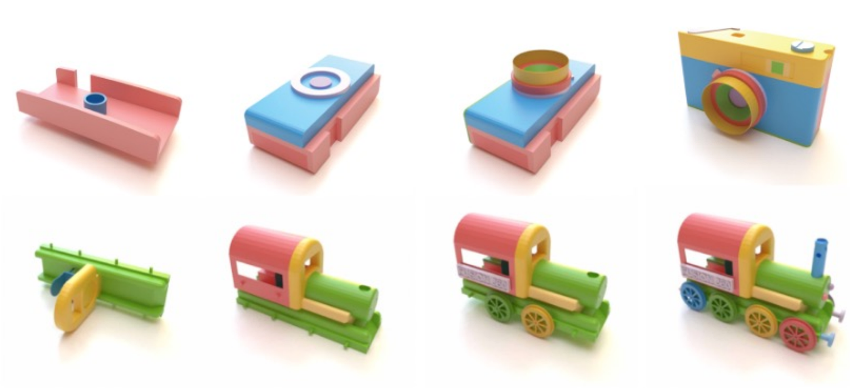

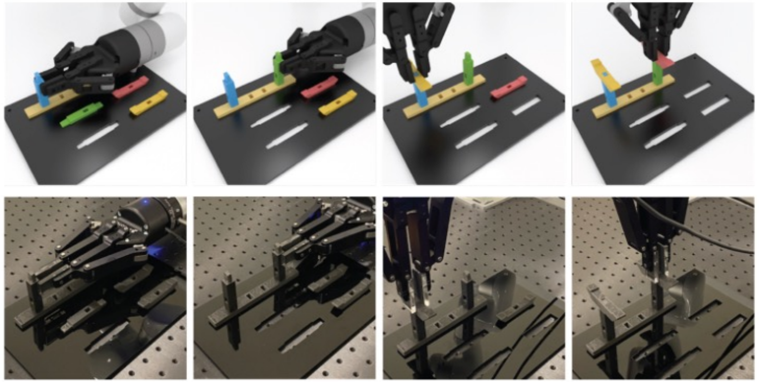

ASAP: Automated Sequence Planning for Complex Robotic Assembly with Physical Feasibility

Yunsheng Tian[1], Karl D.D. Willis[2], Bassel Al Omari[3], Jieliang Luo[2], Pingchuan Ma[1], Yichen Li[1], Farhad Javid[2], Edward Gu[1], Joshua Jacob[1], Shinjiro Sueda[4], Hui Li[2], Sachin Chitta[2], Wojciech Matusik[1]

[1]MIT CSAIL [2]Autodesk Research [3]University of Waterloo [4]Texas A&M University

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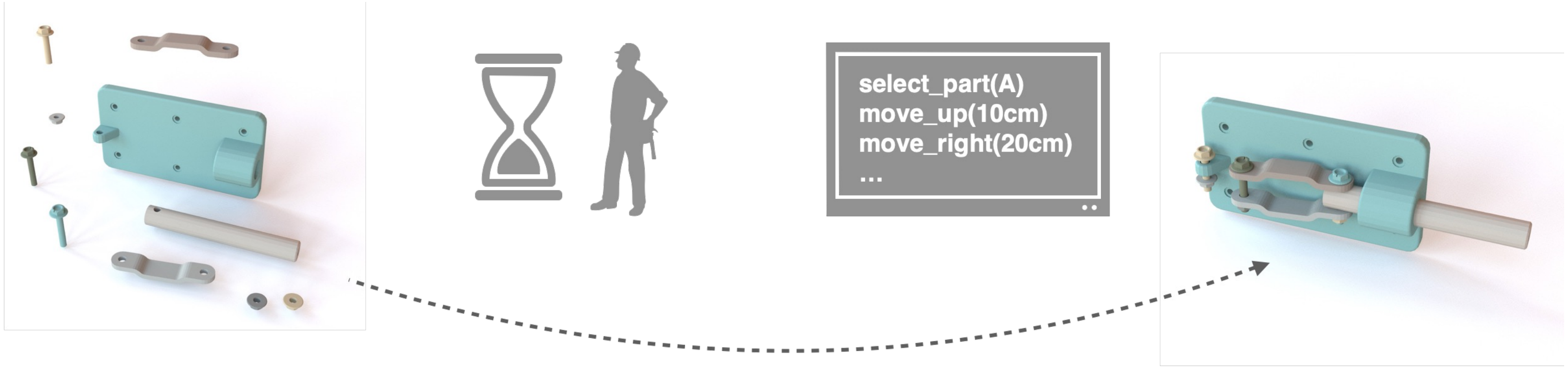
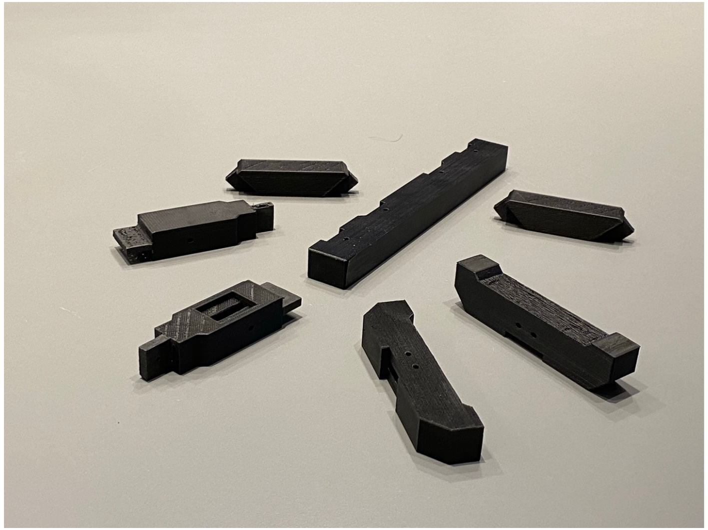
Motivation

In manufacturing industry, the assembly process is usually planned by humans with hardcoded instructions.



