Behavior Trees and Task Failure Identification in Robotic Assembly

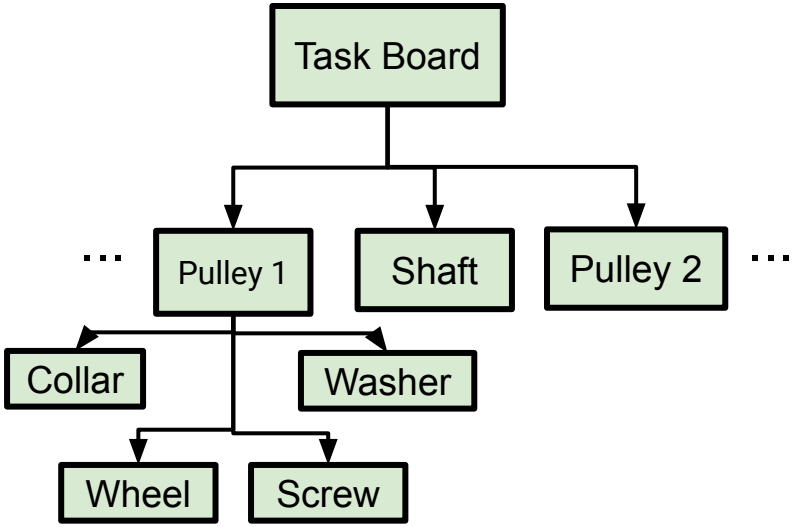
James Watson, Siddhant Keshkar, and Nikolaus Correll

University of Colorado at Boulder

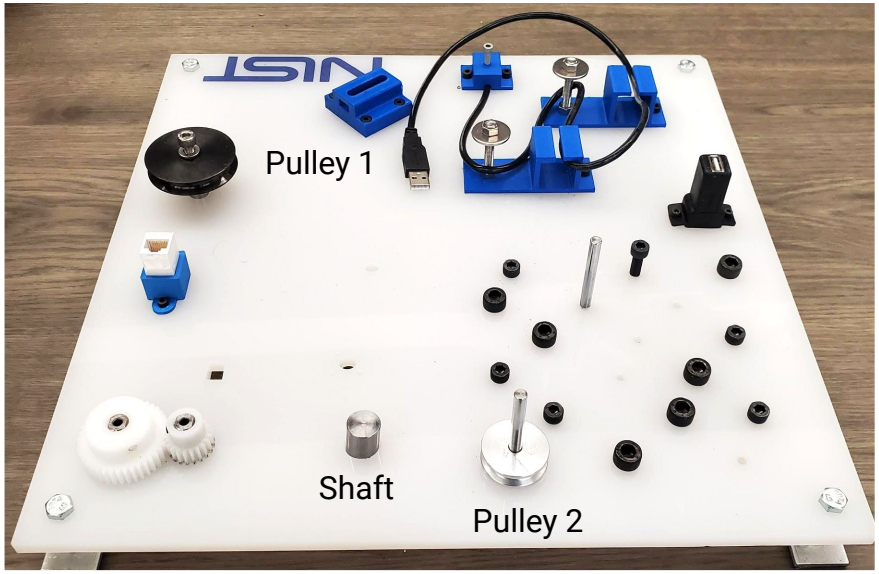
Motivation

- Reliability and flexibility of automated manufacturing systems
- Easily programmable and adaptable to various tasks common to industrial setting
- “Level 5” Automation: An end-to-end automated assembly system
  - Identify task failures
  - Recover from task failures

NIST Challenge (IROS 2019 and Beyond): Competitions providing a venue to test and demonstrate industrial automation techniques



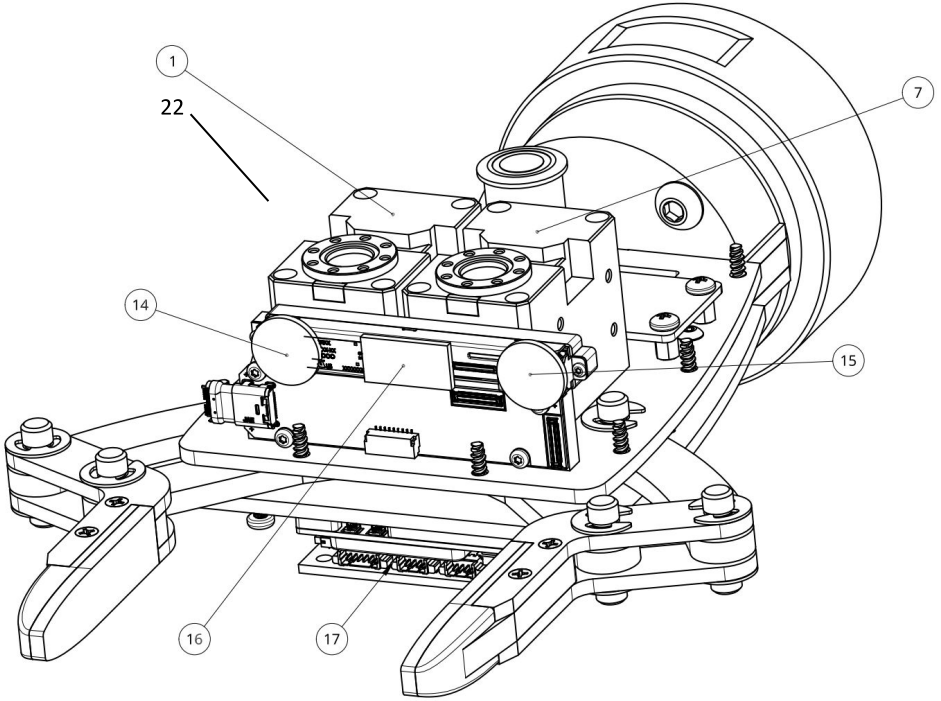
Example Assembly Tree



NIST taskboard requires different join operations,
as well as parallel, sequential, and hierarchical actions

Hardware & Software

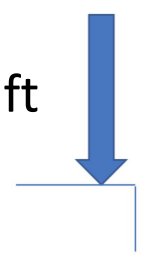
- UR5 robot
- Optoforce 6-DOF load cell
- Robotic Materials SmartHand
  - Intel Realsense
  - Nvidia Jetson
  - Individually impedance-controlled fingers
- Leveraging open-source tools and Python (Jupyter, etc.)

