Physics-Based Planning for Automated and Generalizable Assembly

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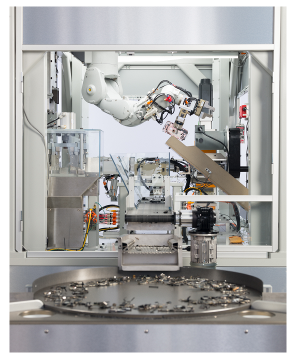
Part of the project[1] was accepted to *ACM Transactions on Graphics (SIGGRAPH Asia 2022)*

SIGGRAPH ASIA 2022 DAEGU

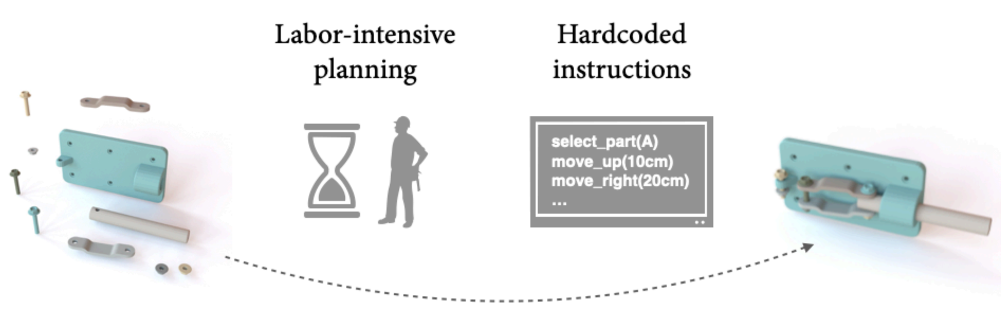
Paper/Video/Code/Dataset
assembly.csail.mit.edu

Motivation

Assembly is the core of modern industrial manufacturing!



However, the assembly process is planned by human, which is tedious and time-consuming. Human needs to send hardcoded instructions to robots, and they only work for a specific assembly.

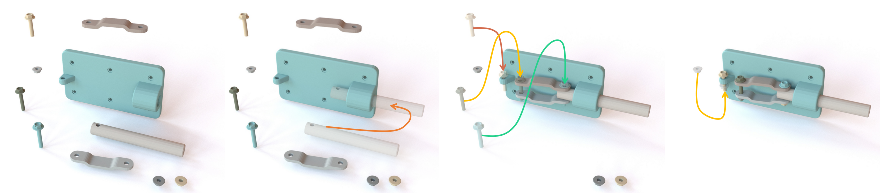


So, can we automate assembly planning for arbitrary assemblies?

Challenges:

- The geometry of objects can be arbitrarily complex. It's non-trivial to plan collision-free paths for assembly.
- The number of potential assembly sequences scales exponentially with the number of parts, and most of the sequences are infeasible.
- How to make sure the assembly process is gravitationally stable and executable by only a few robotic grippers?

Contributions

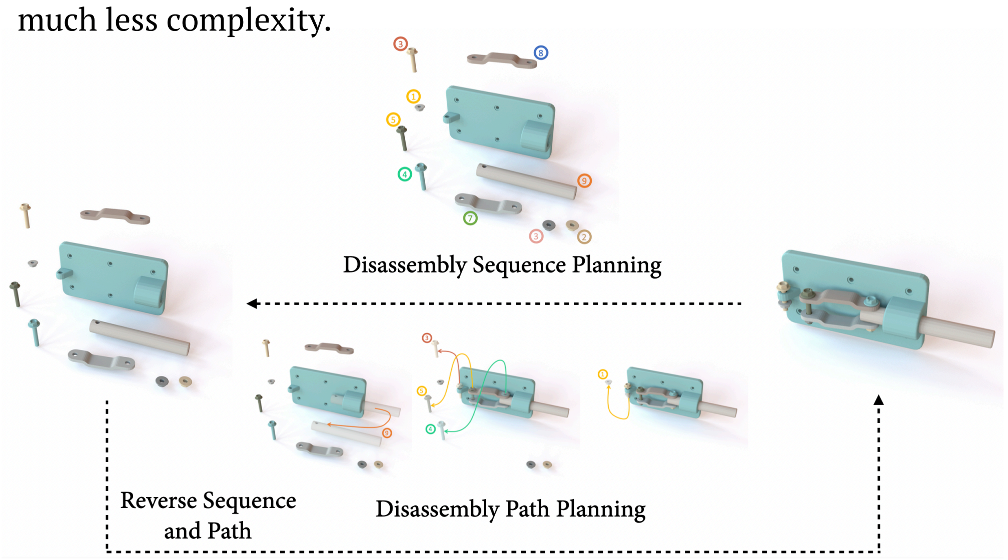


- An efficient assembly sequence planning algorithm that leverages an assembly-by-disassembly strategy and a physics-based simulation to generate physically-feasible sequences for complex-shaped contact-rich assemblies.
- A novel physics-based planning method for translational and rotational assembly motion for arbitrary-shaped assemblies.
- A large-scale dataset and benchmark for assembly planning including thousands of physically valid assemblies.
- A state-of-the-art success rate, computational efficiency, and generalization performance.

