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Latent Diffeomorphic Co-Design of End-Effectors for Deformable and Fragile Object Manipulation

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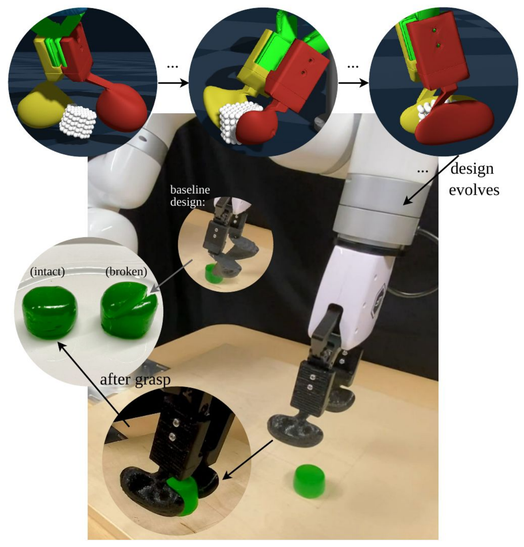
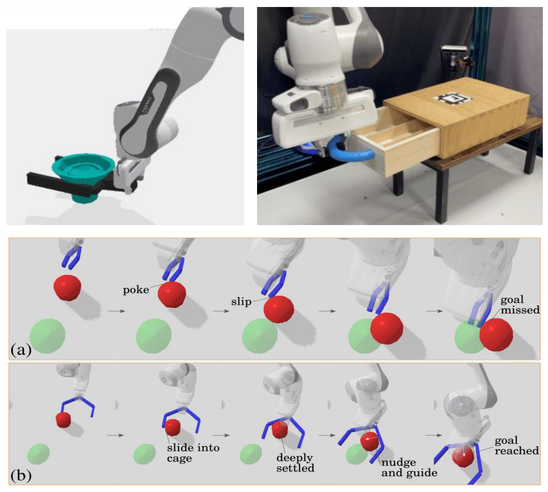
Motivation

- Fragile, deformable objects can break — task success and object integrity trade off.
- Prior work optimizes either the gripper or the controller, in isolation.
- Co-design works for rigid objects, but is unexplored for fragile ones.

> Our idea: jointly optimize end-effector shape and control against an object-integrity objective.





Prior co-design: rigid objects only

Method

1. Latent diffeomorphic design space (LDM)

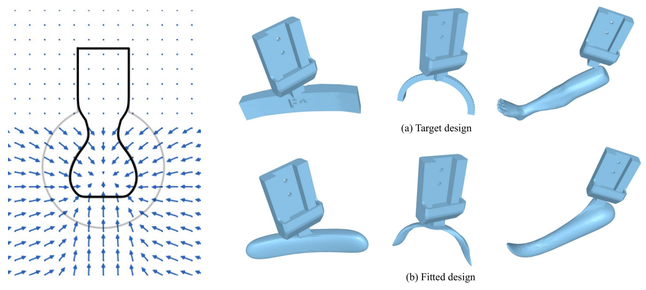
Smooth, self-intersection-free gripper shapes from a ~15-D latent.

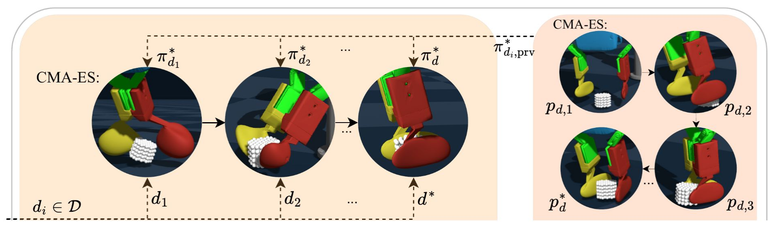
2. Stress-aware bi-level co-design

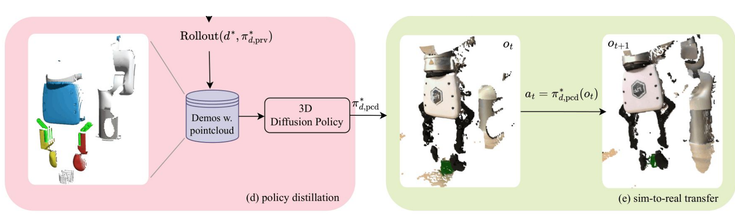
CMA-ES searches shapes; each scored by a controller using privileged stress signals.

