SEIL: Simulation-augmented Equivariant Imitation Learning

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Contributions

- **Transition Simulation:** Utilizes point cloud projection as a simulation of transitions to augment expert data.
- **Equivariant Imitation Learning:** Incorporates symmetry into imitation learning that allows direct generalization on rotations and reflections.

Method

Transition Simulation (TS)

Simulates new expert state-action pairs within the vicinity of existing expert transitions by projecting observation images from the observed point cloud.

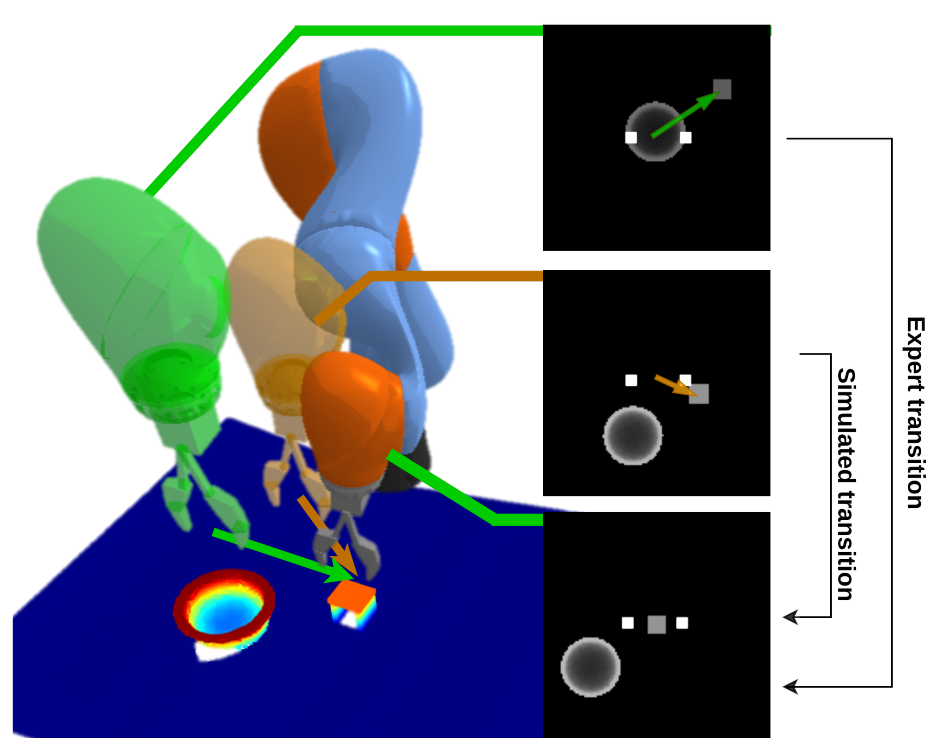
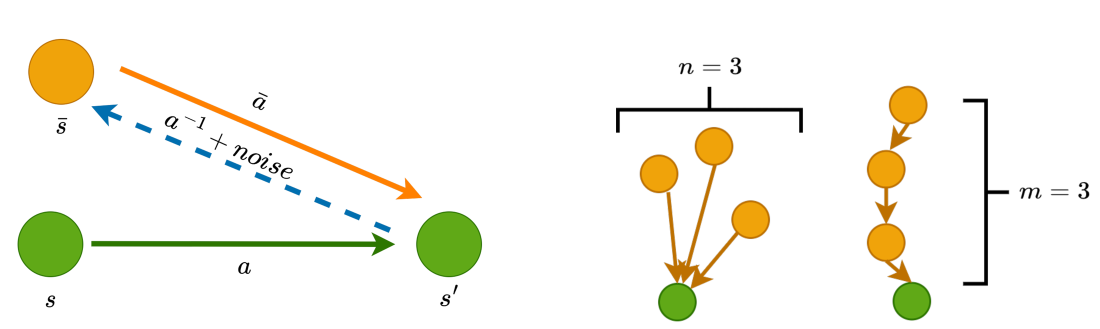


Figure 1. **Overview of Transition Simulation.**



(a) Transition simulation on one transition (b) Breadth and depth simulation

Figure 2. **Concept of transition simulation.** (a) shows how transition simulation is accomplished for one specific transition. (b) shows how two types of transition simulation are accomplished for one specific transition.

