A Compliant Gripper System for Delicate Object Grasping through Intrinsic Contact Sensing

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***Abstract*—Robust and stable grasping is critical for many robotic applications, particularly when handling fragile and deformable objects. However, seamlessly integrating contact sensing and achieving structural compliance during the grasping process poses significant challenges. In this project, we develop a grasping system that includes a soft gripper and a robotic arm, designed to achieve both contact sensing and structural compliance for grasping various objects. Specifically, the soft gripper, equipped with compact deflection sensors, serves as the end-effector on a robotic arm to handle various objects. The deflection sensors are essential for contact sensing about contact conditions, including contact positions and grasping forces, to provide critical information for safely handling fragile and deformable items. Following contact sensing, the inherent structural compliance of the soft gripper allows it to adjust to a broad range of irregular shapes. We conduct and document tests on various objects, such as an egg, a small wine glass, and a glue bottle. These tests not only demonstrate the feasibility of the developed system but also highlight its potential to contribute to a comprehensive grasping dataset that includes data on deformation and forces during grasping.**

I. Introduction

The field of robotics has seen substantial advancements in the development of dexterous manipulators. However, reliable handling of fragile and deformable objects is still a challenging problem. This capability is fundamental for expanding the applicability of robots in various downstream applications, such as healthcare, service, and manufacturing. When interacting with objects that vary widely in shape, size, and material properties, robust and stable grasping mechanisms are vital for ensuring the safe and effective operations of robots. In particular, the ability to adapt to irregular object geometries while maintaining force sensing is essential for achieving stable and safe manipulations.

In this project, to address these challenges, we develop a soft gripper system by integrating a robot arm and a soft gripper with structural compliance and force perception, and test the system on various objects. This system's design not only enhances the operational safety and efficiency of robotic manipulators but also opens new avenues for their deployment in complex, real-world environments where traditional rigid grippers would fail.

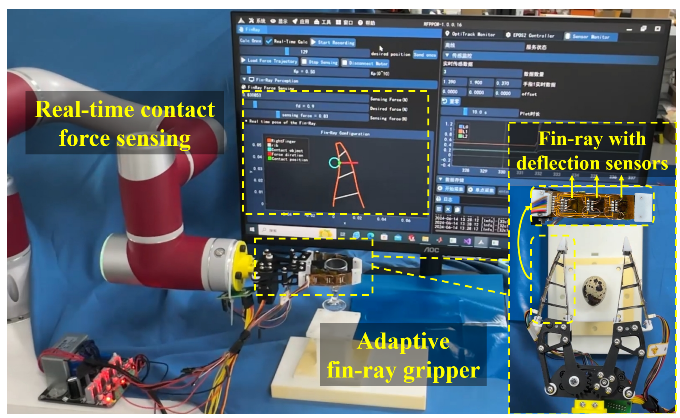


Fig. 1. System overview: sensor-based contact sensing and force feedback control with adaptive finger gripper.

II. Method

Our grasping system mainly consists of a pair of fin-ray fingers with compact deflection sensors and a robotic arm. Pioneered by Festo [1], adaptive fin-ray grippers have been developed to handle objects with free-form shapes [4, 5, 6]. These two fin-ray fingers are actuated by two planar four-bar linkages that are driven via a servo, and three strain gauges are integrated on the back side of the fin-ray structure. Through a model-based contact sensing method in the light of local deformations gathered at a set of discrete positions, contact sensing and the adaptive grasping of objects are achieved. Fig. 1 shows an overview of the developed system.