Method

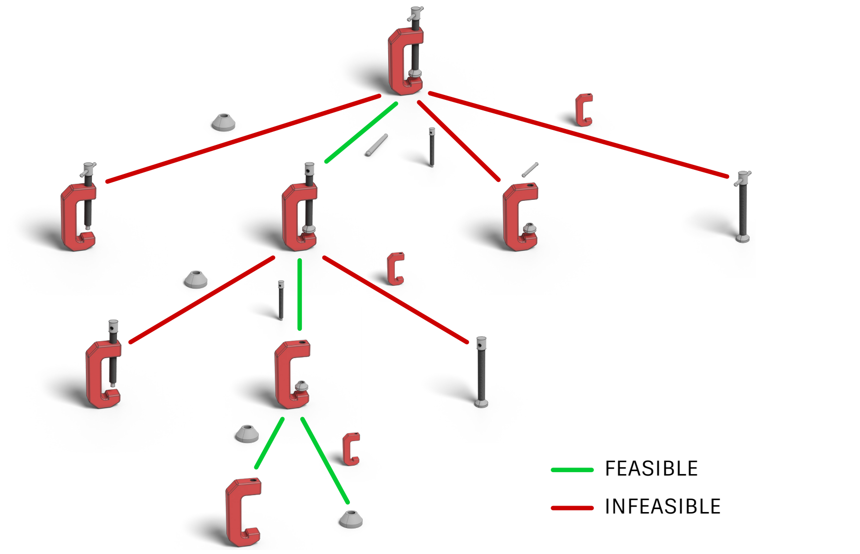
1. Assembly-by-disassembly

Assuming all parts are rigid, a bijection exists between the assembly and disassembly sequences, meaning an assembly sequence can be obtained from the reverse order of its disassembly sequence with much less complexity.



2. Disassembly tree search

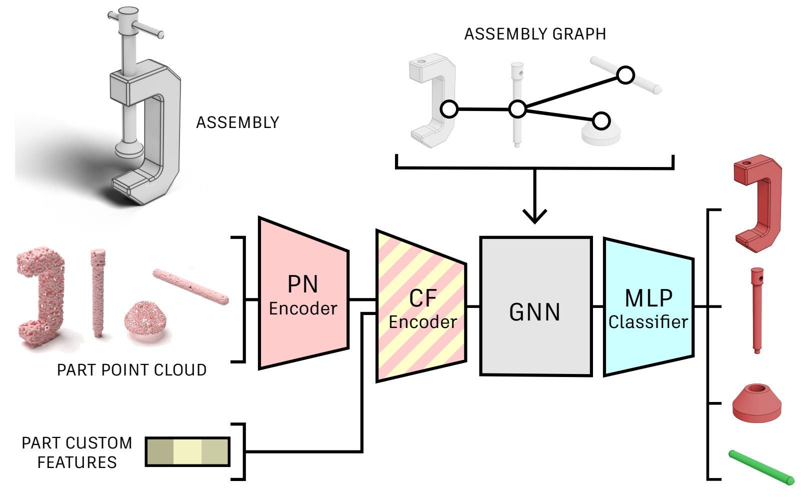
We formulate the disassembly sequence planning as a tree search framework where established tree-search techniques can be applied to search for feasible disassembly sequences efficiently.



Each path of the tree represents a particular way of how the assembly is disassembled from top to bottom (or assembled from bottom to top).

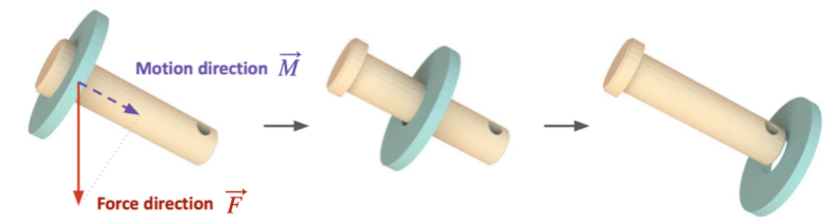
3. Learning-based part selection

We introduce a supervised learning approach to predict the disassembly sequence order on complex contact-rich 3D assemblies using a GNN. Gathering training labels is made possible by our interactive data labeling tool for human-authored labels and a realistic physics-based simulation for synthetic labels. The network trained on a large dataset with diverse assemblies provides effective neural guidance to sequence planning on unseen assemblies.

