffness mapping obtained from vibration analysis provides information only about the lowest stiffness components. If there are multiple components that are similar in values, a more complex vibrational behavior would be observed. Even if superposition of normal modes occur, we can isolate the modes by frequency analysis. Additionally, the observed vibrations would be along the direction of actuation. Hence this would provide information about the force applicability of the manipulator in different configurations.

The stiffness and damping maps can then be used for vibration free kinematic controller design using input shaping (see III-A) and for analyzing manipulator properties. Usually the lowest components of stiffness are of interest to soft manipulator design. Designs

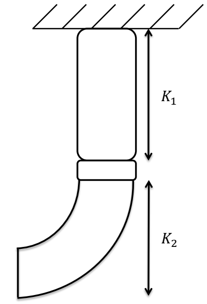


Fig. 2: The manipulator can be approximated as two 3D beams connected in series with stiffness matrices K_1 and K_2.

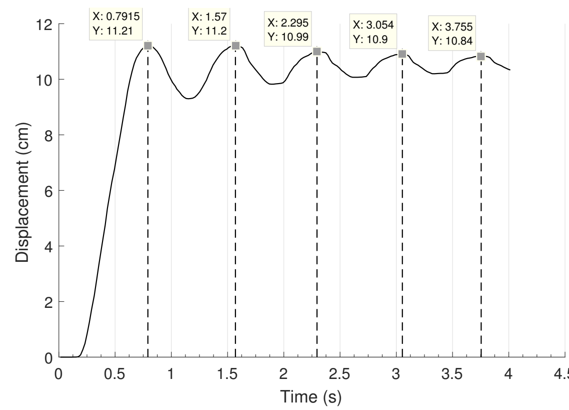


Fig. 3: Step response of the manipulator with proximal section underactuated.

that employ variable stiffness mechanisms can easily be evaluated by analyzing only the lowest stiffness component [15], [16].

A. Input Shaping

Input shaping is an open loop control technique used for reducing vibrations in flexible systems [17]. Possibility of using input shaping for vibration control soft robot has also been demonstrated recently in simulations [18]. Since the two section soft manipulator also behaves like a second order damped system, input shaping techniques can also be directly used for reducing vibrations during point to point motion. The concept behind input shaping is to cancel out vibrations induced by actuation commands by inducing vibrations that are in anti-phase. Vibrations are ensured by convolving the actual input signals with impulse signals. If the damped natural frequency of oscillation is ω_d, the time period between the two impulses will be:

$$\tau = \frac{\omega_d}{2} \tag{3}$$

To ensure that the final actuator configuration stays the same after the convolution operation, the amplitude of

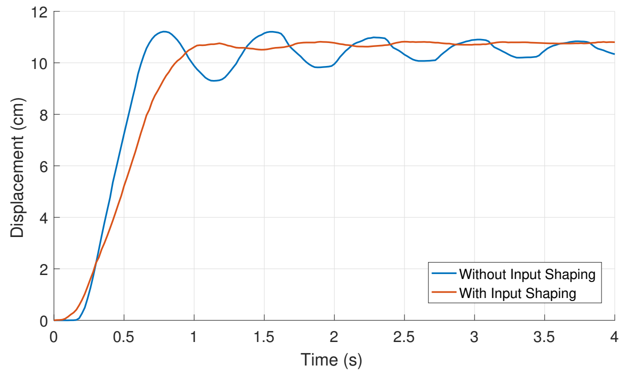


Fig. 4: Vibration reduction in the end effector motion using input shaping.

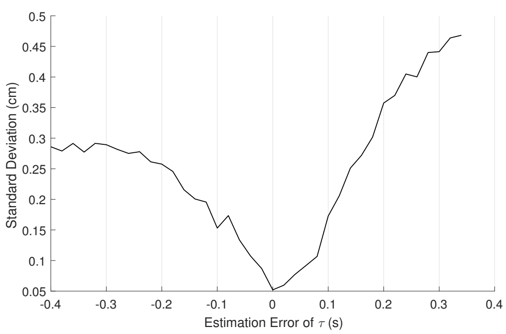


Fig. 5: End effector vibration magnitudes with error in damped natural time period estimation. Note that the vibrations are not completely suppressed with the current controller frequency and damping ratio estimate

the impulse functions would have to satisfy :

$$A_1 + A_2 = 1 \tag{4}$$

Complete compensation of vibrations can be done by choosing the amplitude of the impulse function as:

$$A_1 = \frac{\exp(\frac{\zeta\pi}{\sqrt{1-\zeta^2}})}{1+\exp(\frac{\zeta\pi}{\sqrt{1-\zeta^2}})} \tag{5}$$