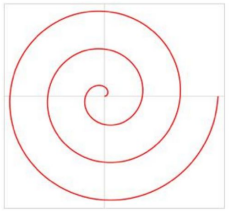


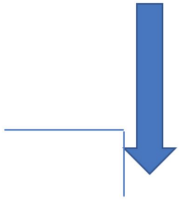
Correll, N., Miller, A. K., & Romero, B. (2019). *U.S. Patent Application No. 16/376,938*.

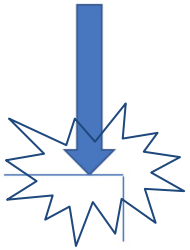
Spiral Insert

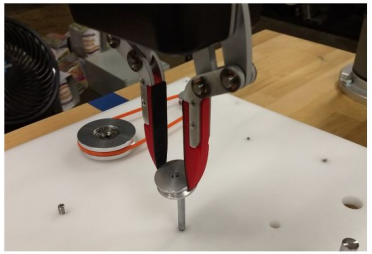
1. Locate part and shaft
2. Move to contact
3. Spiral search until condition met
   a. Drop Force
   b. Lateral Torque
4. Push
5. Tamp (Adv. Rob. 2020 only)

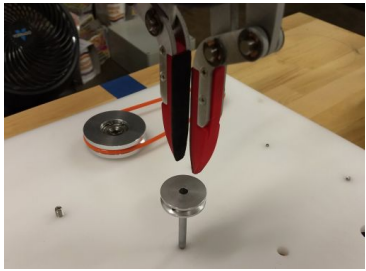






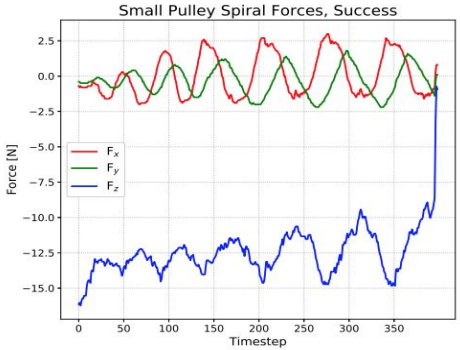


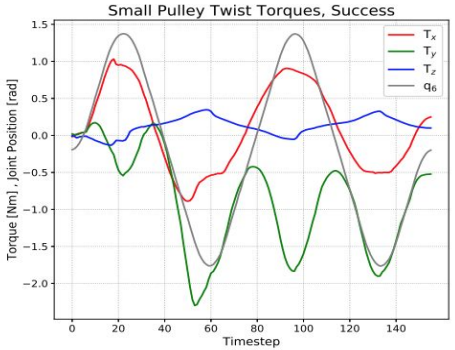


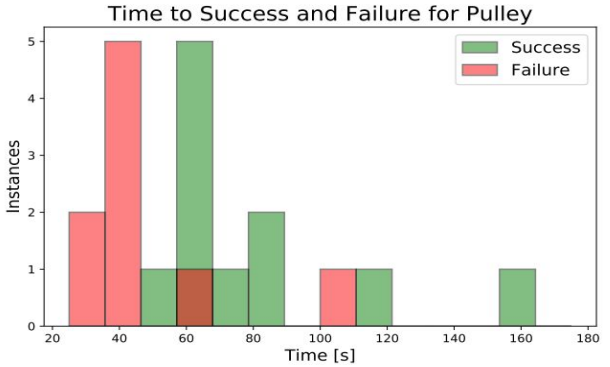


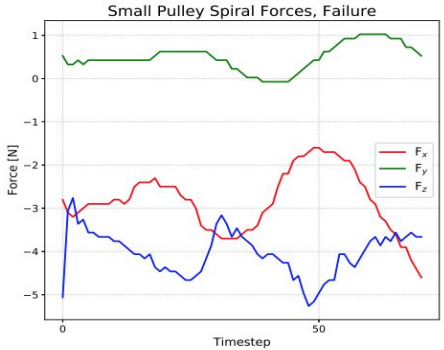
Advanced Robotics 34, no. 7-8 (2020): 546-559.

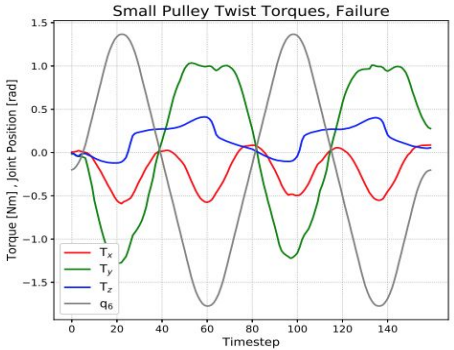
Results: Pulley Assembly (Spiral Insert)