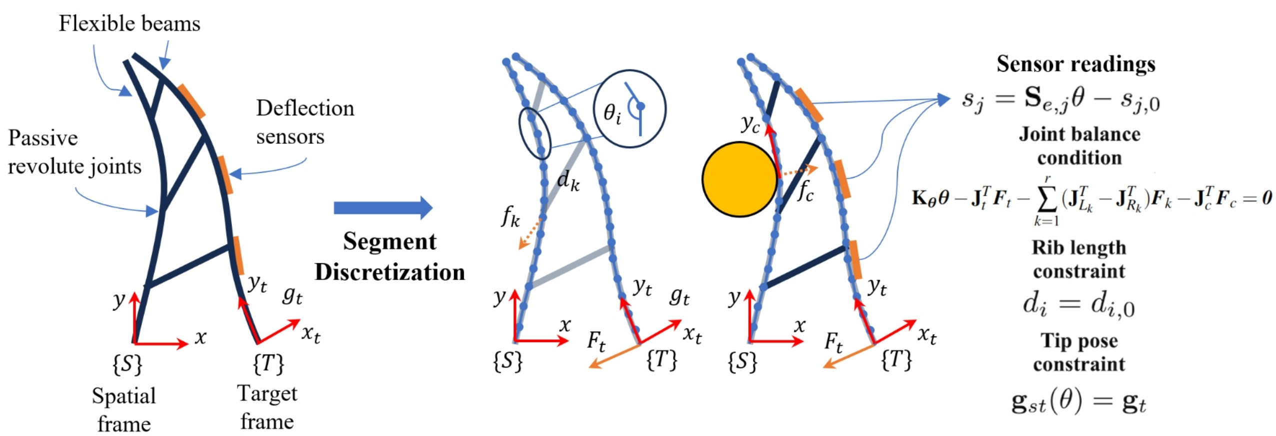
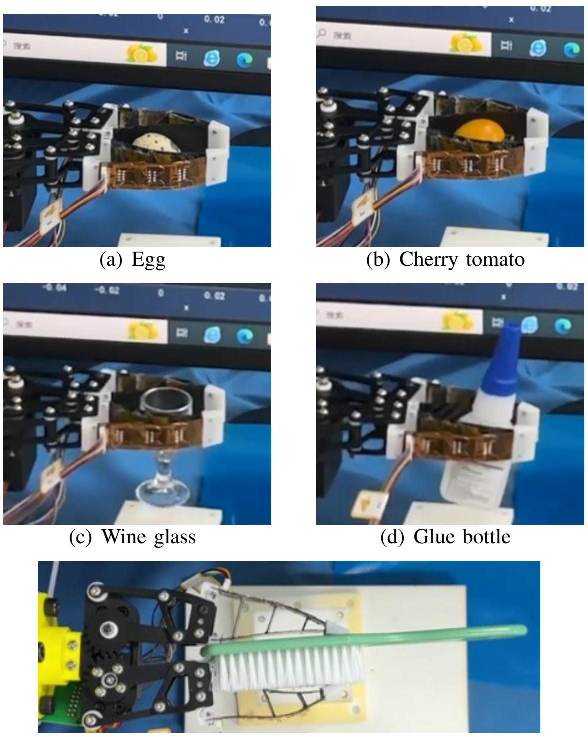


Fig. 2. Elastostatics modeling and analysis of the fin-ray gripper for contact sensing: resolving contact configuration from three local bending curvatures.



(a) Egg (b) Cherry tomato (c) Wine glass (d) Glue bottle (e) Brush

Fig. 3. Gallery of grasped objects.

The fin-ray soft gripper offers a simple yet effective method for facilitating compliant interaction with grasped objects. As shown in Fig. 1, the remarkable adaptability of the fin-ray gripper is due to the passive structural deformations of its flexible components, which conform to the surfaces they touch. Additionally, to measure grasping forces during the grasping process, a systematic kinetostatics model of the studied fin-ray structure is established in the discretization-based modeling framework, based on the prior work [2], for large deflection problems of slender flexible links.