Labor-intensive Slow Tedious Error-prone Inflexible

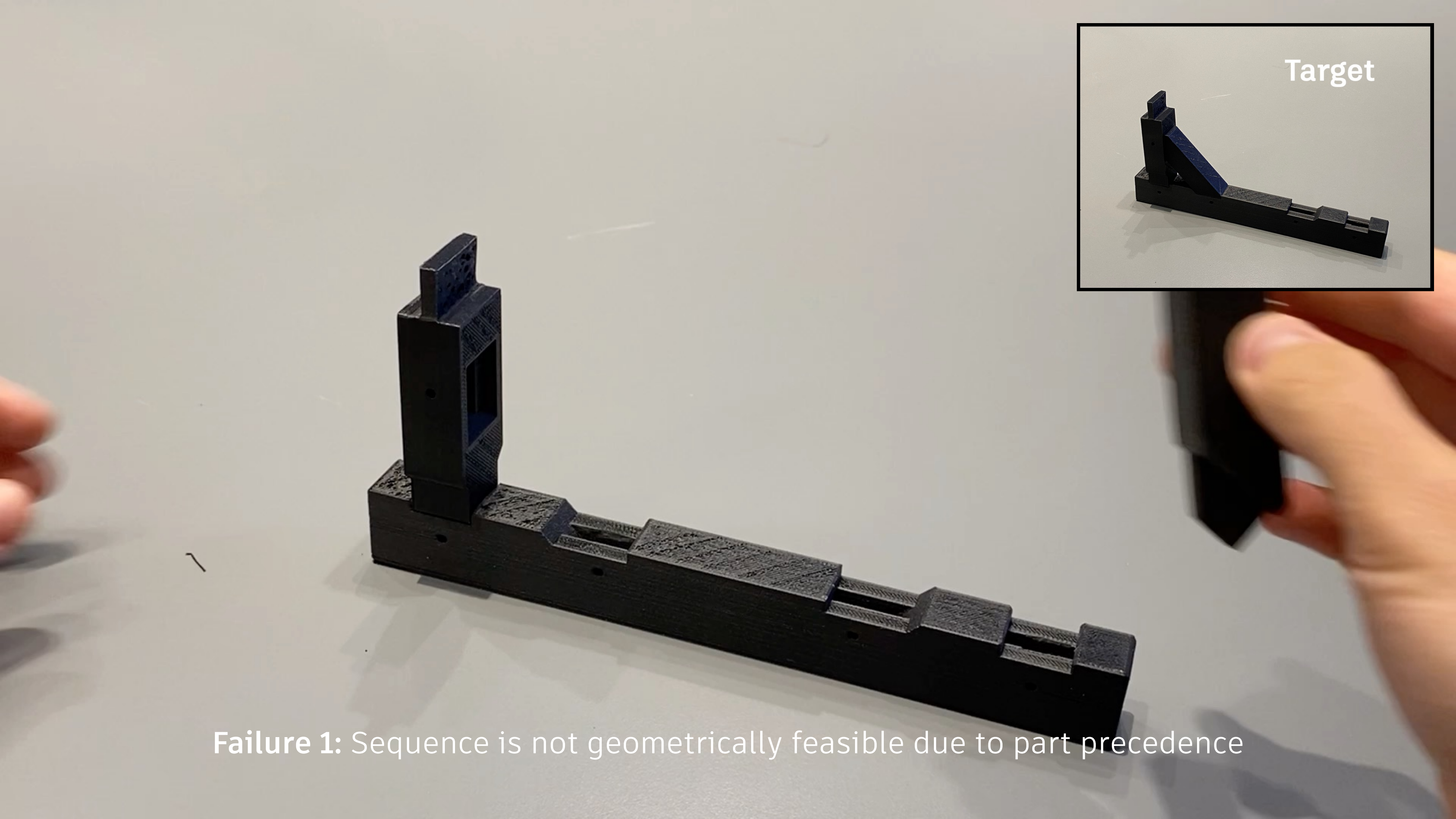
Motivation



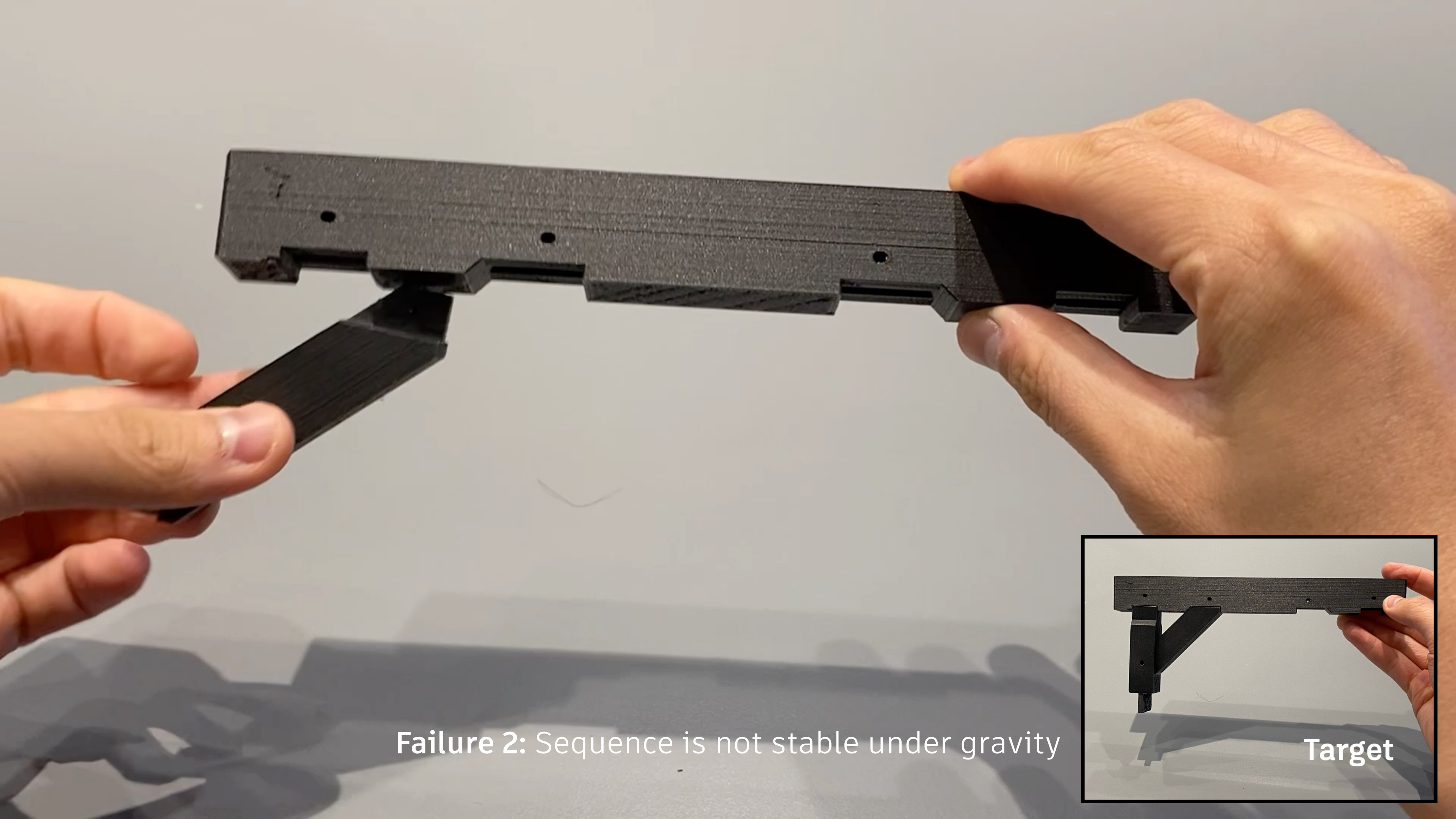
?

→

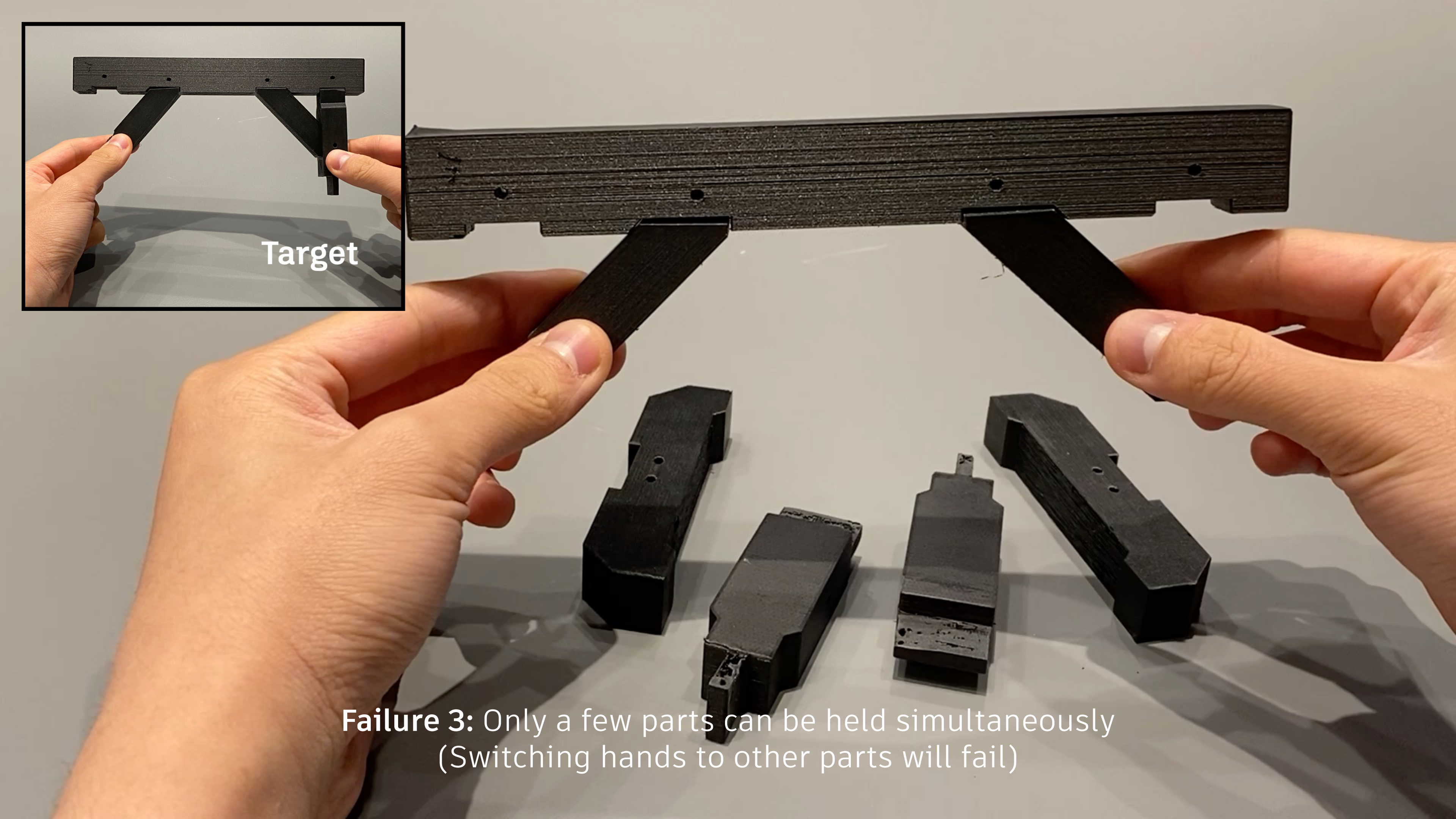
Failures could easily happen during assembly without careful planning …