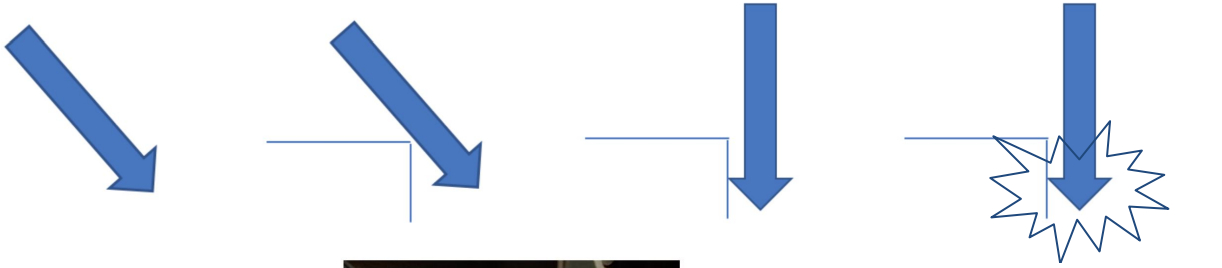




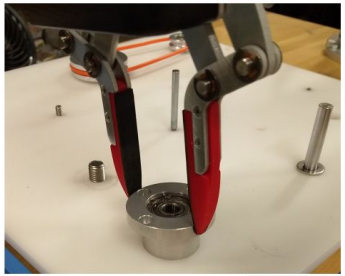
Task	Trials	Success	Rate
Large Bearing	20	13	0.65
Small Pulley	20	13	0.65
Stud	20	7	0.35

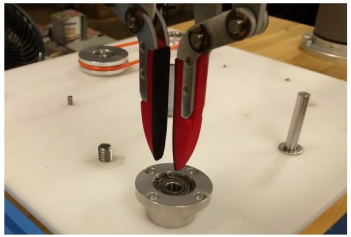
Advanced Robotics 34, no. 7-8 (2020): 546-559.

Tilt Insert

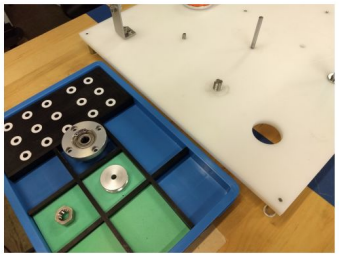


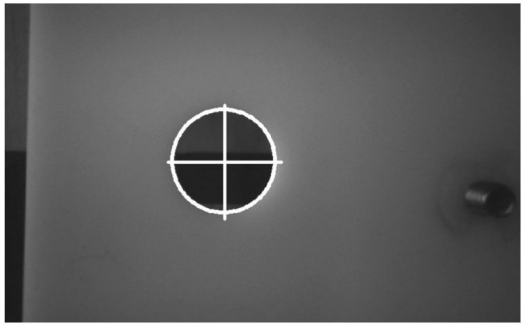
1. Locate hole and bearing
2. Tilt and offset
3. Move to contact
4. Return to vertical and center part on hole
5. Tamp (Adv. Rob. 2020 only)



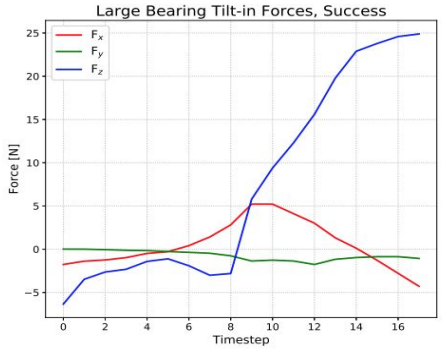


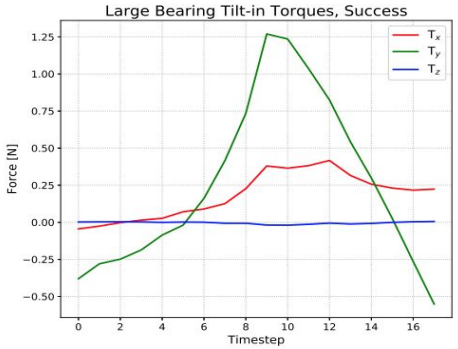
Advanced Robotics 34, no. 7-8 (2020): 546-559.

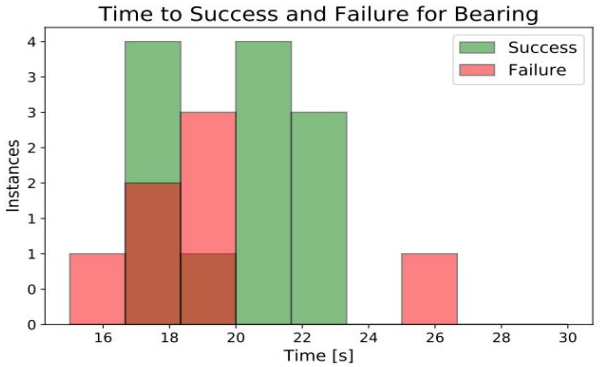


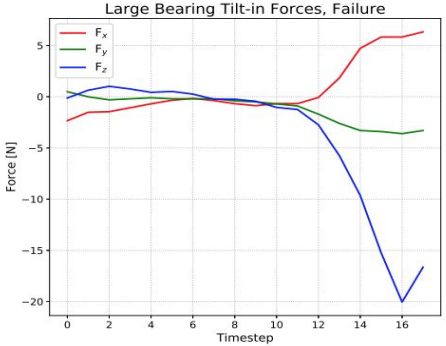


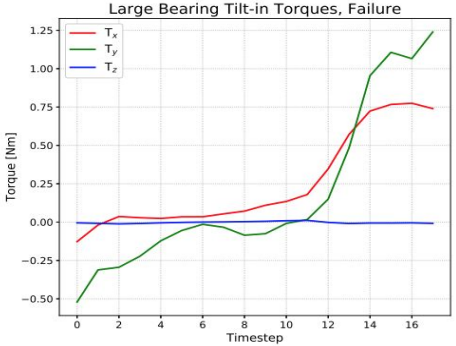
Results: Bearing Assembly (Tilt Insert)









