Density-based Feasibility Learning with Normalizing Flows for Introspective Robotic Assembly

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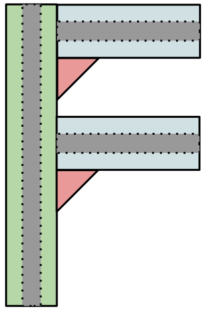
[1:] Institute of Robotics and Mechatronics, German Aerospace Center (DLR)

[2:] Technical University of Munich (TUM)

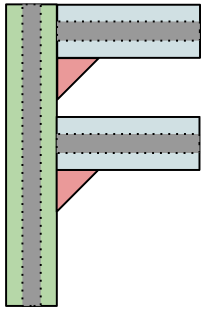
DLR

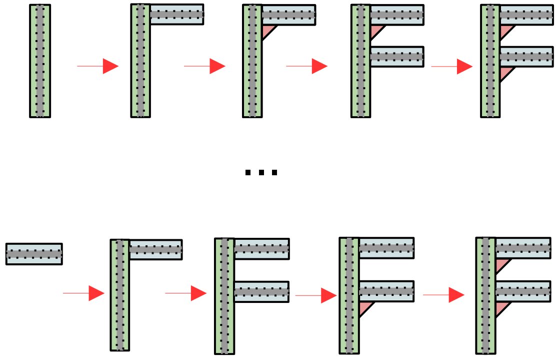
Robotic Assembly



Assembly
Specification

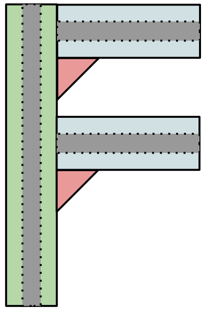
Robotic Assembly

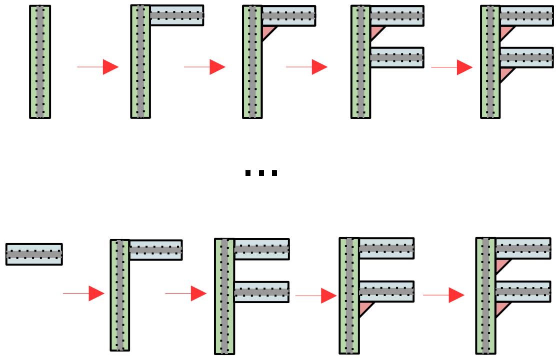


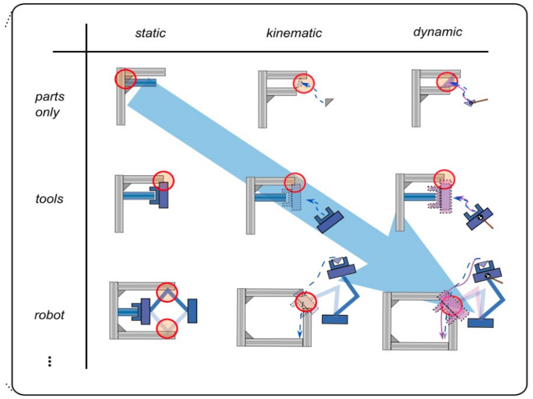


Assembly Specification → Sequence Planner

Robotic Assembly

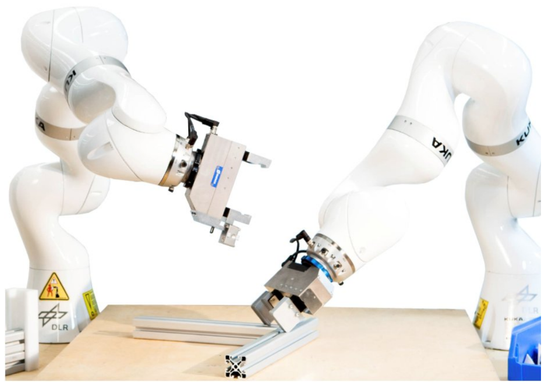




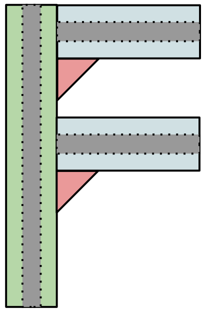


Assembly Specification → Sequence Planner → Feasibility Check → Feasible Sequences

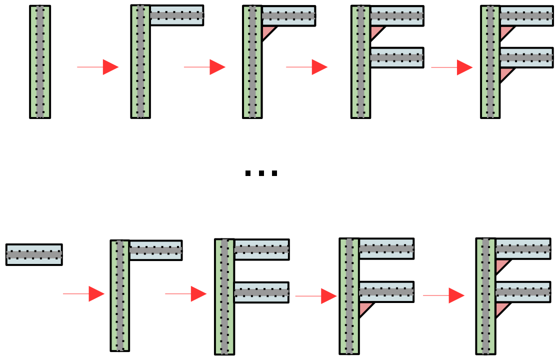
Infeasible Sequences



Robotic Assembly



Assembly Specification



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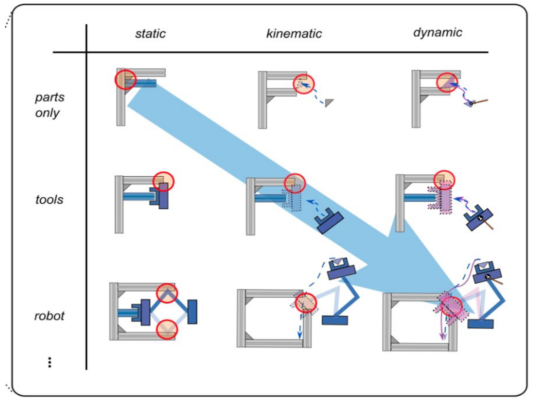
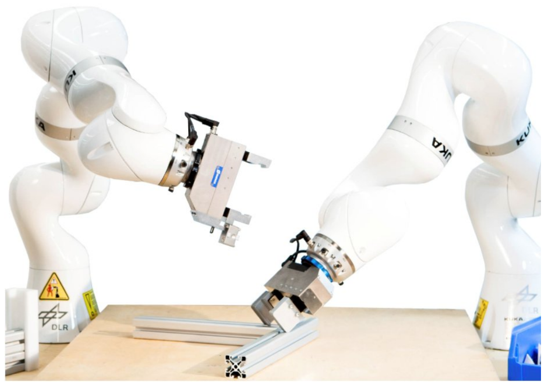