Equivariant Behavioral Cloning (EquiBC)

EquiBC utilizes the existing O(2) (i.e., planar rotation and reflection) symmetry in robotic manipulation to make the policy automatically generalize over different O(2) transformed states.

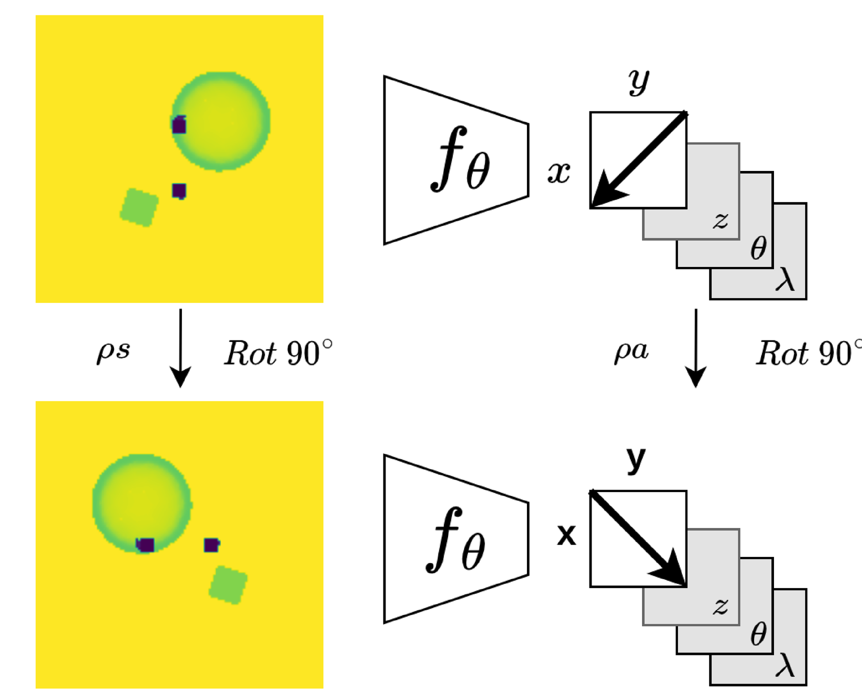
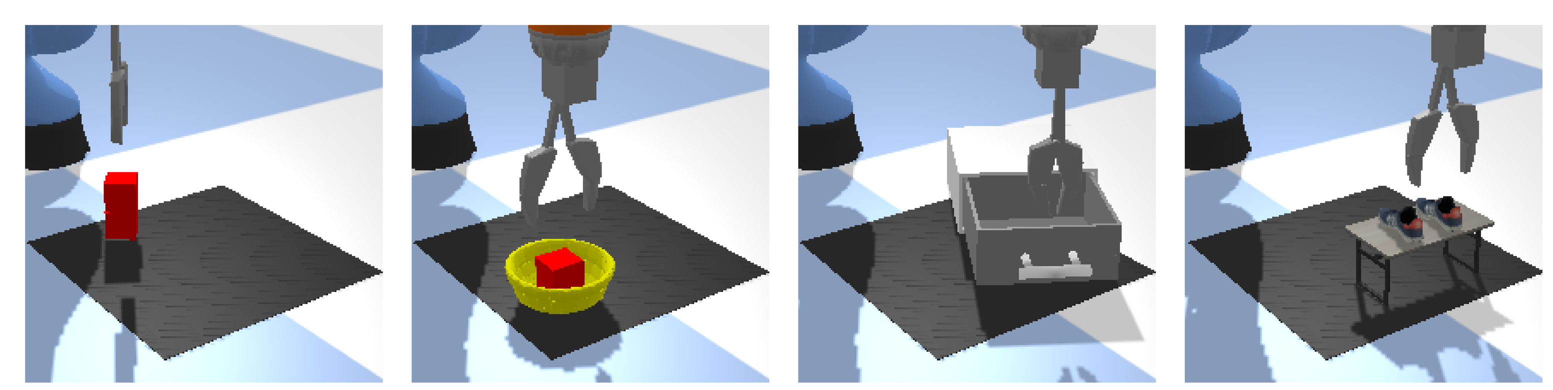


Figure 3. **Equivariant Behavioral Cloning:** The rotation equivariant property in the state and action space. The (x, y) action rotates as the state rotates; the other action components stay invariant.