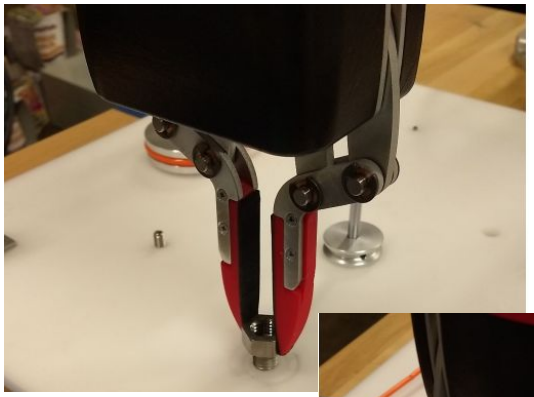


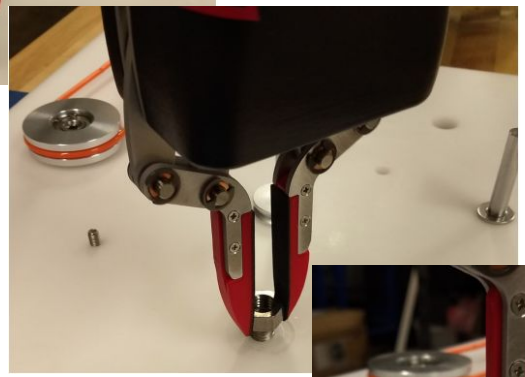
Task	Trials	Success	Rate
Large Bearing	20	13	0.65
Small Pulley	20	13	0.65
Stud	20	7	0.35

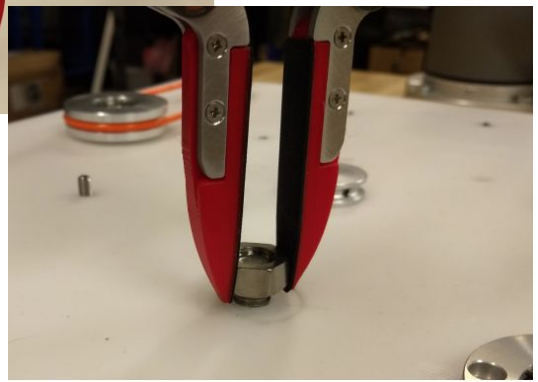
Advanced Robotics 34, no. 7-8 (2020): 546-559.

Nut threading

1. Locate nut and stud
2. Move to contact
3. While no F_z pushback
   a. Grasp
   b. Rotate CW 2 flats and descend
   c. Release
   d. Rotate CCW 2 flats

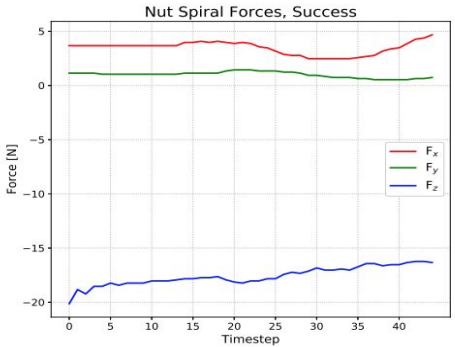


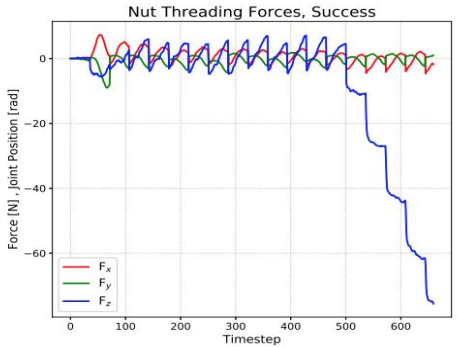


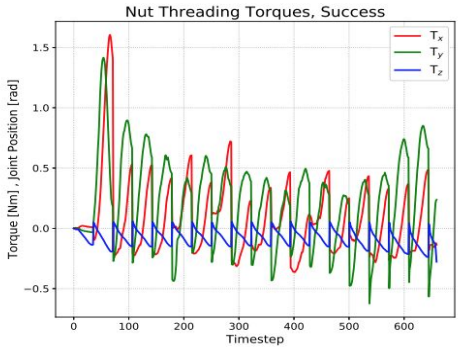


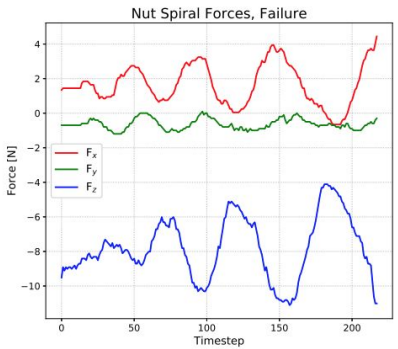
Advanced Robotics 34, no. 7-8 (2020): 546-559.

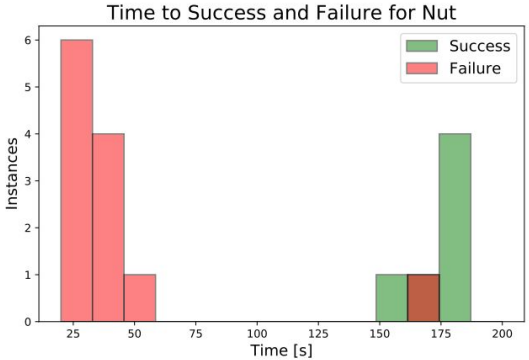
Results: Nut Threading











Task	Trials	Success	Rate
Large Bearing	20	13	0.65
Small Pulley	20	13	0.65
Stud	20	7	0.35

Advanced Robotics 34, no. 7-8 (2020): 546-559.