3. Sim-to-real via distillation

privileged sim policy distilled to a point-cloud diffusion policy, deployed zero-shot

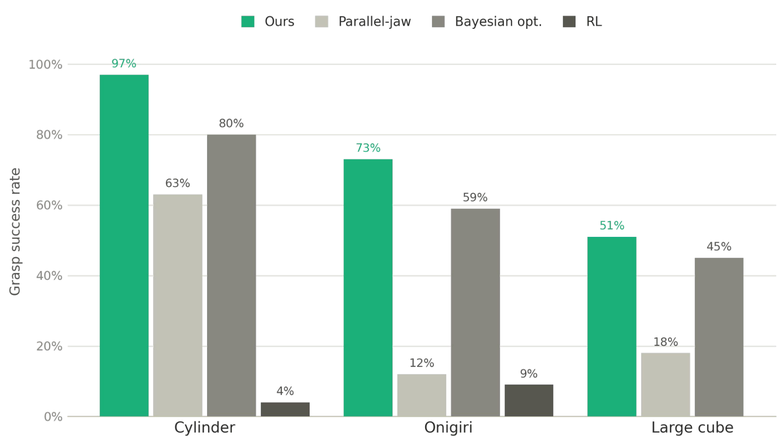






Experiment

Surpass standard grippers across shapes

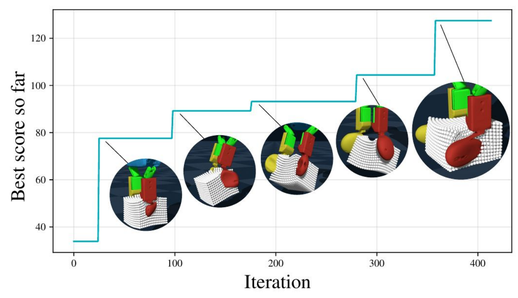


+33% grasp success vs parallel-jaw

−36% contact stress large cube

9 / 9 real-world grasps zero breakages

Shape gets conformed to the object surface

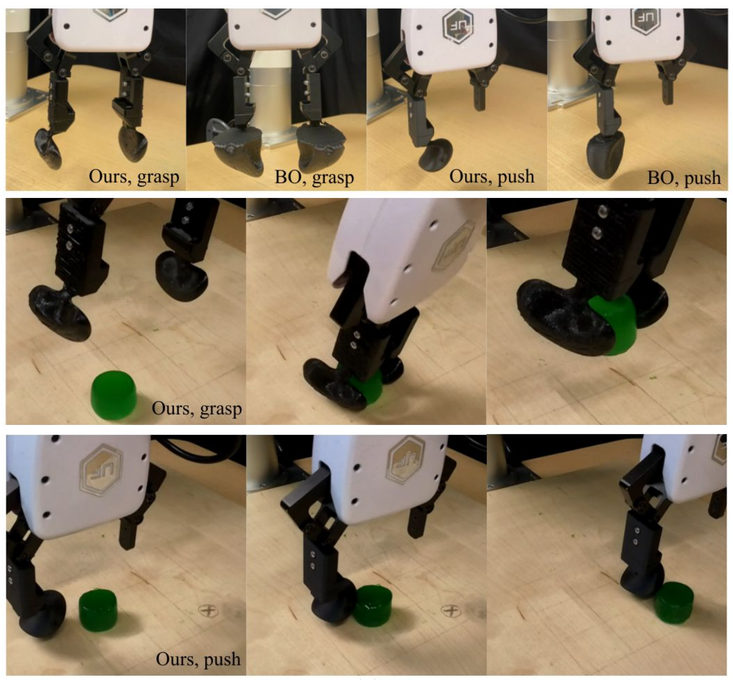


Ablation study against primitive design space

TABLE IV
COMPARISON OF DESIGN SPACES

	score J	success rate q_{succ}	stress $\sigma^{\max}$
Ours	**64** ± 18	**0.727** ± **0.081**	**13973** ± 490
Cubic	10 ± **17**	0.473 ± 0.083	14894 ± **306**
Spherical	13 ± 23	0.540 ± 0.106	15321 ± 386

Real world deployment



Takeaway

- Co-design balances task complexity from control to hardware — good morphology lowers control difficulty
- Gentle, reliable manipulation of fragile objects, learned in sim, deployed zero-shot.
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Limitation & Future Work: Reduce human labor and/or multi-task finger design