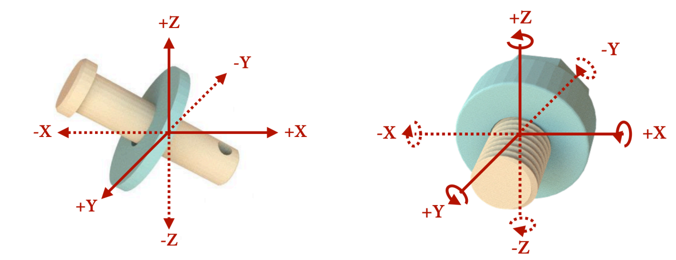


4. Physics-based path planning

By applying forces/torques to assembly parts, we are able to infer the correct disassembly motion direction after the induced movement of the part is observed.

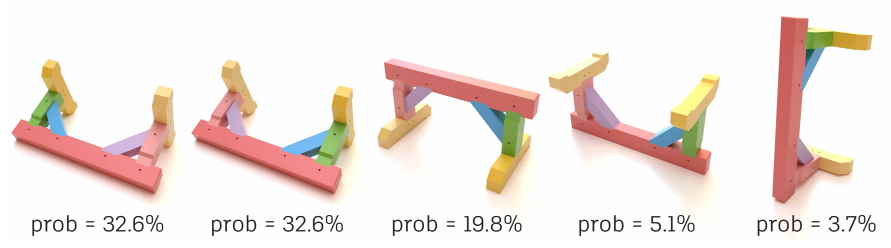


We propose a physics-based planner that efficiently plans the disassembly motion by leveraging feedback from physics. We formulate the disassembly path planning as another tree search problem, which starts from the assembled state and searches for a sequence of actions until a disassembled state has been found or some time/depth limitation of the search has been reached.



5. Quasistatic stable pose generation

Since there is an infinite number of poses in a 3D space for a given assembly, to reduce the search space, we leverage a quasistatic pose estimator to provide a good set of candidate poses which have a higher chance to be dynamically stable during assembly.

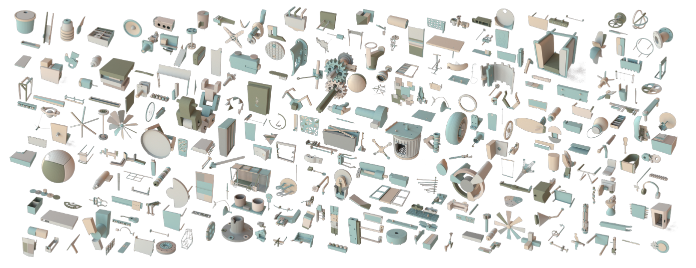


6. Physics-based stability check

Finally, given the assembly and the part to disassemble with a candidate pose, we apply our custom-designed physics-based simulation for accurate gravitational stability check during the assembly process. The stability check result updates the disassembly tree with an either feasible or infeasible edge.

Results

99.8% success rate for collision-free path planning on a dataset of 8,000+ two-part assemblies.



Method	Two-Part Overall	Rotational Screw	Rotational Puzzle	Rotational Others	Rotational Overall
RRT	84.5	0.0	20.8	0.0	6.9
T-RRT	97.4	2.1	18.8	0.0	6.9
MV+T-RRT	97.8	12.5	18.8	0.0	10.4
BK-RRT	93.7	12.5	62.5	**81.3**	52.1
Ours	**99.8**	**75.0**	**87.5**	50.0	**70.8**
Ours (Rotated)	99.8	37.5	62.5	87.5	62.5

~30% success rate improvement over baselines for physically feasible sequence planning on a dataset of 240 complex multi-part assemblies.

Method		Success Rate (%) (Low Budget) 2 Grippers	3 Grippers	4 Grippers	Success Rate (%) (High Budget) 2 Grippers	3 Grippers	4 Grippers
Ours	Random	44.17	52.92	62.50	66.25	**76.25**	81.25
	Heuristics	50.42	60.83	69.17	66.67	75.00	**82.08**
	Learning (from Sim)	**54.17**	**62.50**	**69.58**	**67.50**	**76.25**	**82.08**
	Learning (from Human)	30.83	36.67	42.92	65.00	74.58	79.17
Baseline	Random Permutation	14.58	25.42	41.25	27.92	43.33	55.42
	Genetic Algorithm	14.17	25.83	40.00	30.83	41.25	51.25

Physically feasible sequences with a stability guarantee by leveraging the flat holding surface, a few supporting grippers, and proper reorientations, which is applicable to a real-world assembly setup.

*[1] Assemble Them All: Physics-Based Planning for Generalizable Assembly by Disassembly, **Y. Tian**, J. Xu, Y. Li, J. Luo, S. Sueda, H. Li, K. Willis, W. Matusik, ACM Transactions on Graphics (SIGGRAPH Asia), 2022*