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

***Abstract*— Multi-fingered and reconfigurable grippers offer greater adaptability than fixed designs, but it remains unclear how grasp topology systematically affects object-level interaction patterns in contact-rich manipulation. In this paper, we present a contact-rich simulation framework in AGX Dynamics to analyze topology-dependent grasp behavior of a reconfigurable four-finger gripper under controlled yaw and planar-offset perturbations across representative agri-food objects. Beyond grasp success, we evaluate mechanics-level interaction patterns to compare robustness, torque response, friction demand, load redistribution, and penetration-based deformation tendency. The results show that more enveloping topologies achieve consistently higher robustness to planar placement uncertainty, while object-centered torque is markedly more sensitive to perturbations than contact force and thus provides a more discriminative indicator of topology-dependent robustness. We further find that friction demand is governed primarily by object geometry, whereas grasp topology more strongly affects how interaction mechanics respond to perturbations. These findings provide quantitative guidance for grasp configuration selection and for evaluating reconfigurable multifingered grasping systems beyond success rate alone.**

I. Introduction

Reconfigurable and multi-fingered grippers offer the potential for more adaptable manipulation than fixed grasping devices, but it remains unclear how grasp topology systematically affects robustness and contact mechanics in contact-rich tasks. This question is especially important when handling fragile or compliant objects, where small pose perturbations can significantly alter contact distribution, load sharing, friction demand, and the risk of slip or damage.

Agri-food manipulation provides a particularly challenging setting for studying this problem [1], [2]. Compared with rigid industrial parts, food items exhibit substantial variability in geometry, size, mass distribution, and surface properties, while their compliant and fragile nature makes grasp outcomes highly sensitive to grasp configuration and object pose. In such settings, grasp evaluation should go beyond binary success rates and account for how different topologies influence object-level interaction patterns, including force redistribution, object-centered torques, friction utilization, and deformation-related effects.

In this paper, we present a contact-rich simulation study of a reconfigurable four-finger gripper to analyze how grasp topology shapes object-level interaction patterns under controlled perturbations. As illustrated in Fig. 1, we use AGX Dynamics to systematically vary grasp configuration, gripper yaw, and planar placement offsets across diverse agri-food objects, and we record both grasp outcomes and mechanics-level signals, including contact forces, interaction torques, friction utilization, load distribution, and contact penetration as a deformation proxy. Based on this framework, we make three contributions: 1) a systematic evaluation pipeline for topology-dependent grasp analysis under controlled perturbations; 2) a quantitative characterization of object-level interaction patterns beyond grasp success; and 3) cross-object insights showing that grasp topology affects robustness primarily through torque sensitivity, friction demand, and load redistribution, providing useful guidance for grasp configuration selection and hardware evaluation.

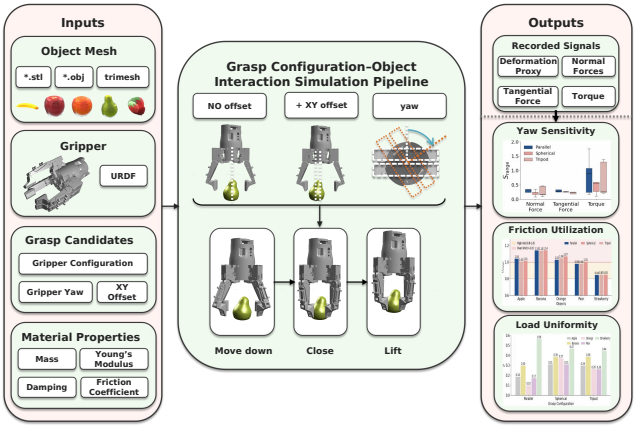


Fig. 1. Overview of the simulation pipeline for analyzing grasp configurations and object-level interaction patterns. Contact-rich grasp trials are executed in AGX Dynamics using object models, material properties, and grasp candidates. Grasp outcomes and key interaction signals are then used for quantitative analysis.