Experiments



(a) Block Stacking (b) Block in Bowl (c) Drawer Opening (d) Shoe Packing

Figure 4. **Simulation environments in PyBullet**

	Block Stacking			Block in Bowl			Drawer Opening			Shoe Packing		
Method	1	5	10	1	5	10	1	5	10	1	5	10
CNN BC	18.5	73.5	79.0	19.0	93.5	99.0	31.0	66.5	76.0	2.0	4.7	12.0
Implicit BC [1]	11.0	9.5	51.0	13.0	**99.5**	**100**	31.0	63.5	71.5	0.5	5.5	12.0
CNN BC + TS	41.0	75.0	87.0	52.2	91.0	96.5	53.5	76.0	75.0	7.5	13.0	22.0
Equi BC (Ours)	33.5	87.5	93.0	46.5	**99.5**	99.5	62.5	**88.5**	91.0	1.5	22.5	39.5
SEIL (Ours)	**71.5**	**99.5**	**98.5**	**75.0**	98.0	**100**	**78.5**	87.5	**93.5**	**16.5**	**57.3**	**68.0**

Table 1. Baseline comparisons in simulation. Task success rates averaged over four runs.

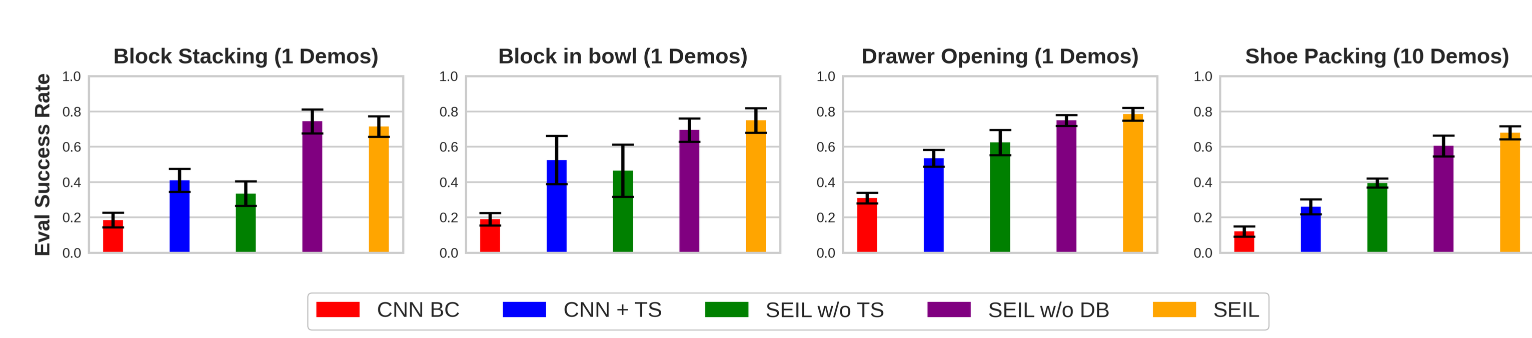
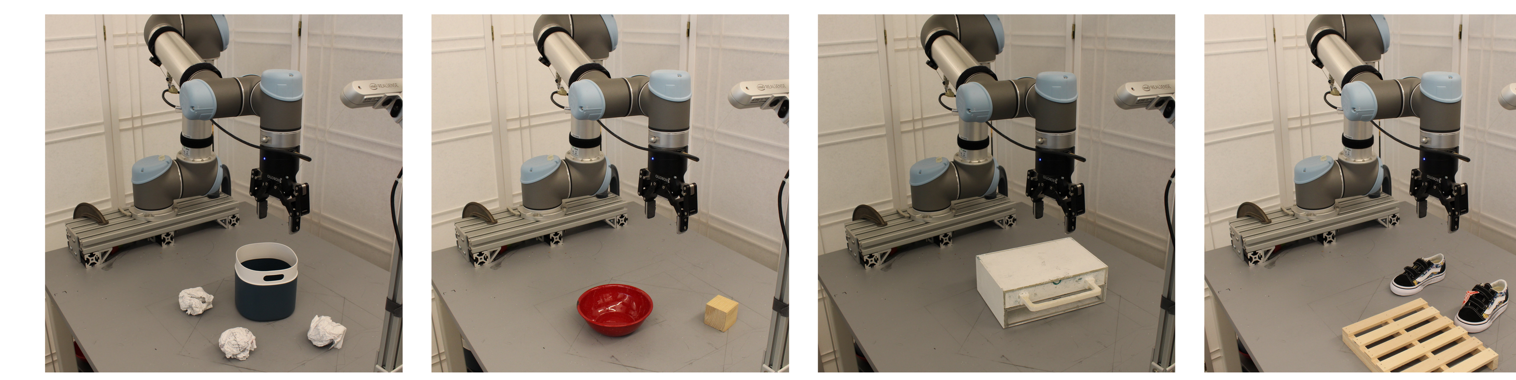


Figure 5. **Ablation study.** The figure shows how every component of our method improves performance. All tasks use one demonstration. Results averaged over four runs.