Here ζ is the damping ratio. Both the damped natural frequency ω_d and the damping ratio ζ can be obtained from the step response.This is demonstrated for a single actuator configuration in Figure 4. Almost complete reduction of the end effector vibration can be achieved by sensing and controlling at 50 Hz. Even if estimates of the natural frequencies and damping ratio have inaccuracies, reasonable reduction in vibrations can be achieved. This can be seen in Figure 5, where the timing of the impulses are varied with a fixed amplitudes. The measure of vibration is the standard deviation of the end effector displacement two seconds after the motion has started.

B. *Kinematic Controller*

To apply the input shaping technique for control of the soft manipulator, we need a controller that can provide the required actuator configurations to reach a desired static point. Due to the complexity involved with analytically modeling the kinematics of the complex manipulator, we use a learning based approach in this paper.

Since the manipulator is non redundant with three control inputs and three task space variables, developing a kinematic controller is more straightforward. We can employ a simple multilayer perceptron to directly learn the inverse kinematics (IK) model. The IK model is represented as the mapping from Cartesian coordinates to actuator values: $(x \rightarrow q)$. The same sampling data obtained by forced vibrations can be used for learning the IK model.

Once a desired target position is selected the IK model can output the desired actuator configurations to be reached. The input shaping process then converts the initial step inputs into the desired inputs by convolving this signal with the two impulses.

IV. Experimental Results

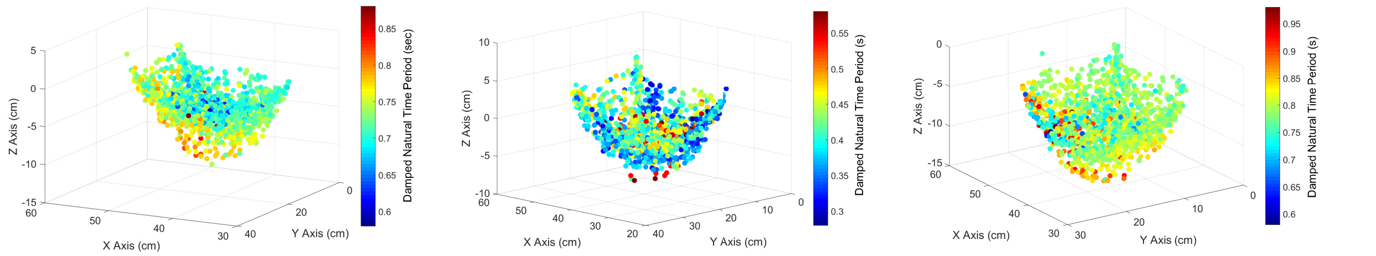
A. *Variable Stiffness analysis*

Since the stiffness of the manipulator is directly related to the configuration of the actuators, to develop a stiffness mapping we need to analyze the vibration characteristics for different manipulator configurations. Since we have only three variable actuator configurations (q_d) this corresponds to analyzing the stiffness properties for different end effector positions in the Cartesian space. To ensure free vibrations of the manipulator at all configurations we can modify the input shaping scheme. The free vibration of the manipulator occurs due to the excitation of the normal modes induced by impulse forces. For actuator configurations that are far away from the origin of the parameter space, this condition is already satisfied. For other configurations we can add an extra constraint on the impulses:

$$\max |A_1 - A_2| \tag{6}$$

This condition forces the actuators to traverse a larger distance in the actuator space before reaching the desired configurations. The time period between impulses are kept as short as possible and equation 4 is still maintained. Another check to avoid negative pressures is also used.

An estimate of the different stiffness configurations achieved with different setting of the proximal module (q_p) is shown in Figure 7. The change in coupled stiffness properties are evident from the histogram data. When the proximal module is contracted by a fixed amount using the three motor driven cables, the manipulator exhibits the highest stiffness configuration.



(a) Unactuated (b) Contracted (c) Extended

Fig. 6: The mapping between damped natural time period and end effector position.