II. Related Works

Robotic grasping of agri-food objects has been widely studied using parallel-jaw, soft [3]–[5], or hybrid end-effectors [6], with most efforts focusing on reducing damage, improving grasp success, or adapting perception and planning to object variability [7], [8]. Reconfigurable and multi-finger grippers offer greater adaptability and grasp enveloping, but existing studies more often emphasize hardware design [9], mechanism versatility, or task-level performance [10], [11], with limited quantitative analysis of how different grasp topologies induce distinct interaction patterns across object categories [12]–[14].

Physics-based simulation has also become an important tool for grasp analysis, especially for contact-rich or

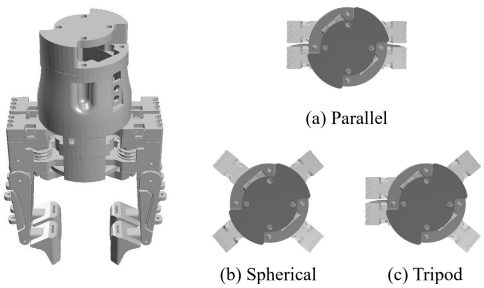


Fig. 2. Reconfigurable four-finger gripper and the three grasp topologies considered in this study: Parallel, Spherical, and Tripod.

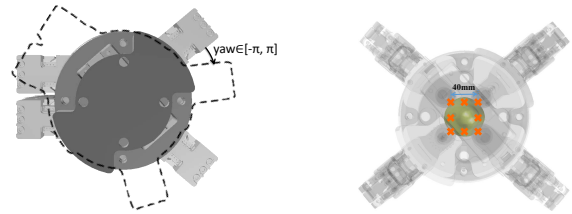
deformable-object manipulation, because it enables controlled perturbation studies and access to interaction states that are difficult to isolate experimentally [15], [16]. However, many existing simulation-based studies remain outcome-oriented, focusing primarily on grasp success, deformation outcome, or data generation, rather than providing interpretable, object-level mechanics analysis. In contrast, our work studies grasp topology as a first-class variable and uses contact-rich simulation to quantify how it shapes robustness, load redistribution, object-centered torques, friction utilization, and deformation-related effects across diverse agri-food objects.

III. System and Evaluation Setup

We study a reconfigurable four-finger gripper that enables controlled comparison of different grasp topologies using the same hardware platform [9]. As shown in Fig. 2, the gripper consists of four symmetrically arranged fingers and a reconfiguration mechanism that adjusts the relative orientation of opposing finger pairs. This design allows the contact geometry of the grasp to be modified without changing the end-effector itself, making it well suited for analyzing topology-dependent interaction patterns. In this work, we focus on three representative grasp topologies: **Parallel**, which arranges the fingers in opposing pairs and produces a pinch-like grasp; **Spherical**, which forms a more enclosing topology around the object; and **Tripod**, which combines a primary opposing pair with two laterally supporting fingers. These configurations provide a compact but representative basis for studying how grasp topology affects robustness, load redistribution, friction demand, and object-centered torques.

We use AGX Dynamics [15], [17] to perform contact-rich simulation of this gripper interacting with representative agri-food objects. Five object models are selected from the YCB dataset [18], covering elongated, near-spherical, and small irregular shapes (banana, apple, orange, pear, and strawberry). To reflect object heterogeneity while keeping the study controlled, each object is assigned category-specific mass and contact parameters in AGX. In our setup, the objects are modeled as rigid bodies with compliant contact, and contact penetration is used as a deformation-related proxy.

Each grasp trial is defined by an object category, a grasp topology, a gripper yaw angle, and an optional planar placement offset. As illustrated in Fig. 3, we systematically sweep yaw and apply planar offsets on a discrete grid with a step of $20\,\mathrm{mm}$ to emulate orientation and positioning uncertainty. Each trial follows a unified descend–close–lift routine, and grasp outcomes together with interaction-level signals are recorded throughout execution.