Sequence Planner

Feasibility Check

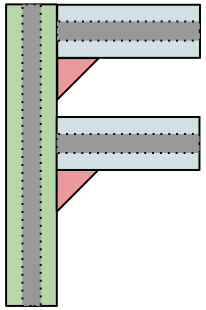
Feasible Sequences

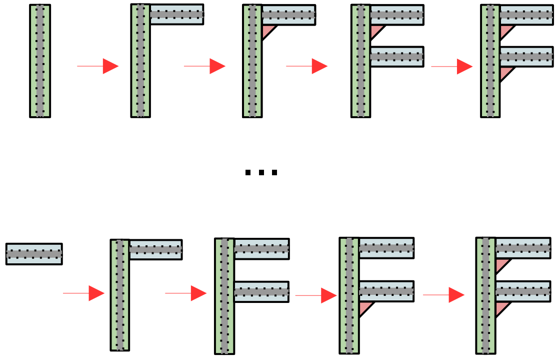
Infeasible Sequences



Rodrıguez, I.,et al. 2019, 2020.

Robotic Assembly





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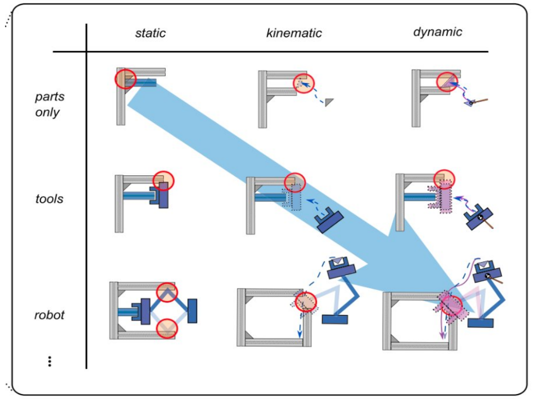

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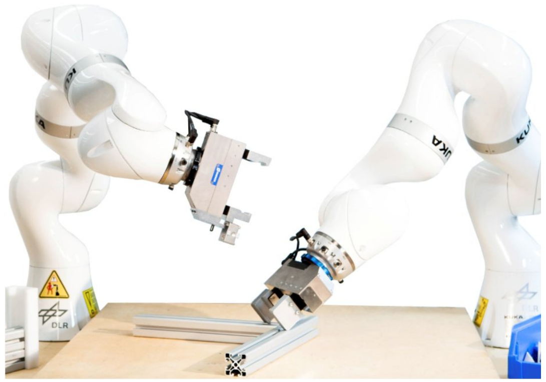
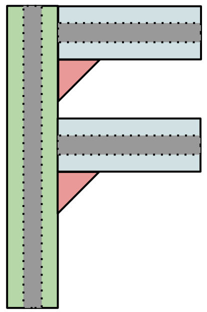
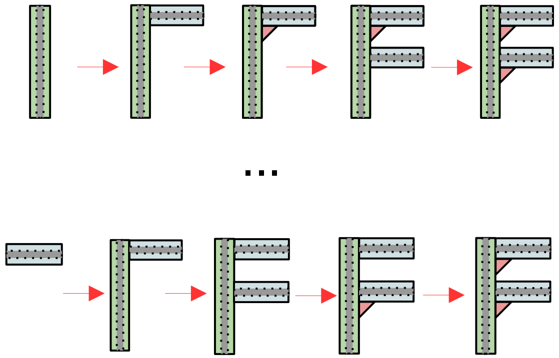


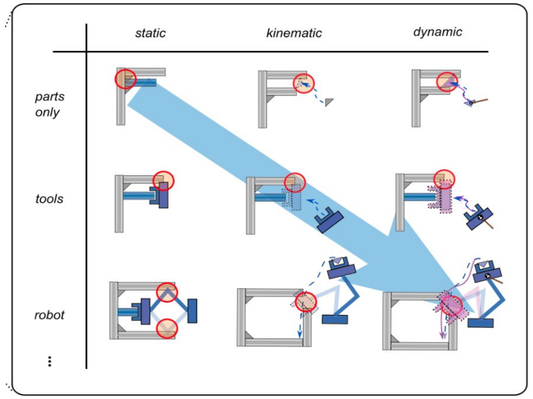
Limited Generalizability

Rodrıguez, I.,et al. 2019, 2020.

Robotic Assembly







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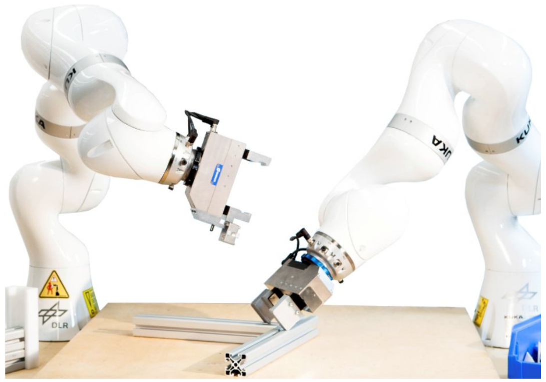
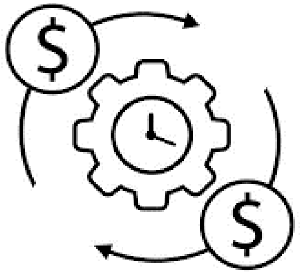
Feasibility Check → Infeasible Sequences → Sequence Planner