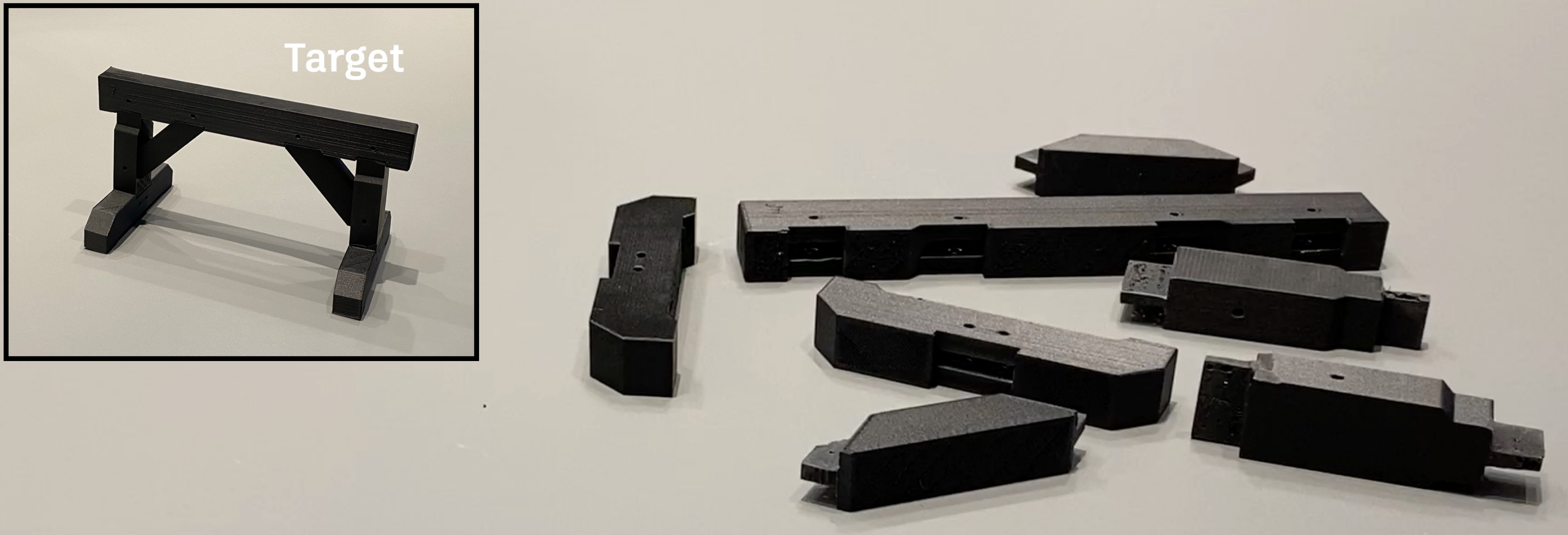


Failure 1: Sequence is not geometrically feasible due to part precedence



Failure 2: Sequence is not stable under gravity
Target

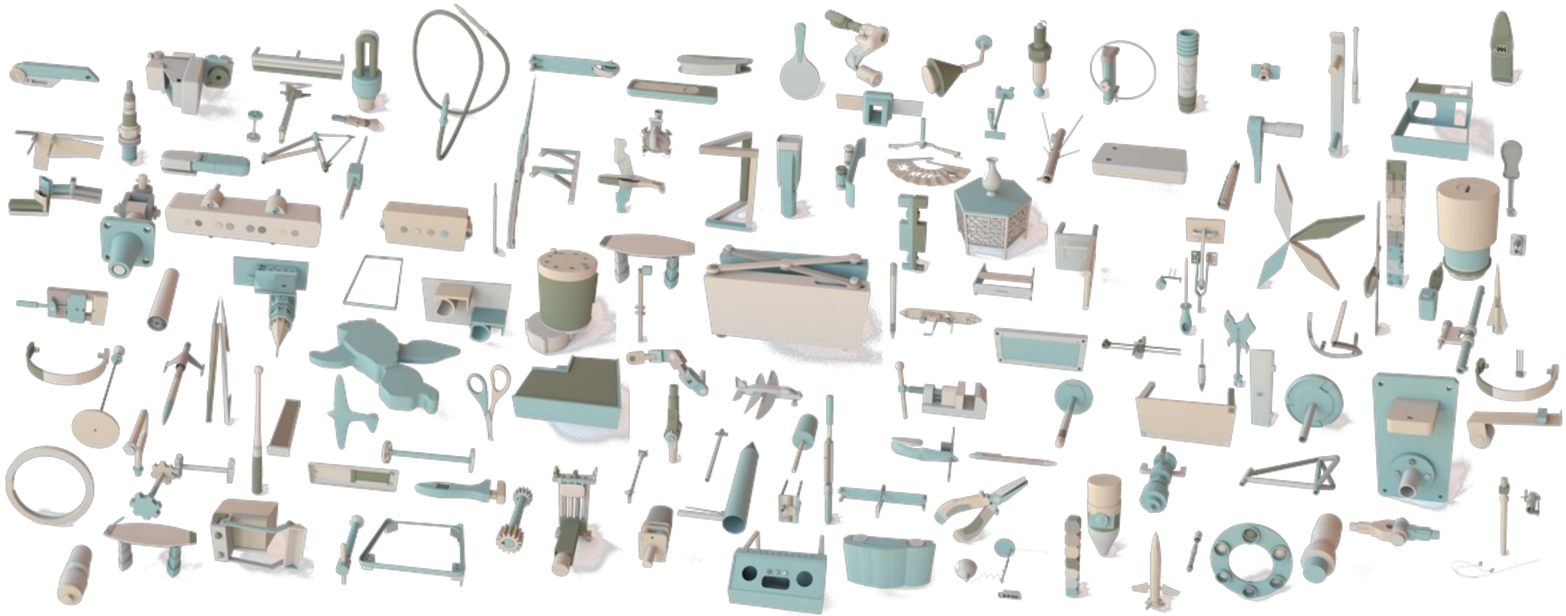

Target
Failure 3: Only a few parts can be held simultaneously
(Switching hands to other parts will fail)



Success: The assembly sequence is **physically feasible** only if the assembly order is correct, collision-free paths can be found, poses are stable, and proper parts are held

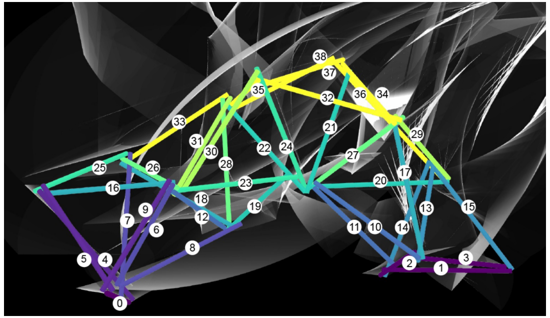
Challenges

How to solve for such physically feasible plans autonomously?