(a) Orientation yaw span. (b) Planar offset grid.

Fig. 3. Controlled pose perturbations applied during grasp evaluation: (a) orientation perturbation and (b) planar placement perturbation.

To analyze topology-dependent interaction patterns, we measure grasp success, contact force distribution, object-centered interaction torque, friction utilization, and contact penetration. *Friction utilization* at contact i is defined as

$$U_i = \frac{\|\mathbf{f}_{t,i}\|}{\mu f_{n,i}},$$

where $\mathbf{f}_{t,i}$ and $f_{n,i}$ are the tangential and normal contact forces, respectively ($U_i = 1$ being the boundary of the friction cone).

The resulting *object moment (torque)* about the object center of mass $\mathbf{r}_{\mathrm{COM}}$ is computed as

$$\boldsymbol{\tau} = \sum_i (\mathbf{p}_i - \mathbf{r}_{\mathrm{COM}}) \times \mathbf{f}_i.$$

where $\mathbf{p}_i$ denotes the contact point position expressed in the world frame.

These measurements provide a compact set of mechanics-level indicators for comparing how grasp topology affects robustness, load redistribution, friction demand, and deformation-related risk across objects and perturbation conditions.

IV. Key Results and Insights

We evaluate the proposed framework across five representative agri-food objects and three grasp topologies under controlled yaw and planar-offset perturbations. Rather than focusing only on binary grasp outcomes, we analyze how topology affects robustness and object-level interaction patterns through success rate, sensitivity of mechanics-level signals, and friction utilization, while using penetration-based deformation proxy and cross-finger load distribution as complementary indicators.

a) Robustness to placement uncertainty: Fig. 4 shows grasp success under planar placement offsets. A clear topology-dependent trend emerges: the Spherical configuration consistently achieves the highest success rates across objects, indicating greater tolerance to lateral misalignment, whereas Parallel is the most sensitive to offset perturbations. This difference is consistent with the underlying contact

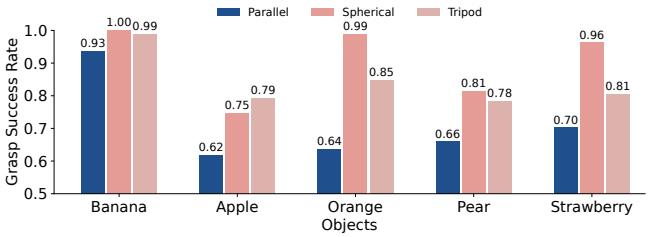
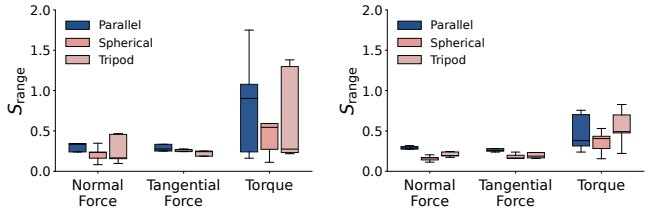


Fig. 4. Grasp success rate under planar placement offsets for different objects and grasp configurations. Success is defined as stable lifting without slip or contact loss. Higher values indicate greater robustness to lateral misalignment.



(a) Yaw Perturbations (b) Planar Offsets

Fig. 5. Cross-object sensitivity S_{range} of normal contact force, tangential force, and object-centered torque during the grasp phase under (a) yaw perturbations and (b) planar placement offsets (success-conditioned).

organization: more enveloping topologies preserve multi-contact support and force closure more effectively under placement errors.

b) Torque is more sensitive than force: To explain robustness beyond binary success, we compare the cross-object sensitivity of interaction signals under perturbations using the normalized variation score

$$S^{f}_{\text{range}} = \frac{\max_{\psi\in\Psi} f(\psi) - \min_{\psi\in\Psi} f(\psi)}{\bar{f}}.$$