Limited Generalizability

Low Run-time Efficiency



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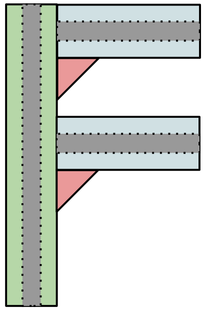
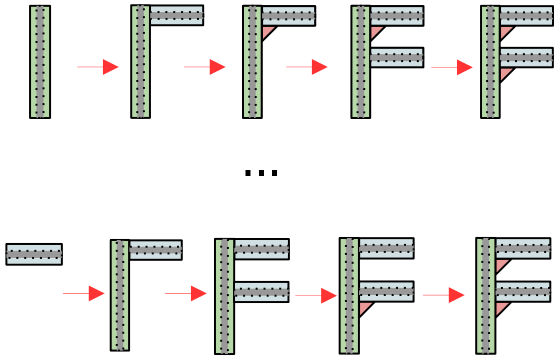
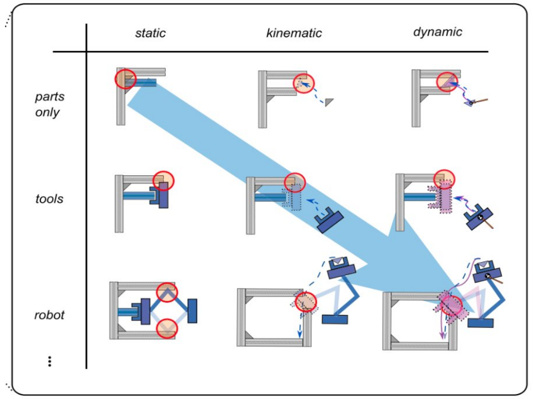
Data-driven Robotic Assembly







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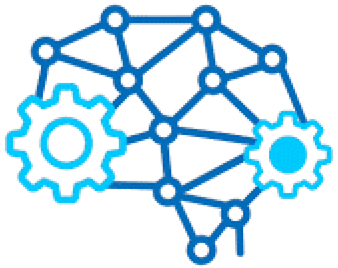
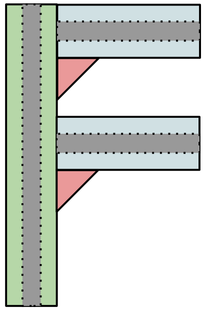
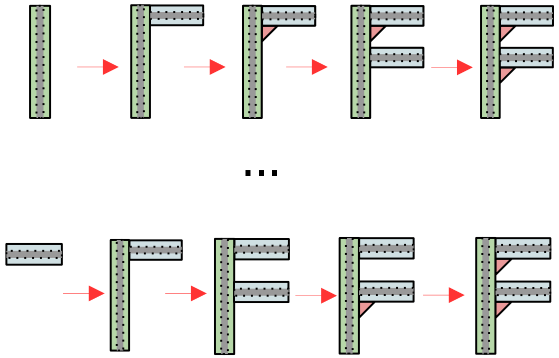


Data-driven approaches for
Generalizability & Efficiency.

GRACE [Atad, M. et al. 2023]

Data-driven Robotic Assembly





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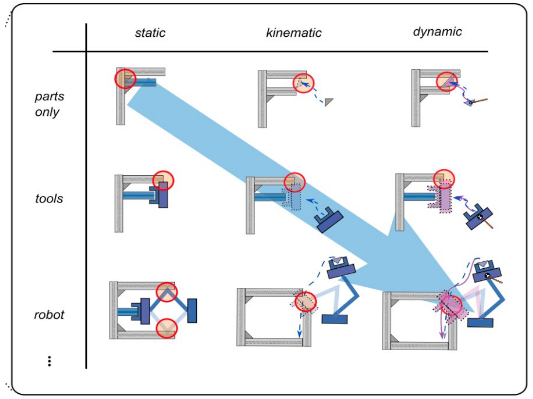

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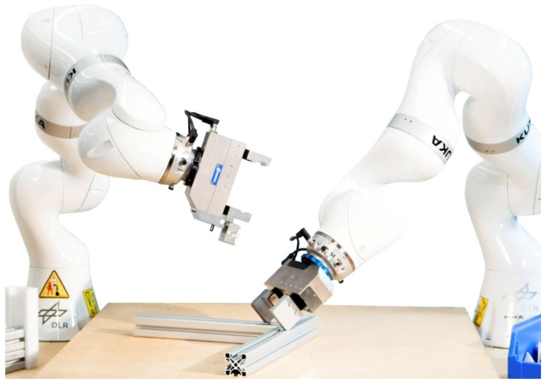

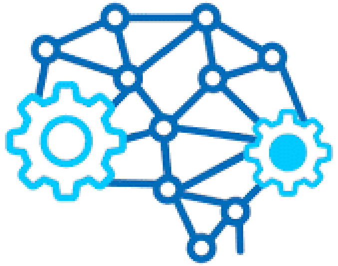

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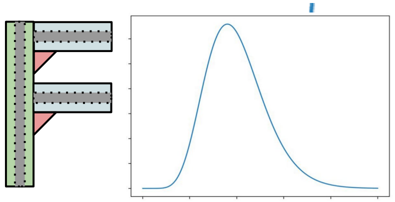
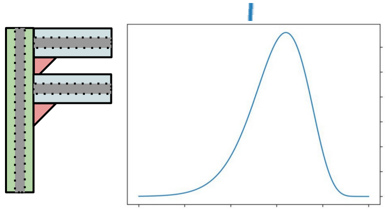


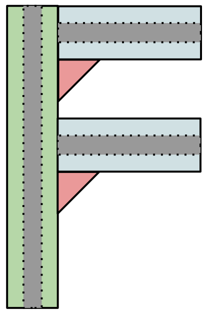
Training Dist.