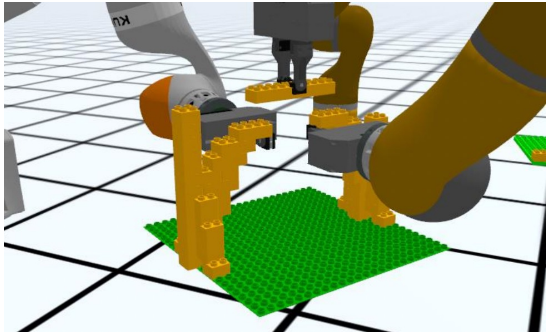


Is it possible to generalize to many more complex assemblies?

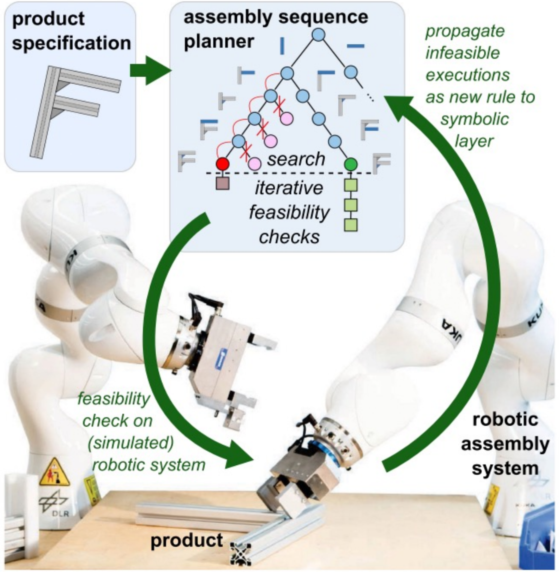
Related Works



Bar Structure Assembly
[Huang et al. 2021]



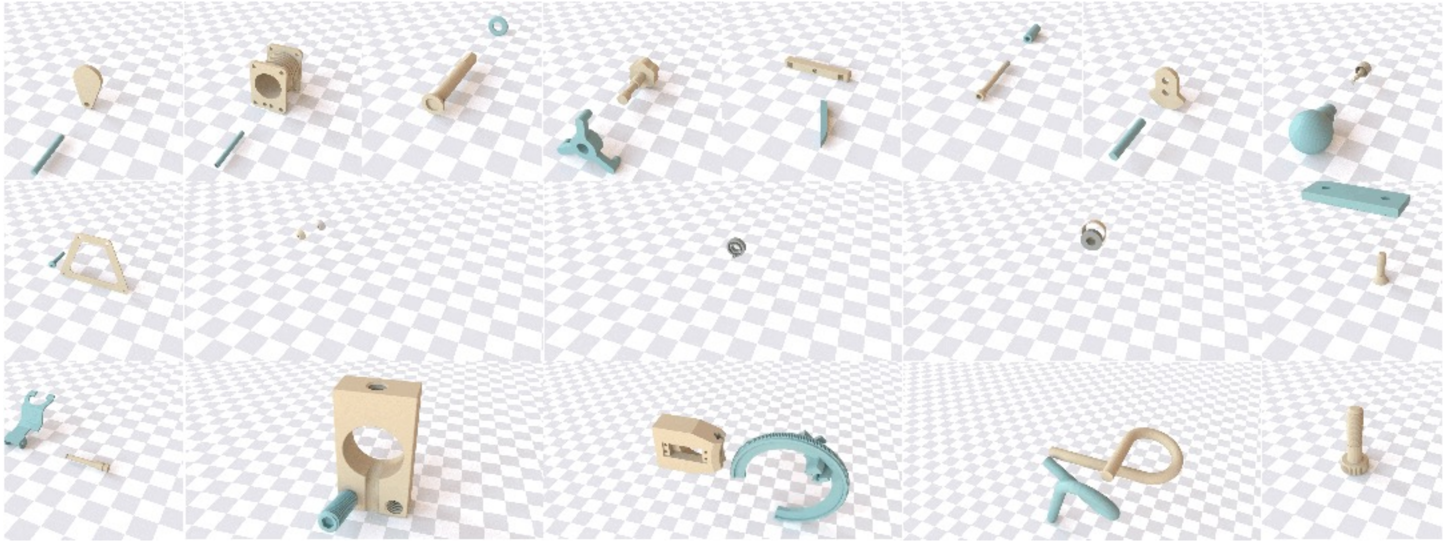
Lego Brick Assembly
[Nagele et al. 2020]



Aluminum Profile Assembly
[Rodriguez et al. 2019]

Not designed for general assemblies

Related Works



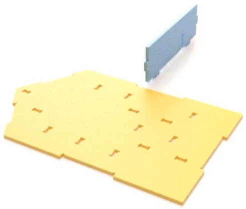
Assemble Them All [Tian et al. 2022]

Not applicable to real world with gravity & robots

ASAP

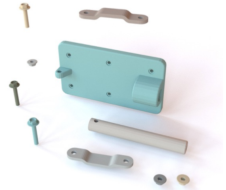
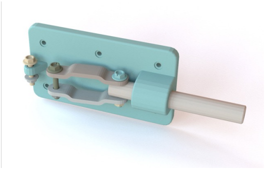
Our contributions

- An automated approach for generating physically feasible assembly sequences
- Efficient planning through tree-search, geometric heuristics, and graph neural networks
- Stability guarantee considering supporting surface and grippers
- Integrated grasp planning and inverse kinematics for robotic execution
- SOTA performance on hundreds of complex product assemblies



Problem Setup

Input & output

Object Meshes

Assembled Poses


Robot Specifications (Optional)