The flexible beams are approximated to articulated mechanisms with a large number of rigid bodies and passive elastic joints, to be characterized by hyper-redundant multi-body systems (MBS). Thus, conventional methods for robot kinematics and statics can be adopted to complete the kinetostatics modeling and analysis, as illustrated in Fig. 2. Through such modeling, the joint force equilibrium $\boldsymbol{\tau}$, local deflection curvature $\boldsymbol{s}$ and geometrical constraints including tip pose $\mathbf{g}_{st}$ and rib length d_k can be derived as

$$\boldsymbol{\tau} = \mathbf{K}_{\boldsymbol{\theta}}\boldsymbol{\theta} - \mathbf{J}_t^T \boldsymbol{F}_t - \sum_{k=1}^{r}(\mathbf{J}_{L_k}^T - \mathbf{J}_{R_k}^T)\boldsymbol{F}_k - \mathbf{J}_c^T \boldsymbol{F}_c = \boldsymbol{0} \quad (1)$$

$$\boldsymbol{s} = \mathbf{S}_e\boldsymbol{\theta} - \boldsymbol{s}_0 = \boldsymbol{0} \quad (2)$$

$$\mathbf{g}_{st}(\boldsymbol{\theta}) = \exp(\hat{\zeta}_1\theta_1)\cdots\exp(\hat{\zeta}_n\theta_n)\,\mathbf{g}_{st,0} = \mathbf{g}_t \quad (3)$$

$$d_k = \|\boldsymbol{r}_{L_k} - \boldsymbol{r}_{R_k}\| = d_{k,0}, \quad k = 1, \cdots, r \quad (4)$$

Thus, a nonlinear equation system on the configuration and contact force of the MBS can be established as

$$\boldsymbol{C}(\boldsymbol{\theta}, \boldsymbol{F}_t, \boldsymbol{f}, l_c, f_c) = \begin{bmatrix} \boldsymbol{\tau} \\ \boldsymbol{s} \\ \boldsymbol{y} \\ \boldsymbol{d} \end{bmatrix} = \boldsymbol{0} \quad (5)$$

where $\boldsymbol{y} = (\ln(\mathbf{g}_{st}\,\mathbf{g}_t^{-1}))^\vee \in \mathbb{R}^{6\times 1}$ represents the pose deviation of the tip frame from its target one, l_c relates to the beam length from the origin $\{S\}$ to the contact point, f_c relates to the norm of contact force. Refer to our previous work [3] for details of modeling and resolution.

The above system can be solved by the classical Newton-Raphson method in a fast and iterative manner. In this way, by measuring three local deflection curvatures on the fin-ray, the contact force and location could be derived by resolving this equation system. Hence, the contact sensing and the active compliant grasping of the fin-ray gripper system can be performed, through a totally mechanical model-based approach instead of network learning.

III. Experiments

To demonstrate the effectiveness of the developed system, we conduct tests on various irregular objects with active compliant grasping and contact force feedback.

Fig. 3 shows a gallery of the testing objects. When handling items like brushes and glue bottles (3(d, e)), the system does not require precise grasping points. Under the circumstances when there are misalignments between the gripper center and objects, our soft gripper system provides additional compliance to buffer the contact, whereas a rigid gripper might simply knock the objects over. This flexibility is crucial for operational safety and broad applicability. In the case of fragile objects like eggs and glass cups (3(a,c)), the gripper adjusts its configuration to adapt to their irregular shapes, ensuring a secure yet gentle grasp that prevents damage. Additionally, when interacting with fruits, such as deformable cherry tomato (3(b)), the integrated force-sensing capabilities of the gripper allow for safe grasping and avoiding damage.

The results demonstrate that the proposed grasping system with sensor-based feedback control can well adapt to fragile, soft, and various objects in diverse scenarios. Please refer to the demo video for more details about the grasping process.

IV. Conclusion and Future Work

In conclusion, this project has demonstrated a robust grasping system that integrates a robot arm and a soft gripper with compact deflection sensors, addressing key challenges in handling fragile and deformable objects. Our system's ability to adapt to various object geometries and monitor grasping forces ensures safe and effective manipulation, which is crucial for a wide range of applications. The testing experiments, including objects like an egg, a small wine glass, and a brush, have validated the system's functionality, showcasing its potential to improve robotic dexterity and sensitivity.

Future work: A promising direction is the expansion of the dataset to include more diverse object interactions, which would refine the system's performance analytics and potentially contribute to the development of more generalized learning-based robotic grasping algorithms.

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