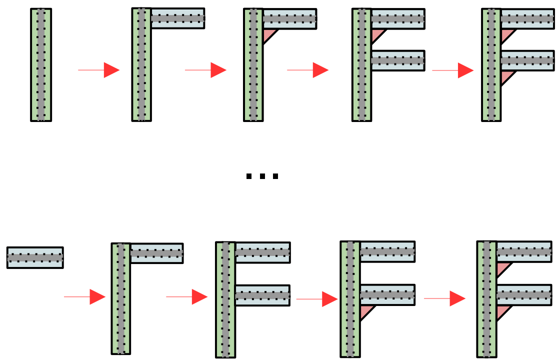
$\stackrel{!}{=}$



Test Dist.

Data-driven Robotic Assembly





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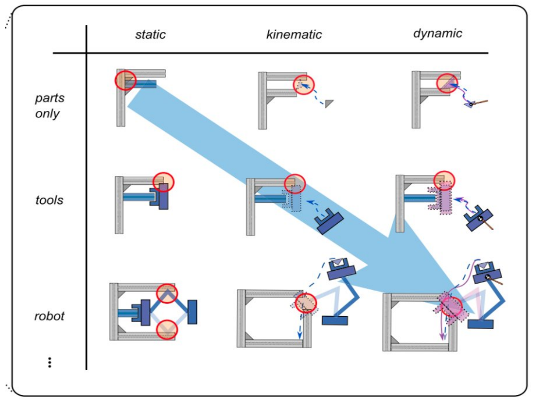

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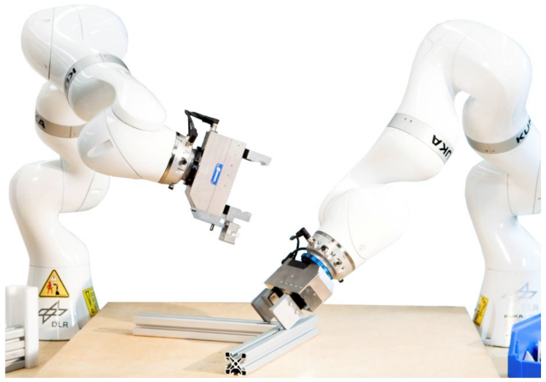
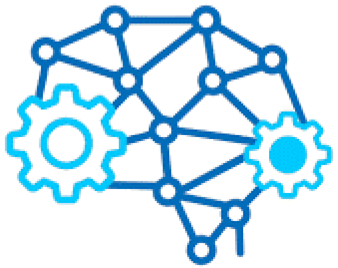


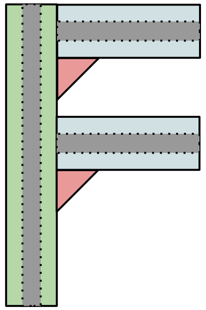


Data-driven approaches for Generalizability & Efficiency.

hard to collect **sufficient** training data;

GRACE [Atad, M. et al. 2023]

Introspective Robotic Assembly – Assembly Feasibility Learning



Assembly Specification

Assembly Feasibility Learning

Feasible Assembly

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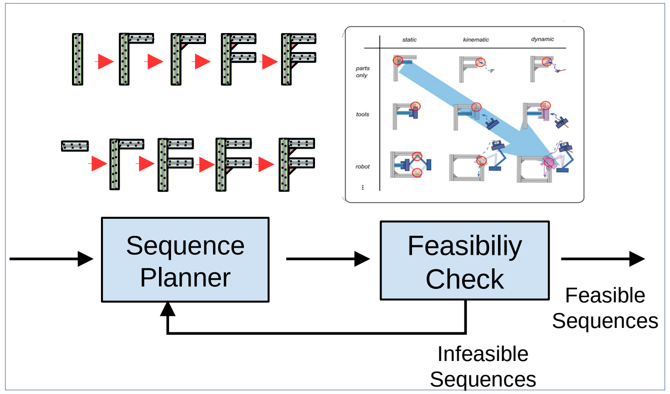
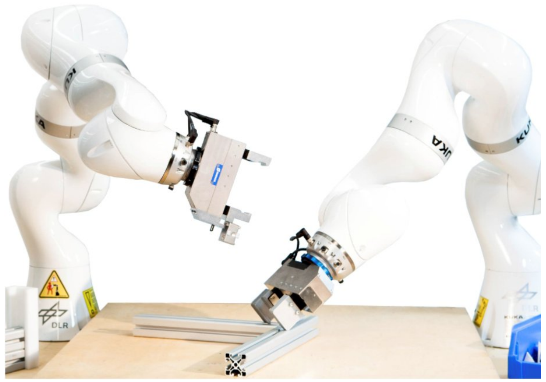
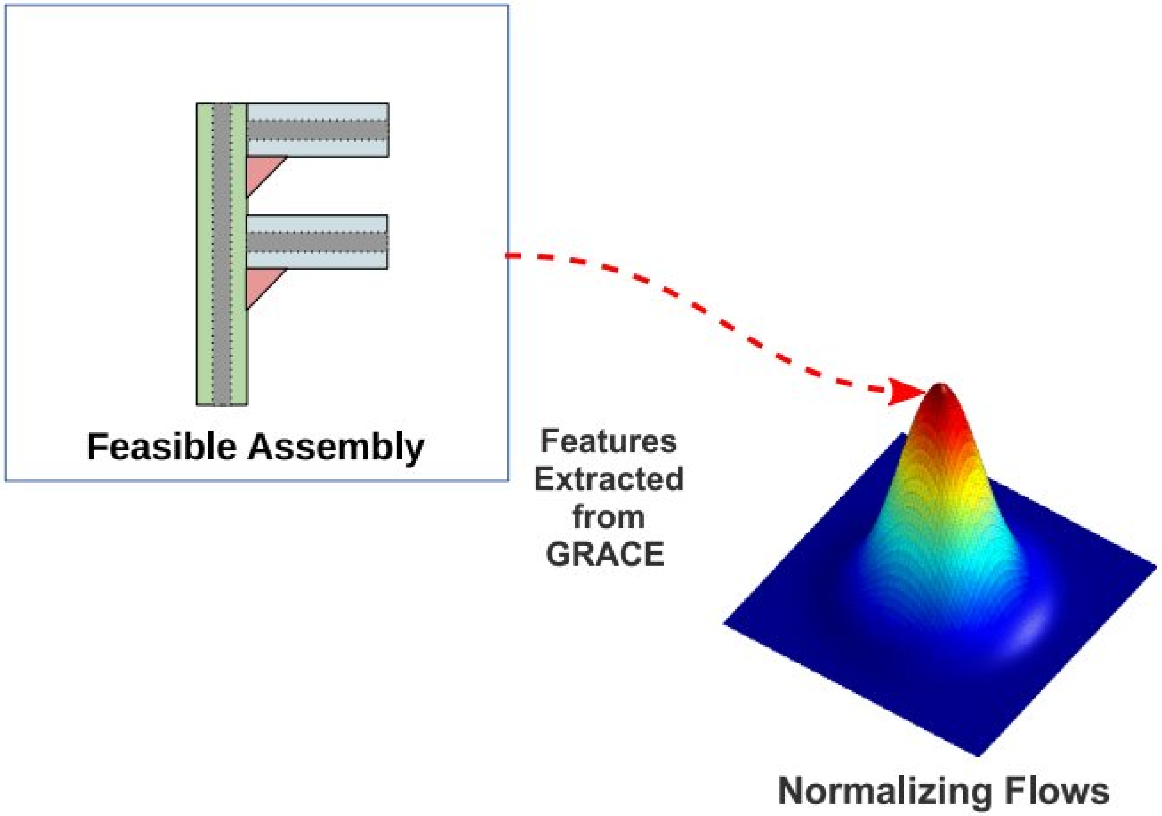