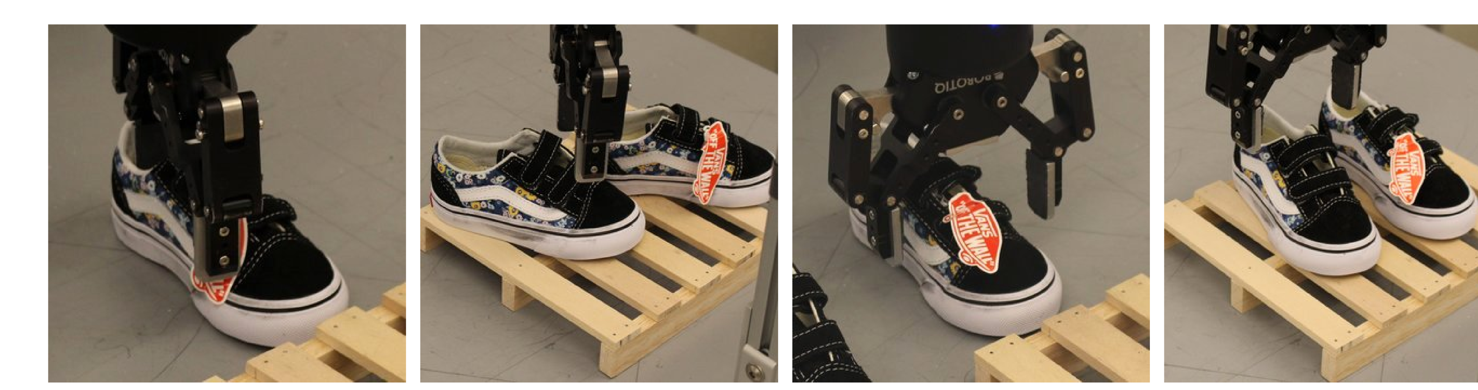
	Trash Tidying			Block in Bowl			Drawer Opening			Shoe Packing		
Method	1	5	10	1	5	10	1	5	10	1	5	10
CNN BC	0.0	3.3	20.0	0.0	50.0	76.7	23.3	60.0	70.0	10.0	46.7	70.0
SEIL (Ours)	**30.0**	**60.0**	**93.3**	**36.7**	**90.0**	**100.0**	**86.7**	**96.7**	**100.0**	**13.3**	**60.0**	**90.0**

Table 2. Baseline comparisons in real-world experiments. Task success rates averaged over 30 episodes across three seeds.



(a) Table Tidying (b) Block in Bowl (c) Drawer Opening (d) Shoe Packing

Figure 6. **Real-world experiments.** SEIL on four real-world tasks. Refer to the QR code for videos.



(a) CNN pick (b) CNN place (c) SEIL pick (d) SEIL place

Figure 7. **Comparison of SEIL and CNN BC in Shoe Packing.** SEIL is able to pack the shoes with reasonable orientations, but CNN cannot.

Limitations

- Transition Simulation only simulates transitions without contact between the gripper and the environment. Can be improved by learning an environment model to predict the outcome of the transition with contact.
- Observations are based on depth images without color information, preventing the agent from solving more complex tasks like color-based sorting.

References

[1] Pete Florence, Corey Lynch, Andy Zeng, Oscar A Ramirez, Ayzaan Wahid, Laura Downs, Adrian Wong, Johnny Lee, Igor Mordatch, and Jonathan Tompson. Implicit behavioral cloning. In Aleksandra Faust, David Hsu, and Gerhard Neumann, editors, *Proceedings of the 5th Conference on Robot Learning*, volume 164 of *Proceedings of Machine Learning Research*, pages 158–168. PMLR, 08–11 Nov 2022.