ASAP

Assembly Sequences

Assembly Paths

Intermediate Poses

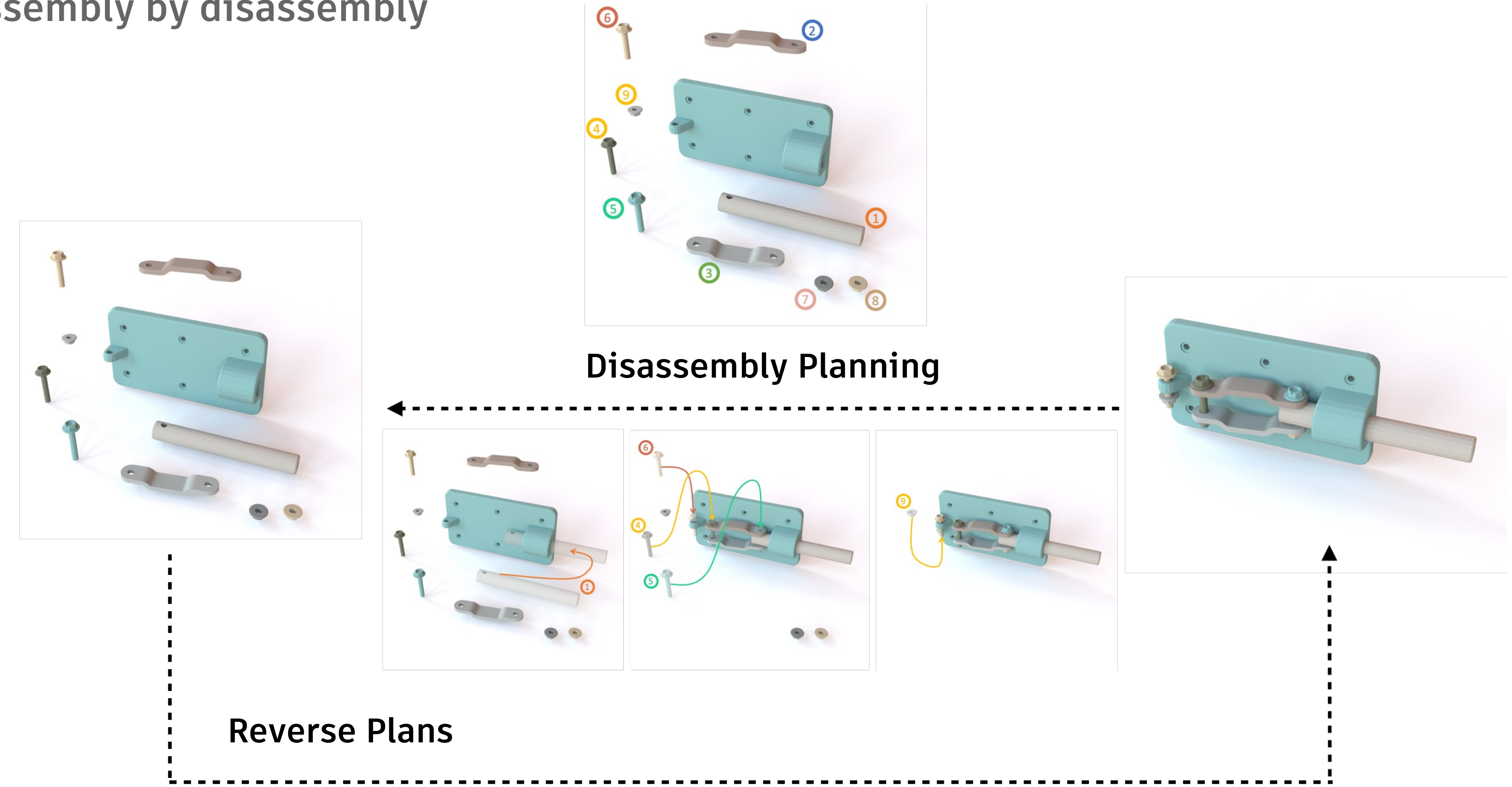
Parts to be Held

Grasps & Robot Motion (optional)

Complete Assembly Plans

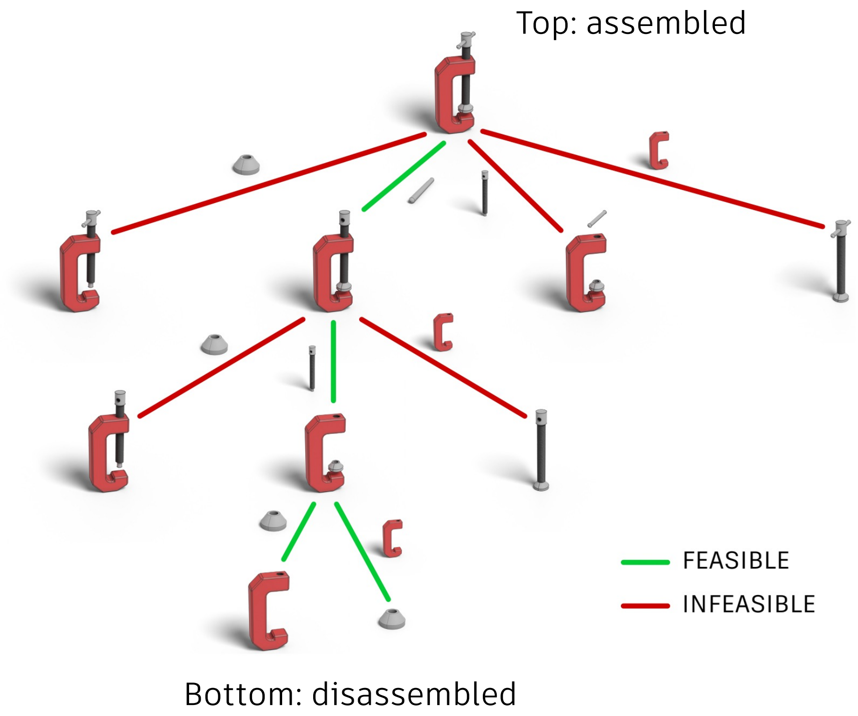
Problem Setup

Assembly by disassembly



Physically-Feasible Assembly Planning

Disassembly tree search




```
def asap():
    tree.add_node(root_node)
    for node in select_node(tree):
        for part in select_part(node):
            for pose in select_pose(node):
                check_assemblable(node, part, pose)
                check_stable(node, part, pose)
                if success:
                    child_node = node \ {part}
                    tree.add_edge(node, child_node)
    return tree
```

Node selection

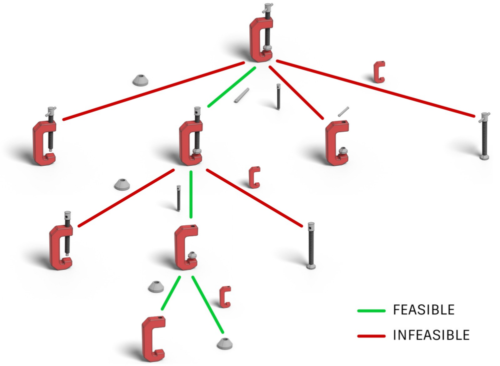
Part selection

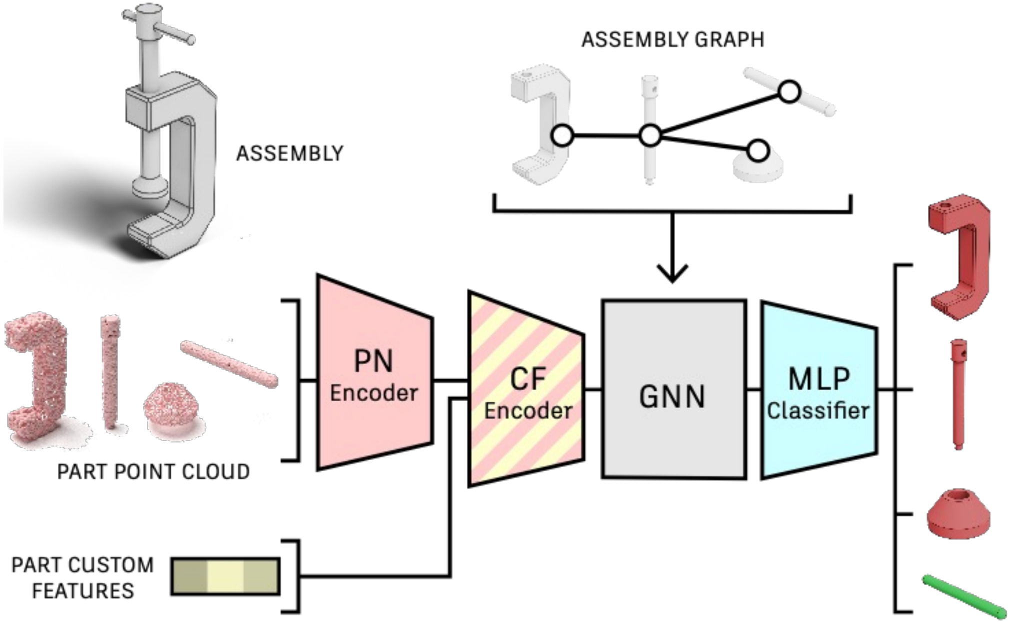
Pose selection

Feasibility evaluation

Physically-Feasible Assembly Planning

Part selection





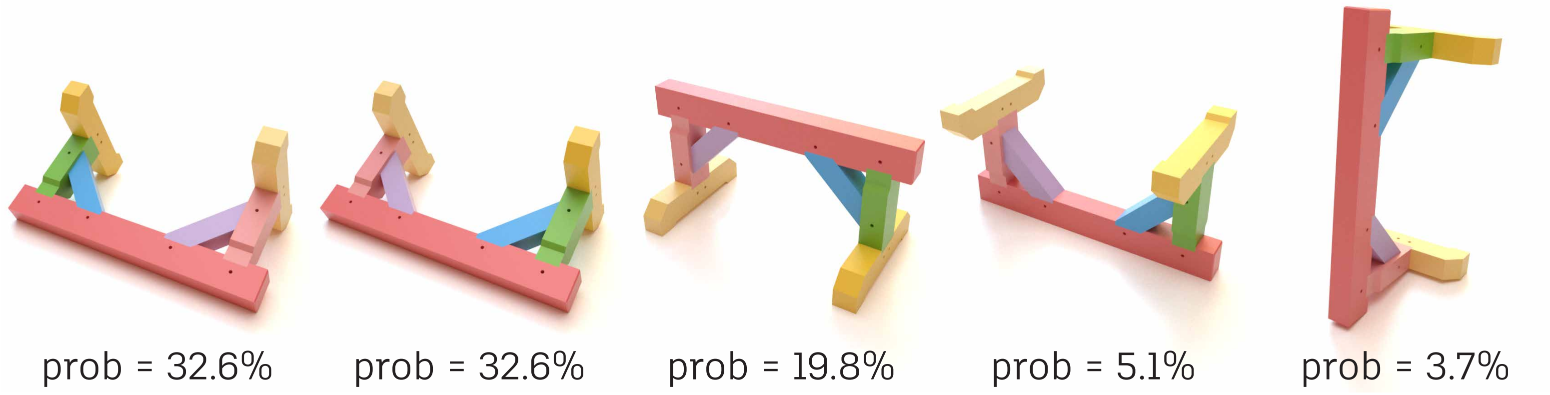
Geometric heuristics: distance of COM to assembly center, part volume, etc.