Codebase Development

WRS 2018

- Largely scripted
- Very brittle
- 2D feature detection

IROS 2019

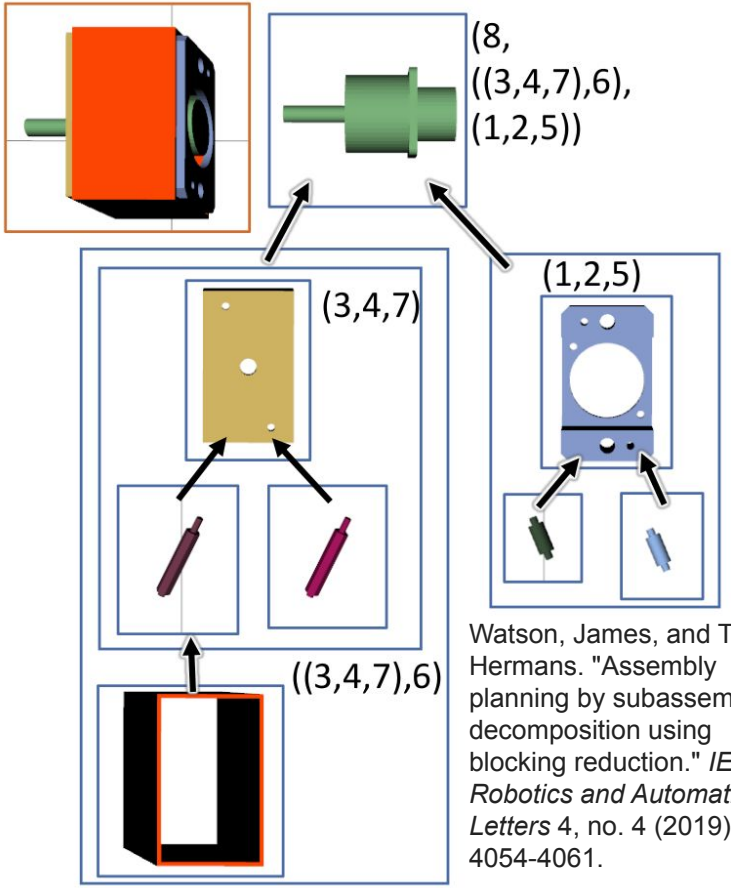
- Skills as functions “mini-FSM”
- Some error checking
- 2D feature detection

Current

- Behavior Trees
- Auto. Error Recovery
- 3D Pose Estimation

Why Behavior Trees?

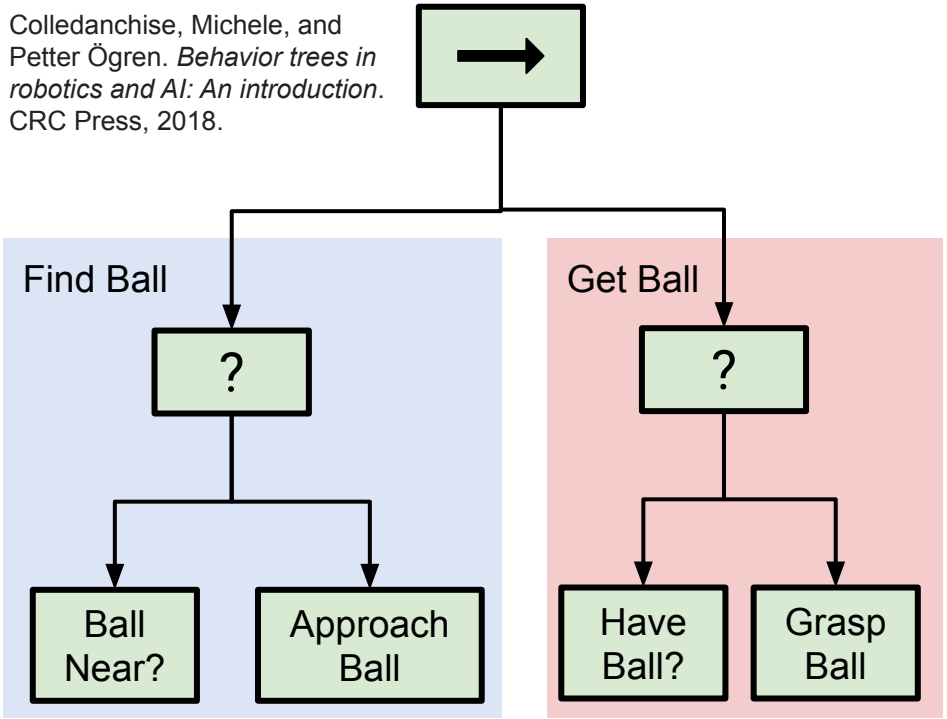
- Industrial tasks are hierarchical
- A planner for industrial tasks should match this tree structure and be reactive as well
- Goals:
  - Planning at the tree level
  - Machine Learning at the node level



Watson, James, and Tucker Hermans. "Assembly planning by subassembly decomposition using blocking reduction." *IEEE Robotics and Automation Letters* 4, no. 4 (2019): 4054-4061.

