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Towards Dexterous Agri-Food Manipulation: Topology-Dependent Interaction Patterns in a Reconfigurable Multifingered Gripper

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Abstract— **Robotic agri-food manipulation remains challenging because food items vary substantially in geometry, compliance, mass distribution, and surface properties, while their fragile nature makes grasping sensitive to small pose errors. This work presents a compact simulation-based study of how grasp topology affects robustness and mechanics-level interaction behavior in a reconfigurable four-finger gripper. Using AGX Dynamics, we evaluate three grasp configurations across representative agri-food objects under controlled yaw and planar-offset perturbations. The results show that spherical grasping is most robust to planar misplacement, torque is more perturbation-sensitive than force, and friction demand is governed more by object geometry than by grasp configuration. These findings provide an interpretable basis for robust and damage-aware configuration selection in agri-food manipulation.**

I. Introduction

Robotic grasping in agri-food environments requires not only stable pickup but also damage-aware interaction. Compared with rigid industrial parts, food items exhibit substantial variation in geometry, size, compliance, mass distribution, and surface properties, which makes grasp outcomes highly sensitive to small errors in perception and placement [1], [2]. In this setting, grasp quality cannot be understood through success rate alone, because perturbations may also alter contact distribution, load sharing, friction demand, and object-centered torque in ways that affect robustness and potential damage risk.

Reconfigurable and multifingered grippers offer a promising way to adapt grasp topology to object variability, but their advantages are still more often discussed in terms of hardware flexibility or task-level success than in terms of interpretable interaction mechanics [3]. In this work, we study grasp topology as the main variable of interest and ask how different configurations shape robustness and mechanics-level behavior under controlled pose perturbations. Our goal is to provide a compact, simulation-based analysis that helps explain not only which topology performs better, but why.

II. Evaluation Setup

We study a reconfigurable four-finger gripper with three representative grasp topologies: *Parallel*, *Spherical*, and *Tripod*. The evaluation is conducted in AGX Dynamics, a physics simulator well suited for contact-rich interaction analysis [4]. Five representative agri-food objects are considered from the YCB dataset—banana, apple, orange, pear, and strawberry—covering elongated, compact near-spherical, and small irregular geometries [5]. Objects are modeled as rigid bodies with compliant contact, and mean penetration depth is used as a deformation-related proxy.

Each grasp trial is defined by an object, a grasp topology, a yaw angle, and an optional planar placement offset. To reflect practical uncertainty, we systematically vary yaw and apply planar offsets on a discrete grid with a 20 mm step. Each trial follows the same descend–close–lift routine, and we record grasp success together with mechanics-level signals, including contact force response, object-centered torque, friction utilization, cross-finger load distribution, and mean contact penetration. This setup enables controlled comparison of how topology influences both outcome-level robustness and physically interpretable interaction patterns under perturbation [6].

III. Key Findings and Discussion

Across the evaluated objects and perturbation settings, three main findings emerge.

First, grasp topology strongly affects robustness to planar placement uncertainty. Among the three tested configurations, *Spherical* consistently achieves the highest grasp success under planar offsets, while *Parallel* is the most sensitive to lateral misalignment. This suggests that a more enveloping multi-contact topology better preserves contact support and force closure when placement is imperfect.

Second, object-centered torque is consistently more sensitive to perturbation than force-related quantities. Across both yaw and planar-offset variations, torque changes more strongly than normal or tangential contact force, indicating that perturbations primarily amplify rotational effects through contact-point migration and changing moment arms rather than through a uniform increase in contact loading. This is an important observation for fragile-object manipulation, because a grasp may remain feasible in terms of mean force while becoming mechanically less stable in terms of rotational response.

Third, friction demand is governed more by object geometry than by grasp topology. Elongated or less compact objects tend to operate closer to the friction boundary, whereas compact objects preserve a larger slip margin across configurations. Planar offsets generally increase friction utilization even when the grasp still succeeds, indicating that reduced safety margin can appear before binary failure. In contrast, differences among the three configurations are comparatively smaller, suggesting that topology mainly affects robustness to uncertainty, while geometry primarily determines how demanding the contact interaction is.

Two additional observations help refine this picture. Yaw perturbations usually have a weaker effect on success than planar offsets for compact objects, whereas the banana remains more orientation-sensitive because of its elongated curved geometry. In addition, the penetration-based deformation proxy varies more strongly across objects than across grasp topologies, suggesting that local indentation tendency is dominated mainly by object-specific material and geometric properties rather than by topology alone.

IV. Conclusion

This extended abstract presented a compact physics-based study of topology-dependent interaction patterns in contact-rich agri-food grasping with a reconfigurable four-finger gripper. Rather than evaluating grasps only through binary success, the study shows that configuration-dependent differences can be interpreted through robustness to placement uncertainty, torque sensitivity, and friction demand. These findings provide a more informative basis for grasp configuration selection in fragile-object manipulation and support the use of mechanics-level indicators in future damage-aware and learning-based grasping systems. Future work will validate the observed trends on physical hardware and investigate how these interaction signals can guide automatic configuration selection.

References

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