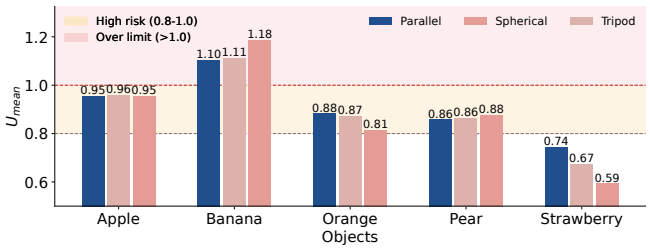
where $\bar{f}$ is the mean over perturbation set Ψ. Lower S^{f}_{range} indicates lower sensitivity and higher robustness.

As shown in Fig. 5, object-centered torque consistently exhibits markedly higher sensitivity than normal or tangential contact force under both yaw and planar-offset perturbations. This indicates that pose uncertainty acts primarily through rotational effects induced by contact-point migration and changing moment arms, rather than through uniform scaling of contact forces. Across configurations, Spherical also shows the lowest force sensitivity, further supporting its more stable interaction behavior under perturbation.

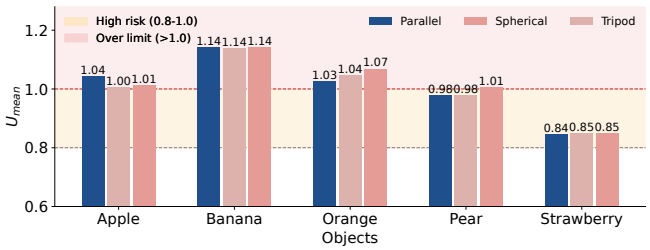
c) Geometry dominates friction demand: Fig. 6 reports the average friction utilization

$$U_{\text{mean}} = \frac{1}{4}\sum_{i=1}^{4} \frac{\|\mathbf{f}_{t,i}\|}{\mu f_{n,i}}.$$

A clear geometry-dependent pattern is observed: elongated or less compact objects operate closer to the friction boundary, while compact objects maintain larger friction margins. Compared with yaw perturbations, planar offsets generally increase friction utilization, indicating reduced slip margin even for successful grasps. In contrast to robustness trends, differences across topologies are more limited, suggesting



(a) Yaw Perturbations



(b) Planar Offsets

Fig. 6. Object-wise average friction utilization U_{mean} under (a) yaw perturbations and (b) planar placement offsets for the three gripper configurations. The dashed red line indicates the nominal friction limit ($U = 1$). The shaded region between 0.8 and 1.0 represents a high-risk regime near the friction cone boundary.

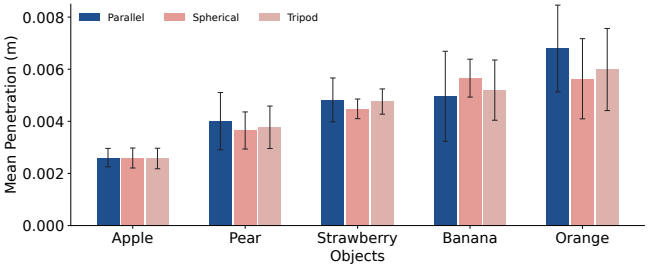
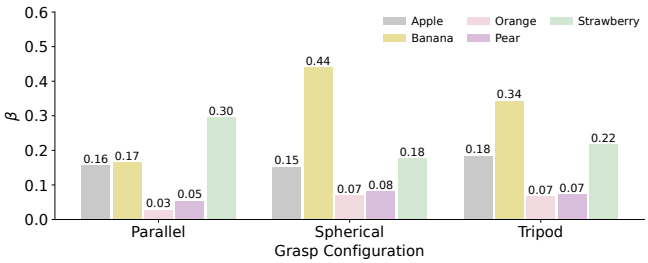


Fig. 7. Average mean penetration depth P_{mean} for each object under the three grasp configurations. Error bars indicate variability across trials.

