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Linear compliant control design for soft robots*

Antoine Alessandrini¹ and Alexandre Kruszewski¹

Abstract—Our research focuses on compliant control of soft robots using a simulation-based model to select the end effector’s dynamics. We use a linearized model to introduce a novel compliance-tuning control structure. It comprises a reference model representing the desired behavior, a force estimator, and a state feedback control law. Through real-world tests, we demonstrate the validity of our approach in terms of position control accuracy and adaptive force response. Our approach achieves less than 0.5mm error in position control and up to 55% force reduction in targeted directions, highlighting its potential for safer and more effective human-robot interactions.

I. BACKGROUND

Soft robotics, an emerging field, promises safer interactions with humans and delicate environments due to its inherent compliance. This compliance minimizes the risk of injury or damage upon contact. However, effective control in soft robots is challenging. Traditional closed-loop control systems can misinterpret environmental interactions as disturbances [1], inadvertently stiffening the robot’s response and reducing safety and effectiveness in cooperative tasks.

Impedance control of flexible joints was an early approach to achieving compliant control in deformable robotic systems [2]. However, soft robotics requires distinct methods to maintain compliance while achieving precise control. Recent advances have explored varying stiffness control in soft robots using tendon-driven mechanisms based on models [3] [4] [5]. Additionally, machine learning has been employed to dynamically alter the dynamics of a robot’s end effector [6] [7] [8], providing adaptability in complex environments.

Our research addresses this by focusing on the dynamic interactions of a robot’s end effector with its environment. We present a novel approach that uses a linear model derived from simulations to develop a new compliant control structure. This structure allows the selection of the robot’s compliant behavior, optimizing human interaction while maintaining its desired position when not being acted upon. To validate our approach, we tested on a real-world soft robot, demonstrating that our theoretical models provide practical improvements in operational settings.

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II. METHOD

Firstly, the soft robot system is supposed to be linear. We assume a quasi-static (i.e. no inertial effect, slow motion) relationship between actuators and the end effector position, with dynamics introduced through actuator velocities. The system discrete state space representation is given in Fig 1, where q_m represents the position of actuators, u the velocity of actuators, q the end effector position, and d the external forces. The matrices H and E map actuator positions to end effector positions and modulate the impact of external forces, respectively. In order to find them, we simulate the system behavior using SOFA simulation framework FEM model. We gather all states, outputs, and inputs of the system. They are finally obtained using least squares identification on this data.

A reference model, defined as a system of damped mass-spring systems, represents the desired behavior of the end effector perceived by the environment in response to desired positions and external disturbance. The equation presented in Fig. 1 can be transformed into a discrete state space with the state $x^T = (q_r \quad \dot{q}_r)$ where q_r is the reference position. The inputs are a desired position q^* and external forces d .

This reference model requires external forces applied to the end-effector. Therefore, an estimator that inverts the robot system’s output is introduced as both actuators and end-effector positions are measured.

Finally, we use a state feedback with integral action, x_i , to obtain the velocity of actuators to follow the reference position as described in Fig. 1. To tune the gains, we defined a Linear Matrix Inequalities problem to ensure two characteristics: the time response is below a desired value and a command amplitude constraint.

III. RESULTS

Our robotic platform, presented if Fig. 2, has central end effector supported by four deformable legs, controlled by DC motors for movements primarily on the horizontal plane (X and Z axes). Measures are made using a depth camera.

Firstly, we wanted to provide highly flexible X-axis behavior to facilitate user interaction, while maintaining near-rigidity on the Z-axis. We then checked the force required for nearly the same displacement in open-loop and closed-loop cases. Fig. 4 shows a 55% reduction in force on the first axis, and a 70% increase on the second due to our control.

Secondly, we checked the accuracy of position control in the absence of external force. Fig. 3 shows that we achieve an error of less than 0.5mm for a 10mm position input. This error is mainly due to a non-zero force estimation as we move away from the equilibrium point.

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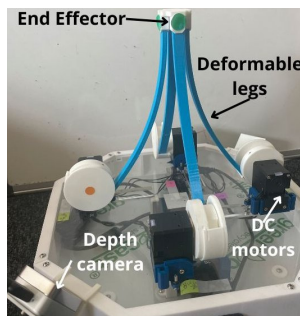


Fig. 2: Experimental setup.

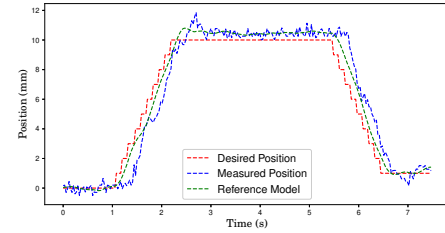
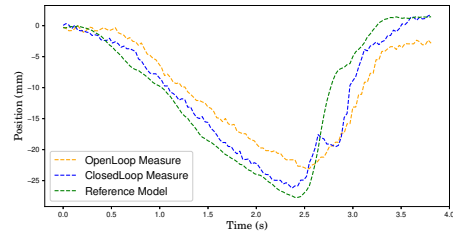
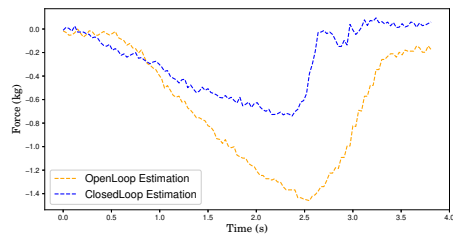


Fig. 3: Position Control Performance in X axis for a desired position without external interaction.



(a) X axis position



(b) X axis force

Fig. 4: Position (a) and force (b) control performance in X axis with external interaction compare to the open loop behavior.

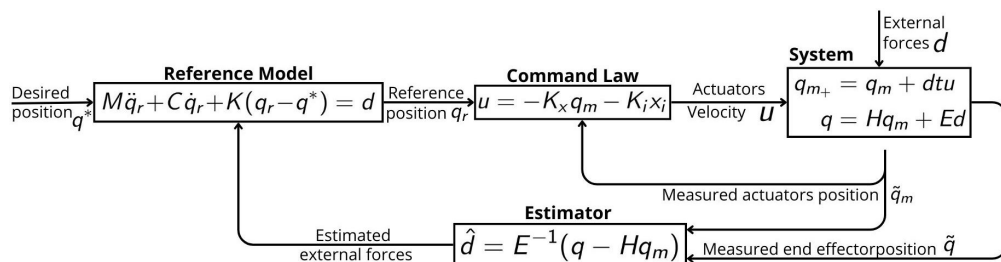


Fig. 1: Control structure of the soft robot.