The lowest setting is observed when the pneumatic chambers of the proximal module is used to extend the module. The span of damped natural time period is higher for when the proximal module is contracted, indicating the increase in role of the distal module is deciding the coupled stiffness values. This can be seen also in individual stiffness mapping for each proximal section configuration (See 6). With the estimate of the damped natural frequency and damping ratio, the natural frequency can also be estimated. However for our purpose this is not required.

The stiffness map obtained for different end effector position can also provide vital information about the manipulator properties. As seen in Figure 6, the stiffness configuration can be associated directly to the manipulator configuration (The end effector position in this case due to non redundancies). When the proximal module is unactuated or pneumatically actuated, the observed compliance increases with extension of the manipulator. So the lowest compliance is observed is near the unactuated configuration. Asymmetries in manufacturing can also be observed by the vibration analysis (See Figure 6c). When tendons are used to stiffen the proximal module, different patterns in the stiffness map can be observed. This is possibly because now the distal module contributes more to the coupled stiffness properties. In other words, the contribution of K_1 to the observed vibration is less (See Figure 2). Hence the contribution of the distal chambers in increasing the overall stiffness of the manipulator is evident with directional increase in damped natural frequencies (See Figure 6b).

B. Point to Point Motion

With the help of the stiffness to actuator space mapping and the actuator space to end effector mapping, simple kinematic controllers can be developed which incorporates input shaping. We present here the control results only for the unactuated proximal module case as a proof of demonstration.

With the IK model (see Section III-B) and stiffness mapping, we evaluate the performance of the controller. The appropriate values of damped natural

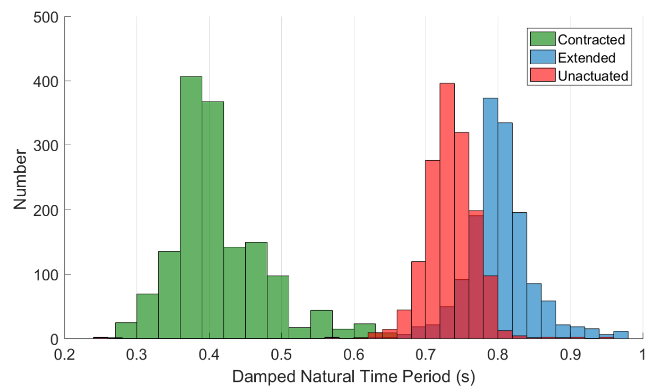


Fig. 7: Distribution of the damped natural time periods for different proximal module configurations. 1500 samples are collected for each configuration.

frequency is found by a nearest neighbor search. The damping ratio is kept fixed for all the tests for isolating the contribution of the stiffness estimates. The results of the point to point controller is shown in Table I. As expected, the vibrations of the tip (represented by the standard deviation of the tip displacement after two seconds) is reduced significantly. The tracking error is not affected since it is dependent of the IK model. However, the controller without input shaping performs slightly better.

Here it must be noted that the IK mapping incurs errors due to unwanted vibrations during sampling process. Therefore if the IK model obtains new samples with input shaping techniques then more reliable samples can be obtained for learning. The accuracy of the new IK controller with the same input shaping algorithm is shown in Table I. The accuracy of the controller has improved because of the better sampling process. The tip vibrations remain the same.

V. Conclusion and discussions

This paper presents a vibration analysis based methodology for estimating the dominant stiffness component of a soft manipulator. The procedure requires only a low time resolution motion tracking system for its implementation. Although we estimate only

TABLE I: Point to Point reaching performance for 100 random points

Strategy	Tracking Performance	
	Error[cm]	*SD.[cm]*
Without Input Shaping	0.70±0.30	0.29±0.18
With Input Shaping	0.76±0.31	0.10±0.05
Sampling with Input Shaping	0.49±0.25	0.11±0.05

the natural frequencies of vibration along the direction of actuation, this information is sufficient for analysis of soft manipulator design and variable stiffness mechanisms. We also show how unwanted vibrations can be reduced using this stiffness estimate and traditional input shaping technique. The suppression technique does not guarantee complete cancellation of vibrations. This could be because of components that are not in the direction of actuation, possibly excited due to friction. These however can only be passively suppressed.

Stiffness modeling of soft robotic manipulators is a rather unexplored field. This is largely due to the complexity involved with analytical modeling and sampling. Future work would involve extending the methodology to higher dimensional systems and multi-directional stiffness estimation. Machine learning based approaches for modeling stiffness and kinematics simultaneously would be suitable for developing hybrid force/position controllers.

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