Learning-based guidance: GNN trained from simulation labels to suggest next parts to disassemble.

Physically-Feasible Assembly Planning

Pose selection

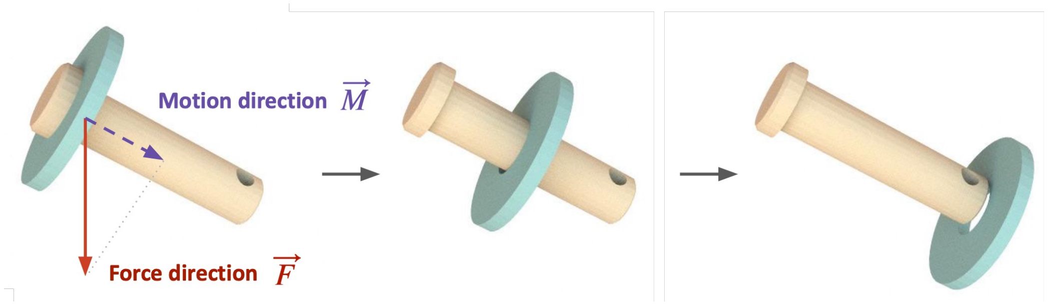
Quasistatic pose estimator for generating stable pose candidates

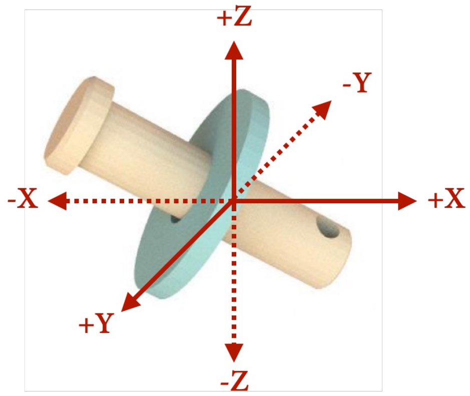


Pose reuse: try sticking with the same pose as much as possible

Physically-Feasible Assembly Planning

Feasibility evaluation: assemblability





Physics-based simulation + **Tree search (BFS)**

Applying force to disassemble

Finding correct force sequence

Assemble Them All [Tian et al. 2022]

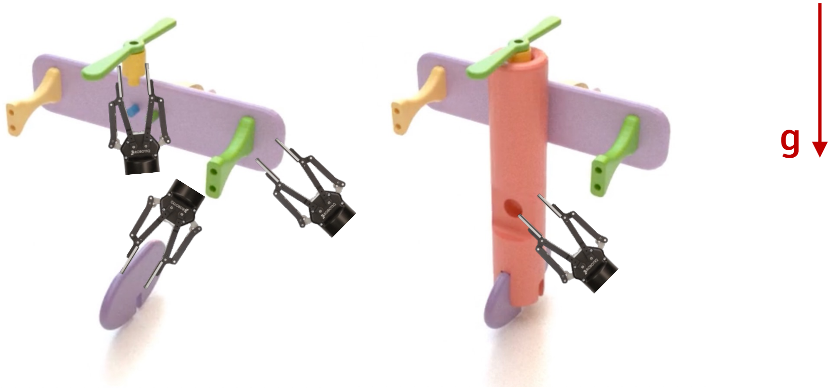
Physically-Feasible Assembly Planning

Feasibility evaluation: stability

Physics-based simulation

Check if any parts fall after certain time steps

Evaluate stability conditioned on the pose and parts to hold



Part-holding strategy

Identify which parts are to be held (by grippers/fixtures)

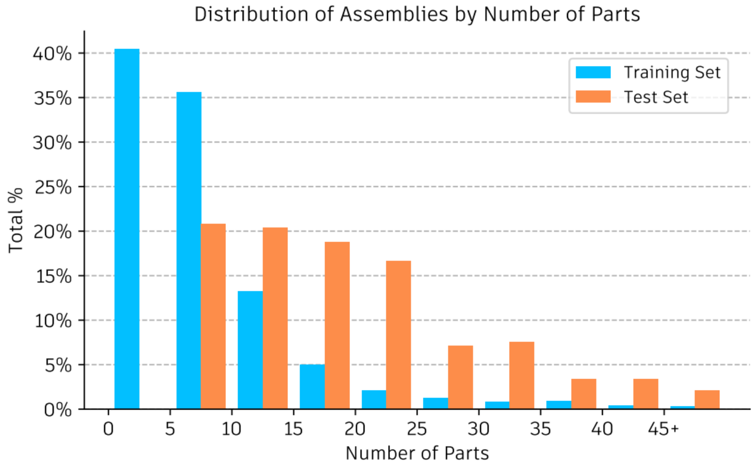
How to hold *N* parts by *M* fixtures?

# Parts to Hold	Acc. (%)	Speed Up
2	89.0	13.90x
3	90.5	17.03x
4	94.7	23.04x

Greedy strategy compared to combinatorial strategy

Result

Quantitative evaluation



Method		Success Rate (%) (Low Budget) 2 Parts Held	3 Parts Held	4 Parts Held	Success Rate (%) (High Budget) 2 Parts Held	3 Parts Held	4 Parts Held
ASAP (Ours)	Heuristics	51.25	61.25	68.75	66.67	74.17	80.83
	Learning	**54.58**	**62.92**	**69.58**	**67.08**	**76.25**	**82.08**
Baseline	Random Permutation	14.58	25.42	41.25	27.92	43.33	55.42
	Genetic Algorithm [9]	14.17	25.83	40.00	30.83	41.25	51.25
	Assemble Them All [5]	19.17	27.08	35.42	30.42	46.25	56.67