Behavior Trees (BT): A Very (Very) Short Course

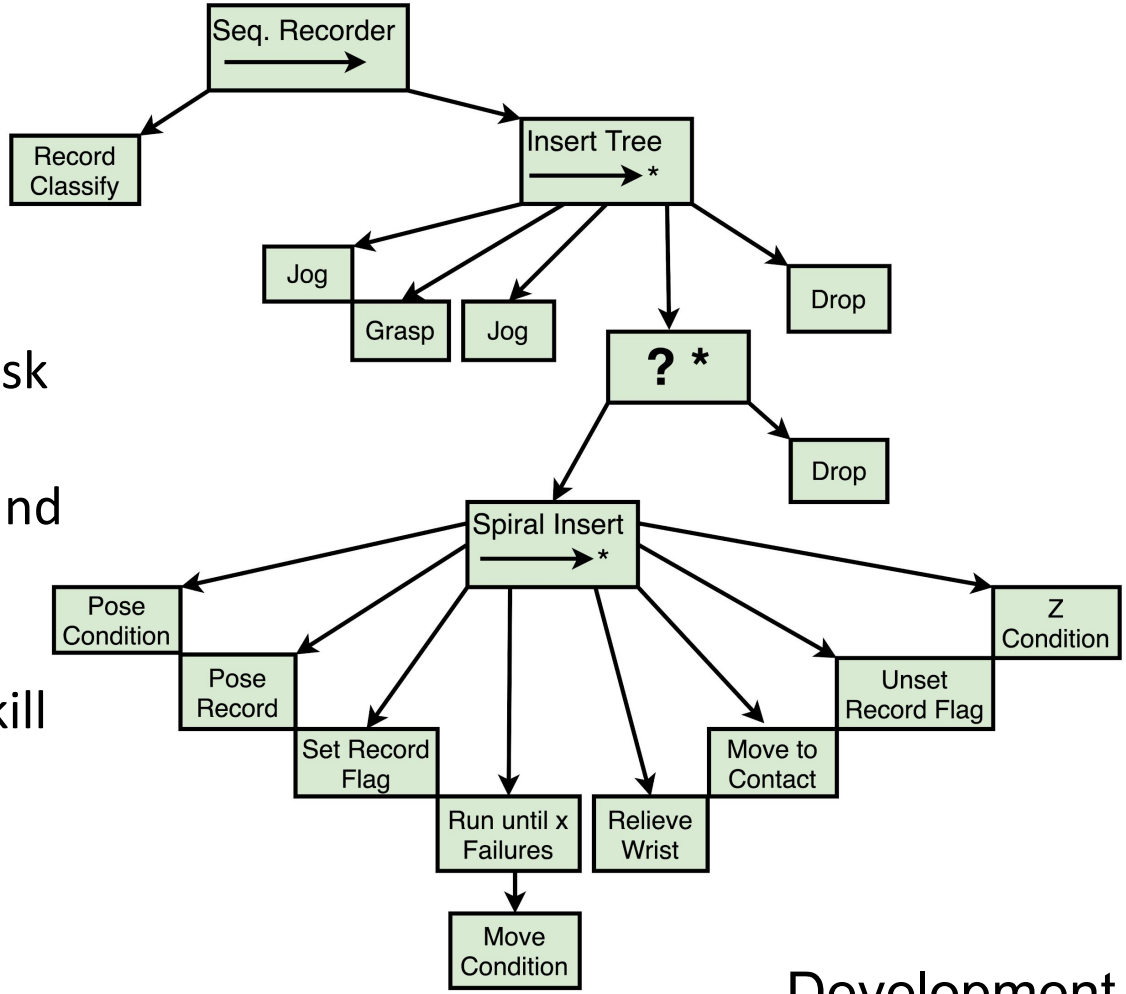
Colledanchise, Michele, and Petter Ögren. *Behavior trees in robotics and AI: An introduction*. CRC Press, 2018.



- Flow control via distribution of "ticks"
- When ticked, a behavior returns one of {Running, Success, Failure}
- + *Modular/Composable*
- + *Reactive*: Error handling is part of flow control
- Any FSM has an equivalent BT

Spiral Insert BT

- Top Level: Record and run task
- Middle Level: Retrieve part and run insert skill
- Bottom Level: Spiral insert skill



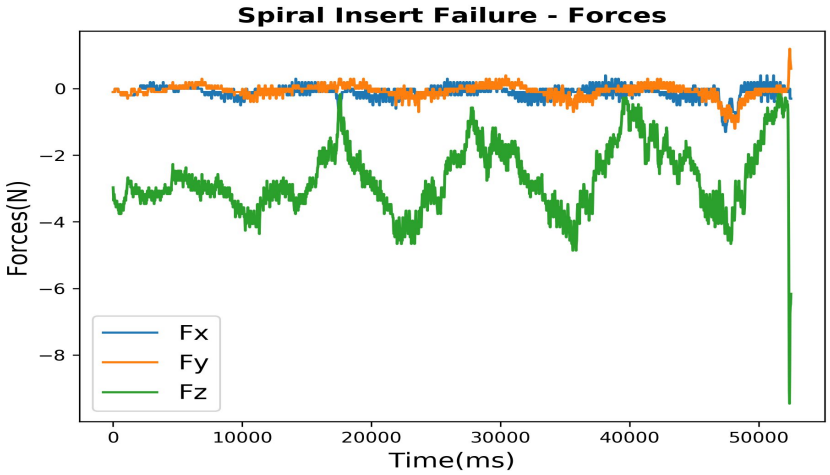
Experimental Setup

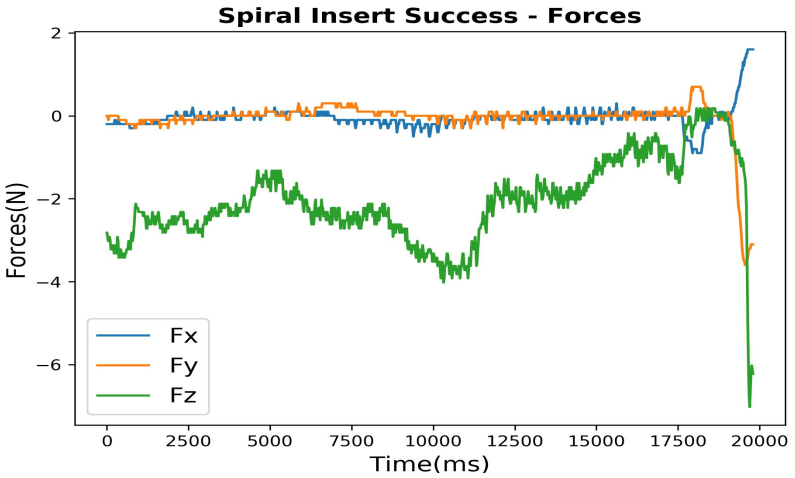
- Repeat insertion actions,
  ≤±2mm X/Y offsets at grasp point (9 total initial grasp poses)