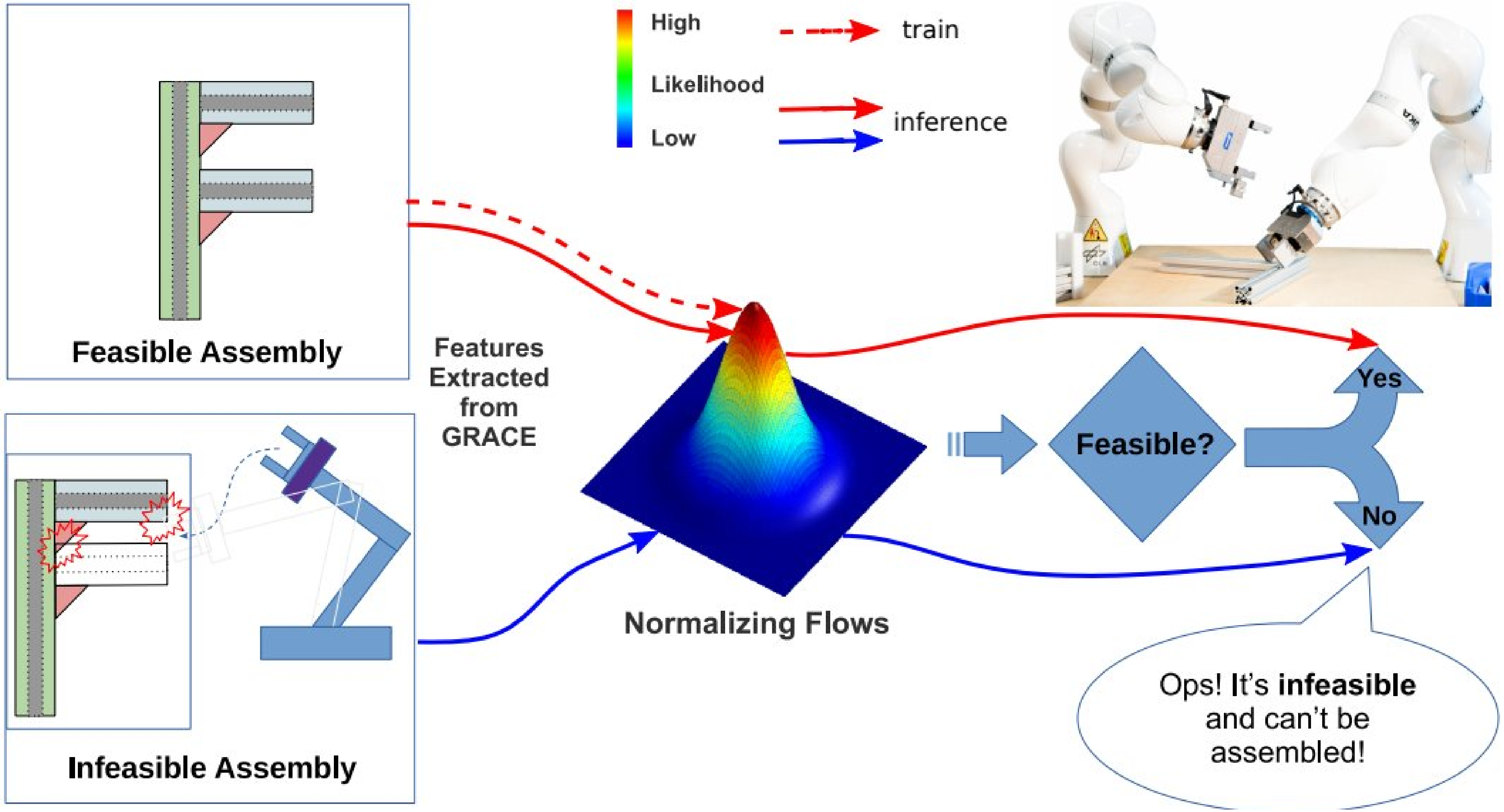
Introspective robotic assembly:
Assembly feasibility learning as Out-of-distribution (OOD) detection based on **purely feasible cases**.

Assembly Feasibility Learning via Density Estimation



- Training: **Maximizing** the likelihoods of feasible assemblies.

Assembly Feasibility Learning via Density Estimation



- Training: **Maximizing** the likelihoods of feasible assemblies.
- Test: Detecting infeasible assemblies with **low** likelihoods.