Result

Qualitative evaluation

Result

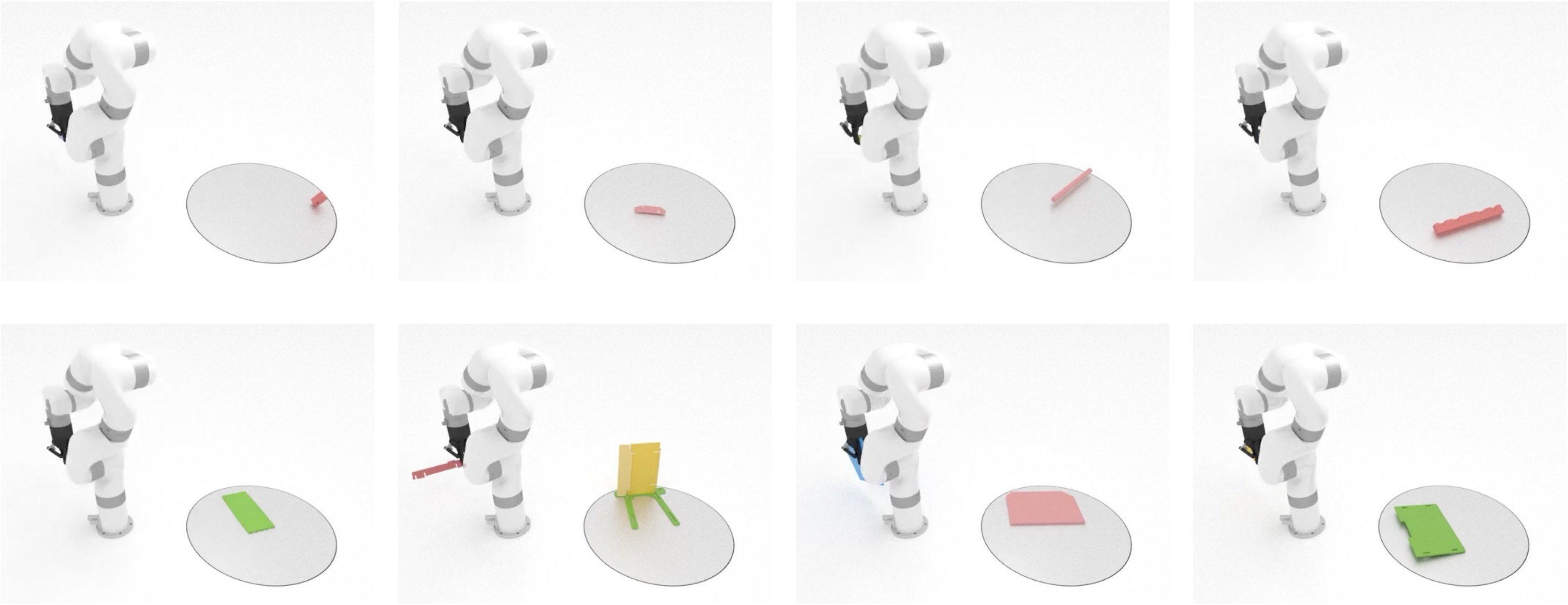
Qualitative comparison

ASAP (Ours)

Assemble Them All [Tian et al. 2022]

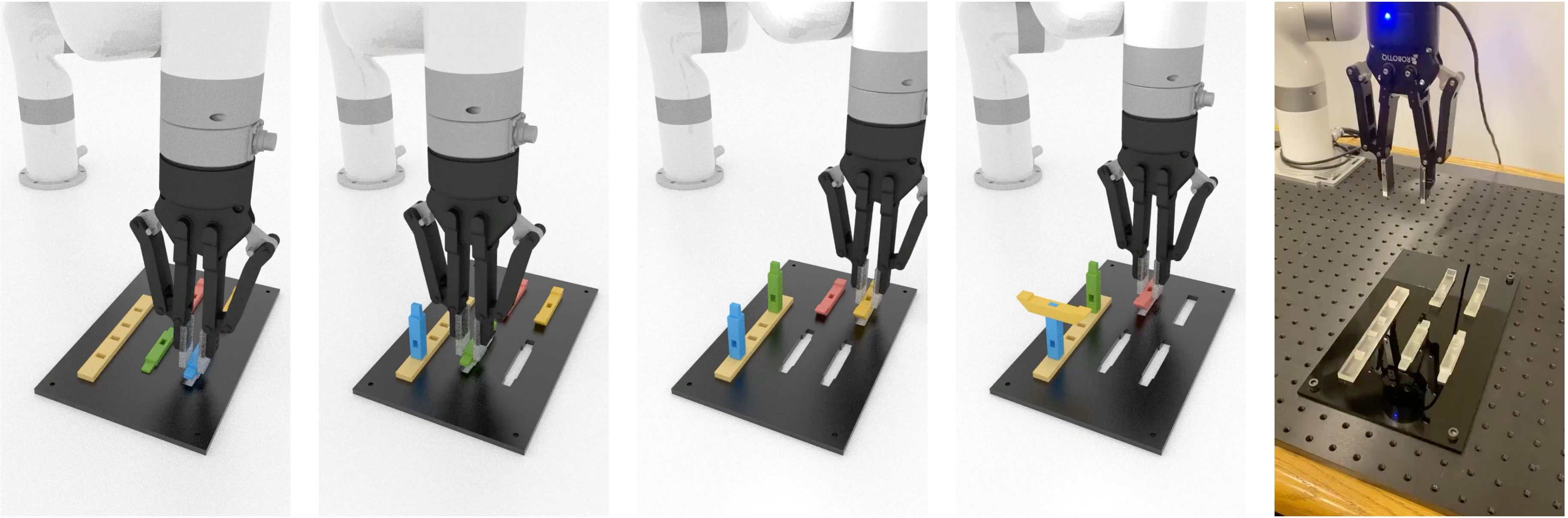
Result

Robotic execution – simulation



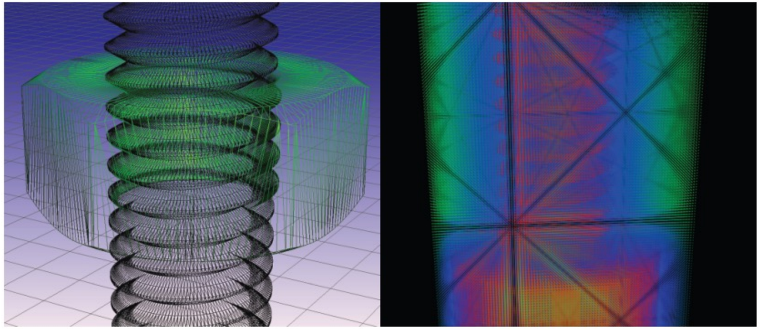
Result

Robotic execution – real world

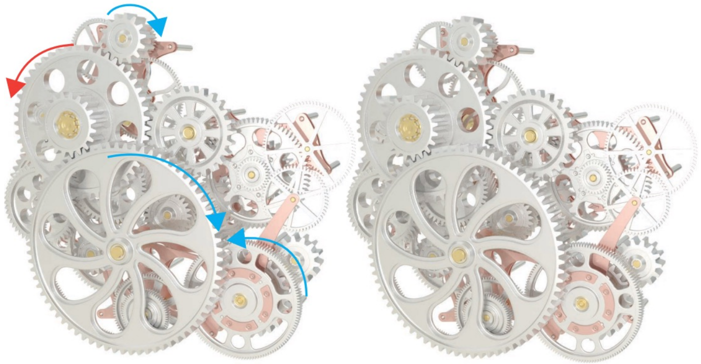


Future Work

Fast and robust physics simulation



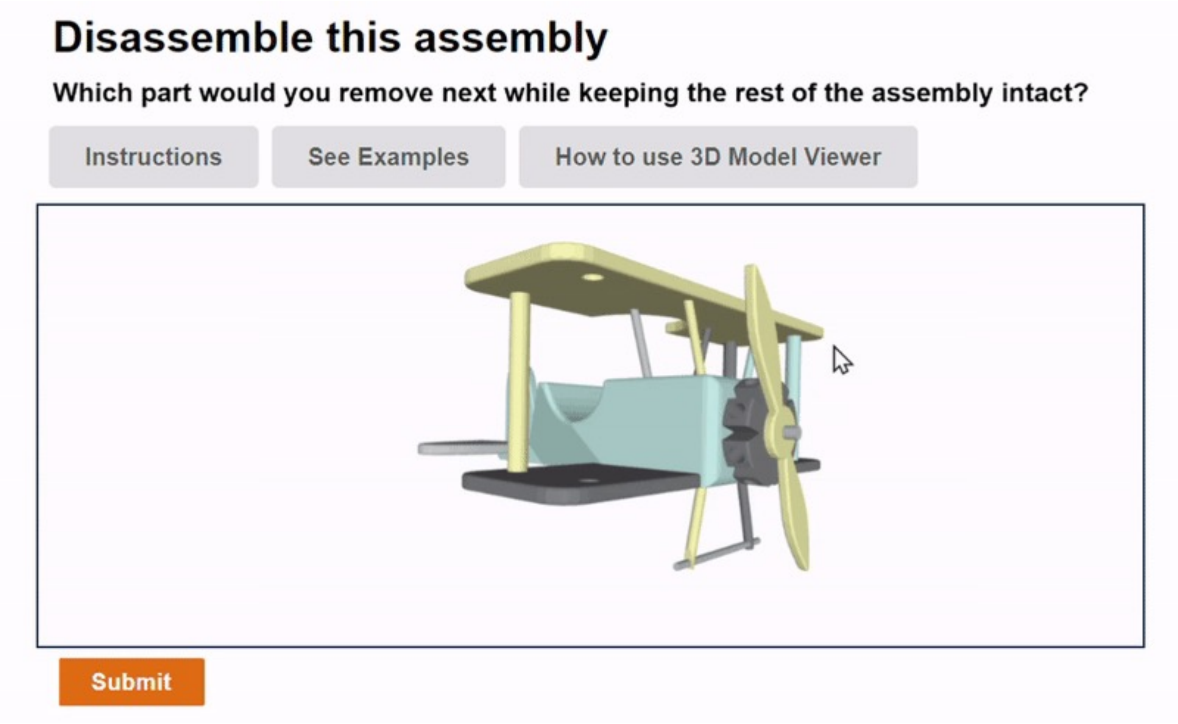
Factory [Narang et al. 2022]