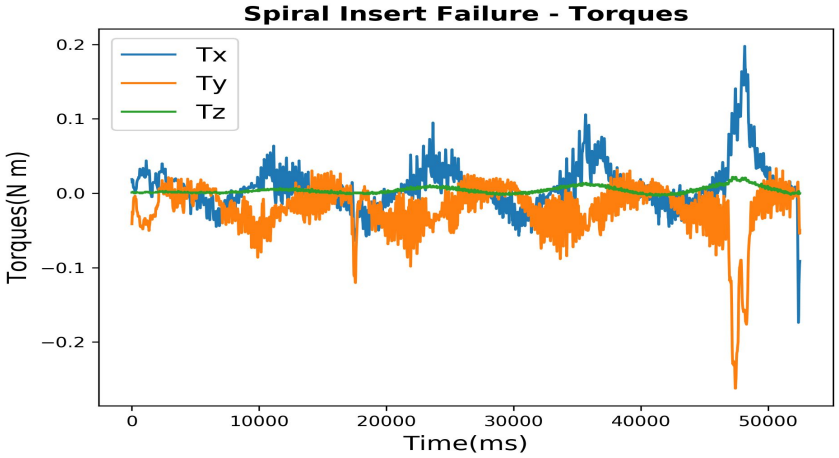
- Tilt Insert
  - 15mm round shaft, peg-in-hole
  - 459 trials

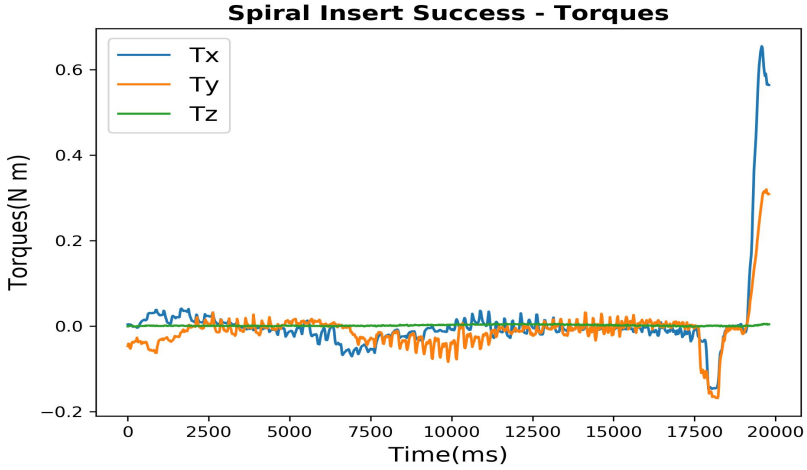
- Spiral insert
  - 26mm pulley wheel, hole-on-peg
  - 450 trials