Density Estimation with Normalizing Flows

Normalizing flows are a popular class of deep generative models:

- flexible density estimation;
- fast and exact likelihoods computation;

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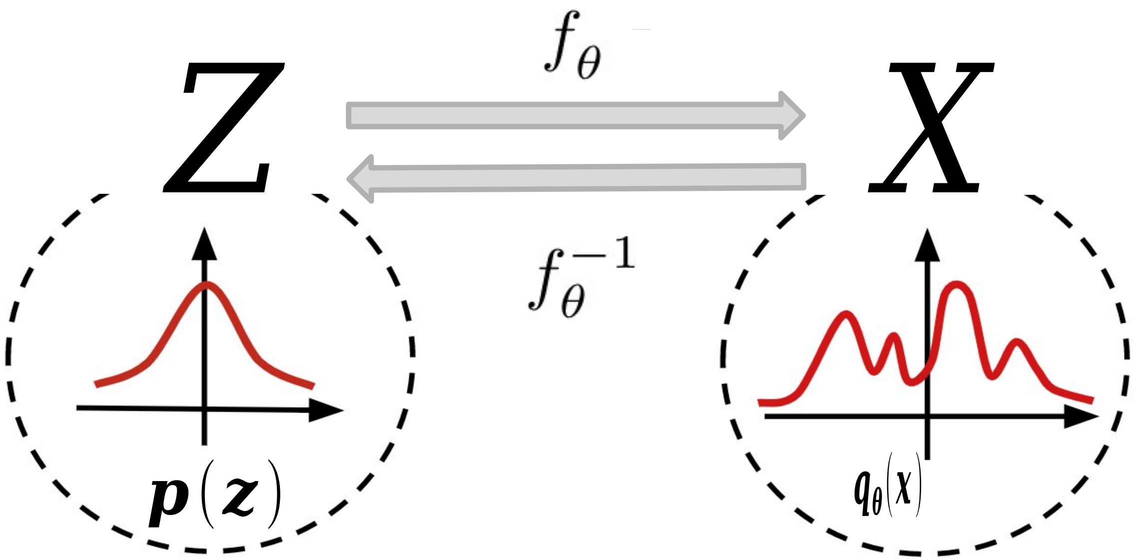


$$\log q_\theta(\mathbf{x}) = \log p(f_\theta^{-1}(\mathbf{x})) + \log\left|\det\left(\frac{\partial f_\theta^{-1}(\mathbf{x})}{\partial \mathbf{x}}\right)\right|$$

Log Likelihood of base distribution

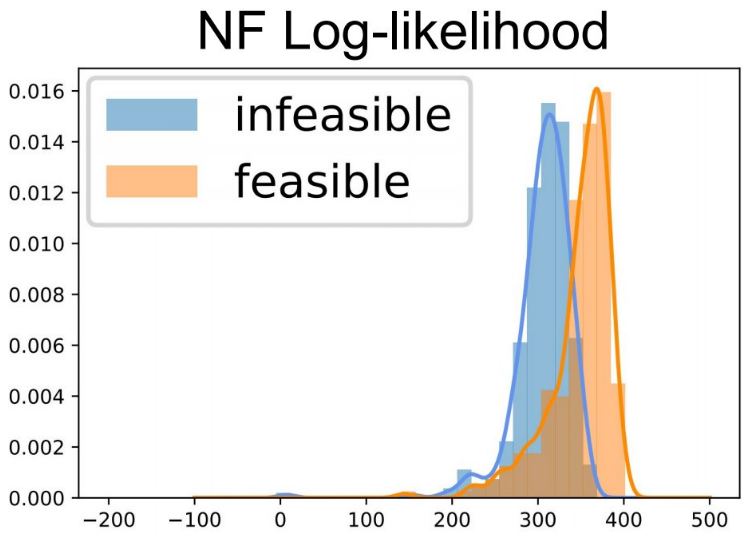
Log Determinant of Jacobians

Experiment - Infeasible Assemblies Detection

	Area Under ROC ↑	
	A_5	A_6
NF, 749 layers, gaussian base	**0.85**	**0.83**
NF, 109 layers, resampled base	0.83	-
OC-SVM [4]	0.74	0.59
Baseline (size of predicted set)	0.61	0.57

A_n: assemblies with *n* parts.

Ablation – Normalizing Flow Density Estimation



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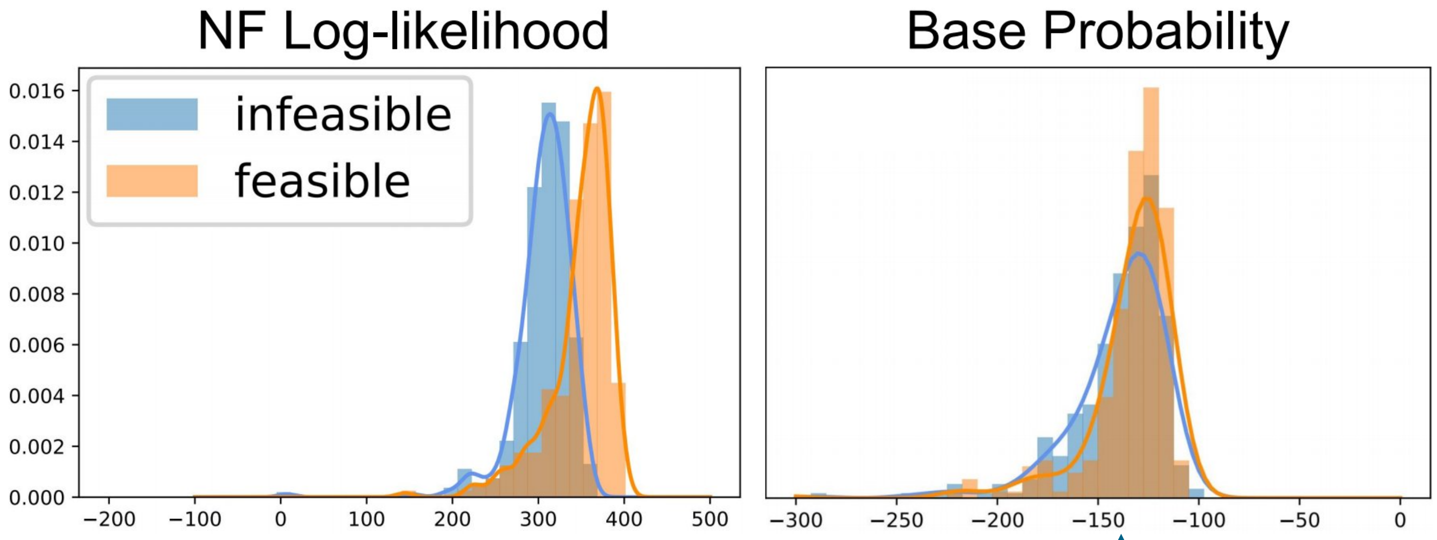