Affine Body Dynamics
[Lan et al. 2022]

Future Work

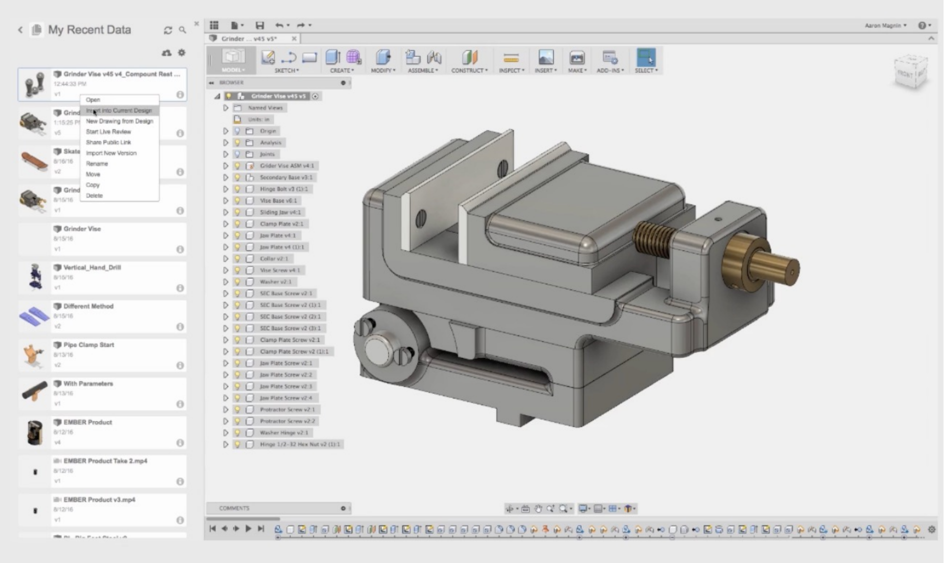
Learning from human demonstration



GNN can be trained from human-annotated labels to suggest next parts to disassemble

Future Work

Design tool integration

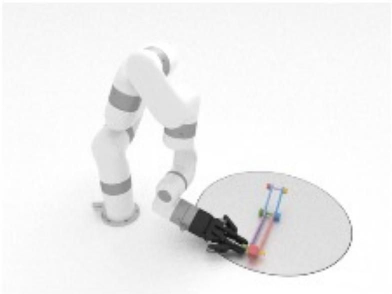


Autodesk Fusion 360

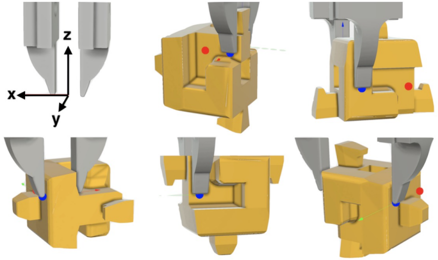
- Assembly manual generation
- Design feasibility verification
- Design-to-manufacturing

Future Work

Real robot deployment



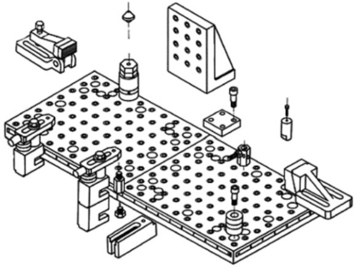
Sim2real



Grasp Planning

Multi-Arm Collaboration

Multiple Tools



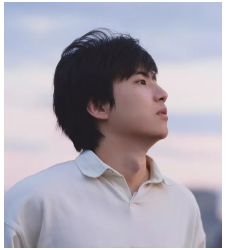
Fixture Generation

Collaborators


Karl D.D. Willis[2]

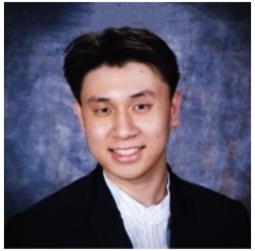

Bassel Al Omari[3]


Jieliang Luo[2]

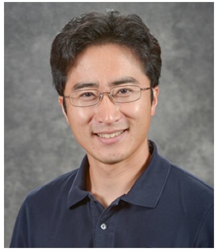

Pingchuan Ma[1]


Yichen Li[1]


Farhad Javid[2]


Edward Gu[1]


Joshua Jacob[1]

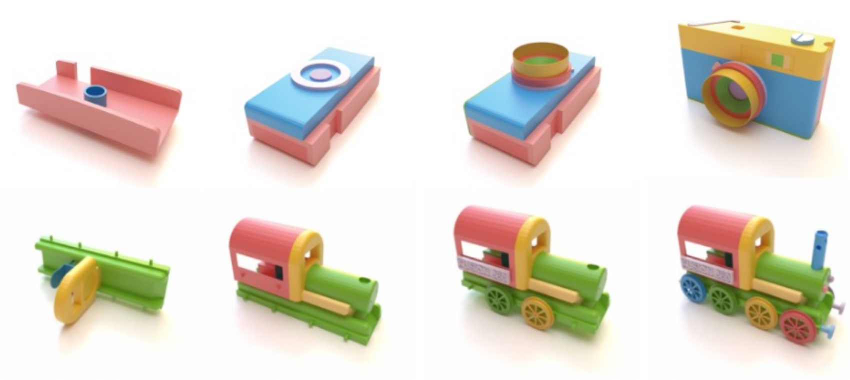

Shinjiro Sueda[4]

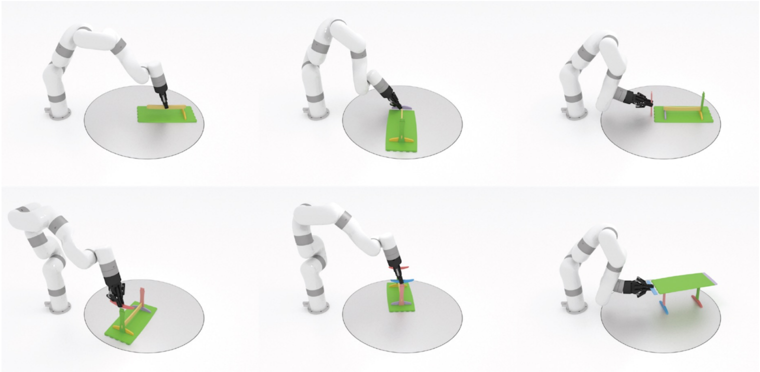

Hui Li[2]


Sachin Chitta[2]

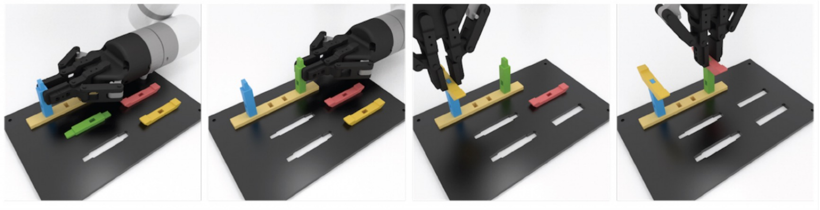

Wojciech Matusik[1]

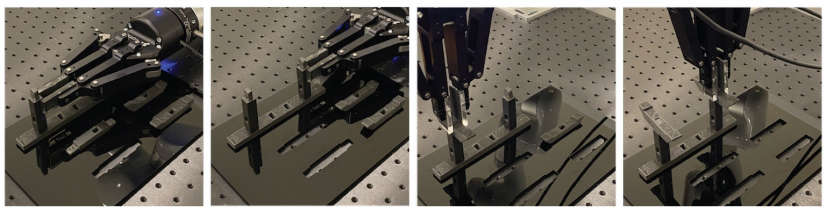
[1]MIT CSAIL [2]Autodesk Research [3]University of Waterloo [4]Texas A&M University





Thank You





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