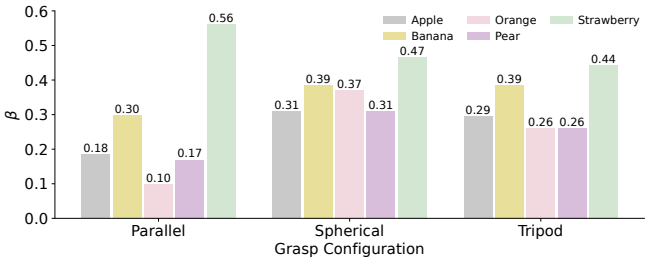
that object geometry primarily determines friction demand, whereas topology more strongly shapes robustness and perturbation sensitivity.

d) Deformation-related effects are mostly object-dependent: To connect robustness analysis with damage-aware manipulation, we further examine the penetration-based deformation proxy in Fig. 7. The absolute penetration level varies more strongly across objects than across grasp topologies, indicating that local indentation tendency is governed primarily by object-specific compliance and geometry. In our experiments, the orange and banana exhibit the highest penetration levels, whereas the apple remains consistently lower. This suggests that penetration is not the main discriminator for topology selection in the present study, but remains a useful complementary indicator for checking that mechanically robust grasps do not come at the cost of elevated deformation-related risk.

e) Load redistribution provides additional physical interpretation: Fig. 8 reports cross-finger load uniformity under yaw and planar-offset perturbations. Compared with success rate and torque sensitivity, the trends in load uniformity are less strongly topology-dominated and remain influenced by object geometry and scale. Nevertheless, this metric



(a) Yaw Perturbations



(b) Planar Offsets

Fig. 8. Cross-finger load uniformity under (a) yaw perturbations and (b) planar placement offsets. Lower values indicate load concentration on fewer fingers, while higher values indicate more uniform force distribution.

adds useful physical interpretation: robust grasps should not only resist slip and rotation, but also avoid excessive load concentration on a small subset of fingers. In this sense, load uniformity complements torque sensitivity by indicating whether stability is achieved through balanced multi-contact support or through more concentrated loading patterns.

Overall, the results support three primary transferable insights: (i) enveloping topologies improve tolerance to planar placement uncertainty, (ii) torque is a more discriminative indicator of topology-dependent robustness than contact force, and (iii) geometry dominates slip-related demand, while topology governs how interaction mechanics respond to perturbations. The penetration-based deformation proxy and load uniformity further refine this picture by showing that damage-related indentation risk is largely object-dependent, while load redistribution helps explain how robustness is physically realized across fingers. Together, these findings provide quantitative guidance for grasp configuration selection and for evaluating reconfigurable multifingered grasping systems beyond success rate alone.

V. Conclusions

This work studied grasp topology as a key variable in reconfigurable multifingered manipulation and showed how it shapes robustness and object-level interaction patterns in contact-rich agri-food grasping. Across objects and perturbation conditions, three main findings emerged: (i) more enveloping topologies improve tolerance to planar placement uncertainty, (ii) object-centered torque is a more discriminative indicator of topology-dependent robustness than contact force, and (iii) object geometry primarily determines friction demand, whereas topology more strongly affects perturbation response. Penetration-based deformation proxy and cross-finger load redistribution further complement this picture by clarifying damage-related indentation tendency and how robustness is physically realized across contacts.

These results provide quantitative guidance for grasp configuration selection and for evaluating reconfigurable multifingered grasping systems beyond success rate alone. As a next step, we will validate whether the relative ranking of configurations and the structure of the observed response trends remain consistent on physical hardware. More broadly, the proposed interaction metrics may serve as useful design signals for hardware evaluation and as supervision or reward signals for future learning-based, damage-aware grasp selection.

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