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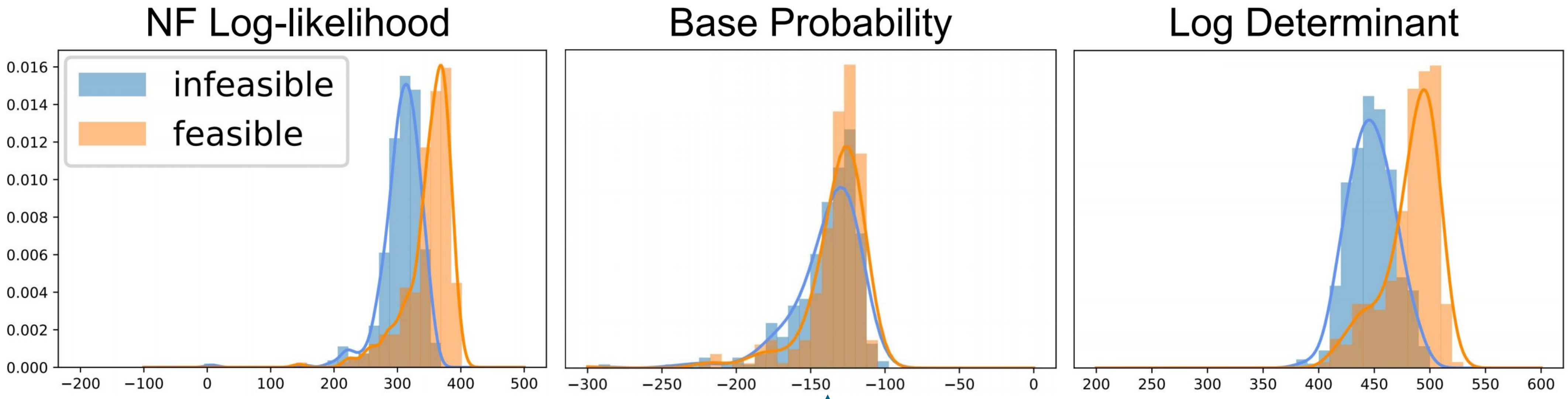

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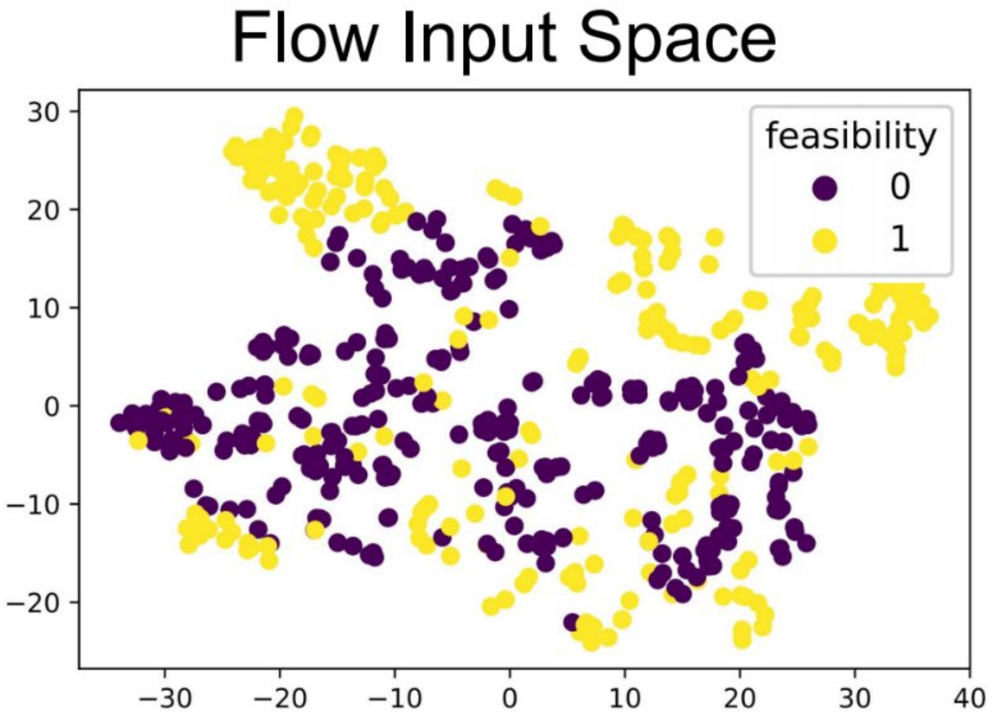
- Log Determinants of Jacobians is the main contributing factor to the final likelihoods.

Ablation – Normalizing Flow Transformation

T-SNE Visualization



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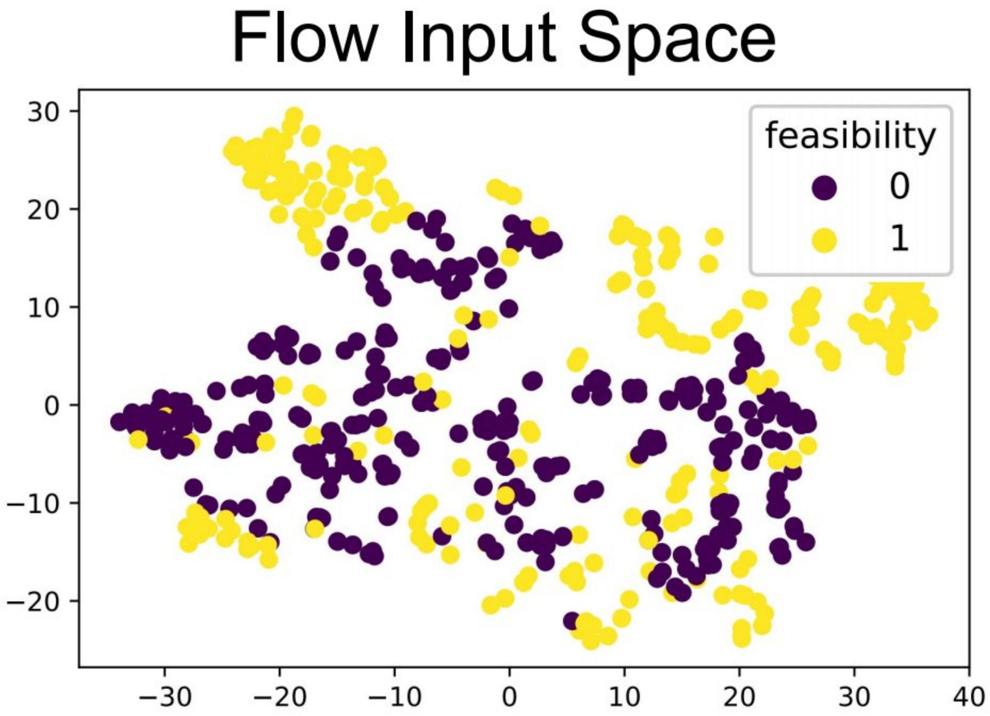
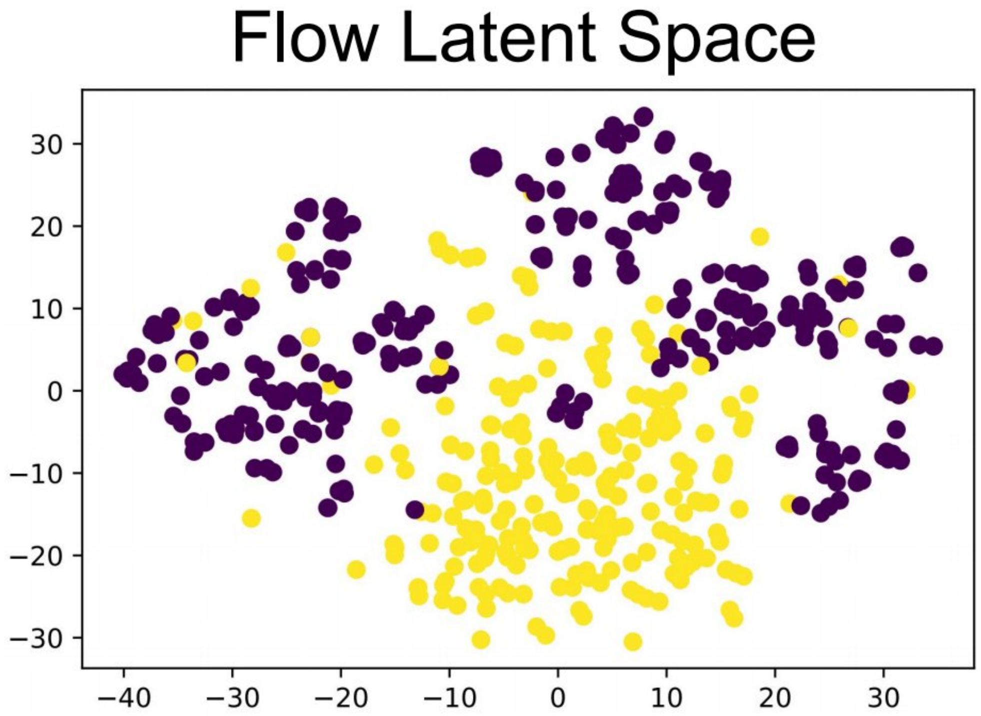




- Feasible assemblies are pulled together and clustered more compactly when compared to those in the input space before the flow transformation.

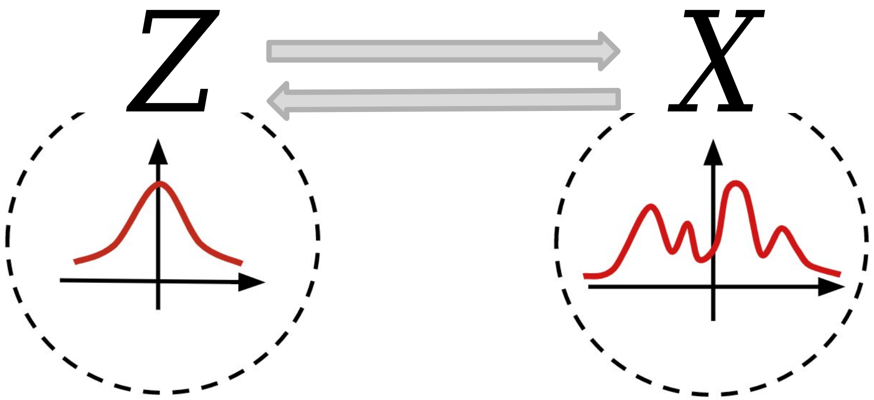
Conclusion

- Raising Importance of **Introspection** for data-driven approaches in robotic assembly sequence planning (RASP).

- Formulating feasibility learning as Out-of-Distribution (OOD) detection with normalizing flows based on **only** feasible assemblies;

- Validating on **infeasible assemblies detection** task in simulation, with ablation studies on the working mechanisms of the flows.

- **Explaining** the in/feasibility based on NFs as future work.



Thank you for your attention!