Task	Trials	Success	Rate
Spiral	450	126	0.280
Tilt	459	373	0.813



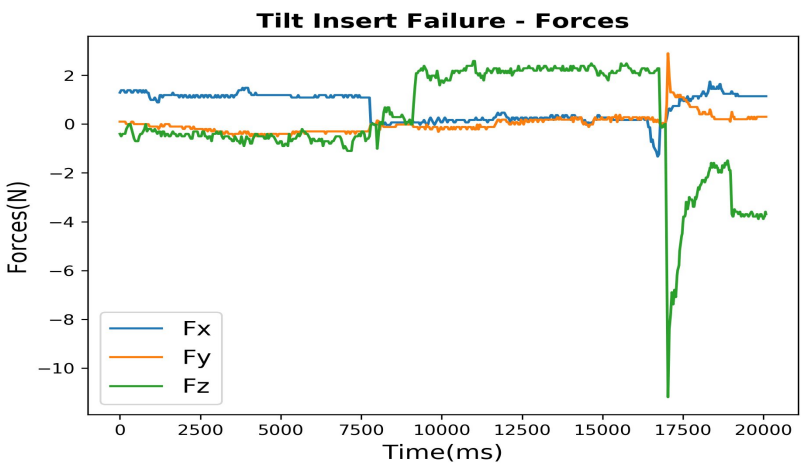


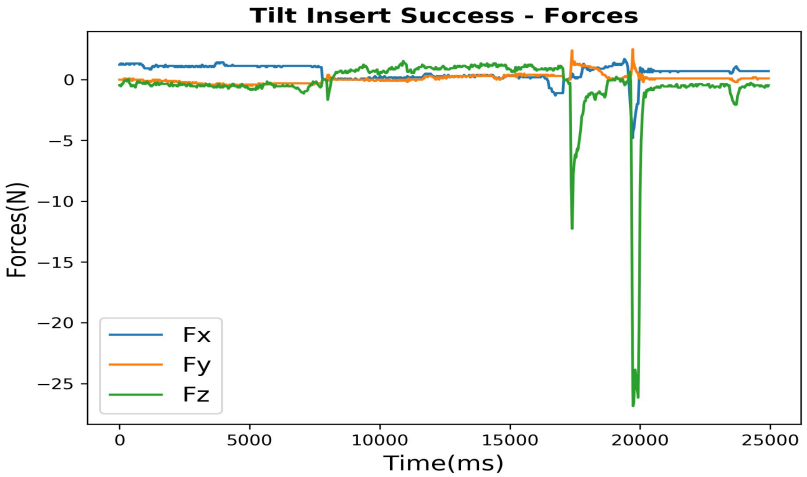


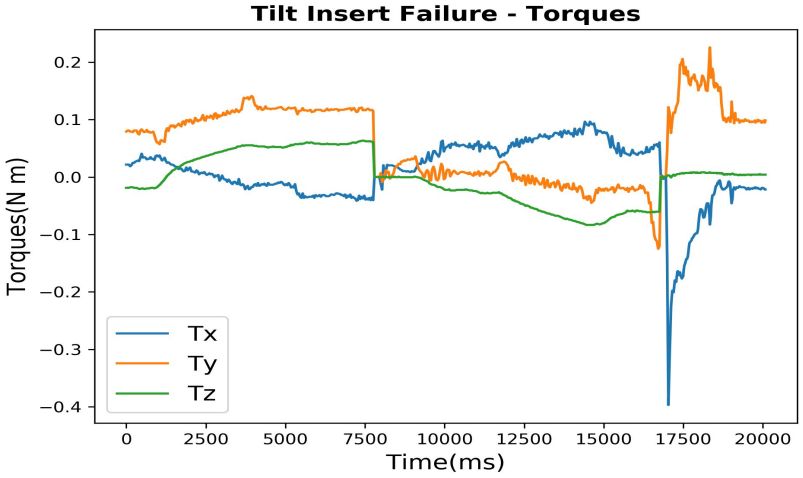


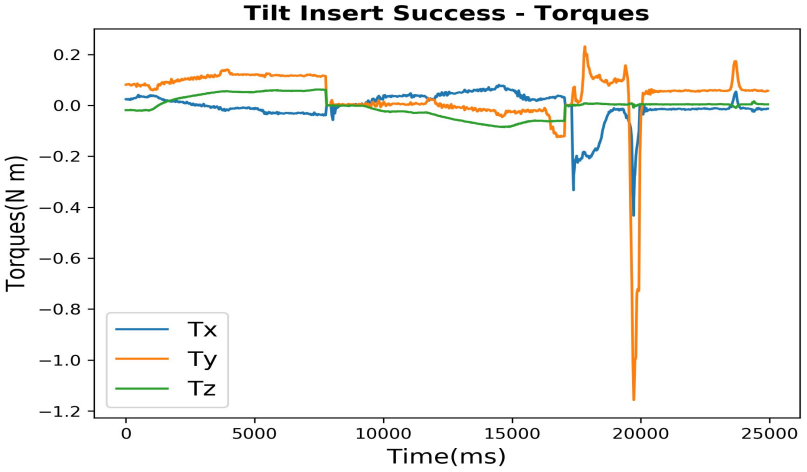
University of Colorado **Boulder**

Spiral Insert Initial Results for Failure ID







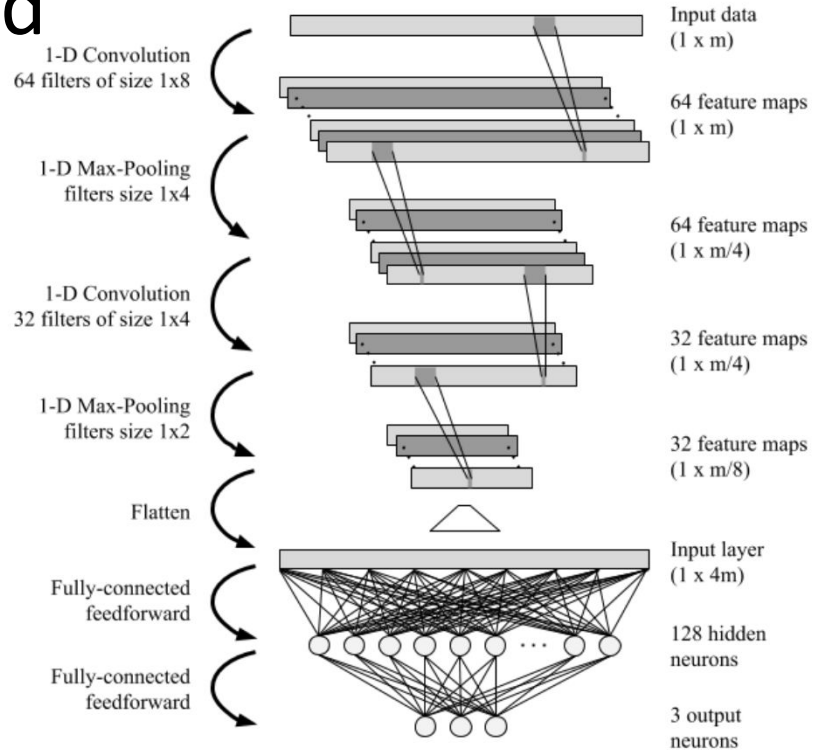


University of Colorado **Boulder**

Tilt Insert Initial Results for Failure ID

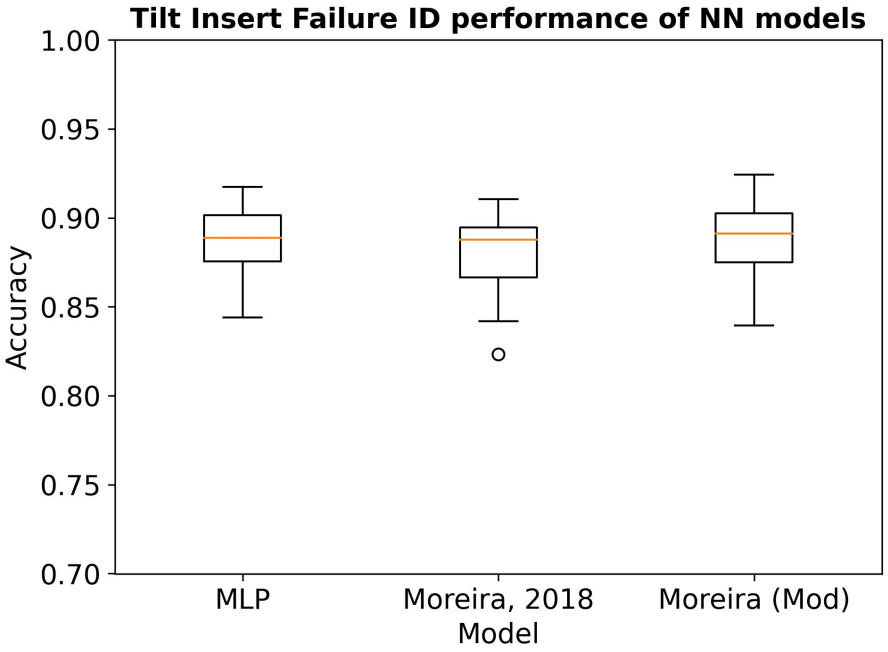
Neural Network Models Tested

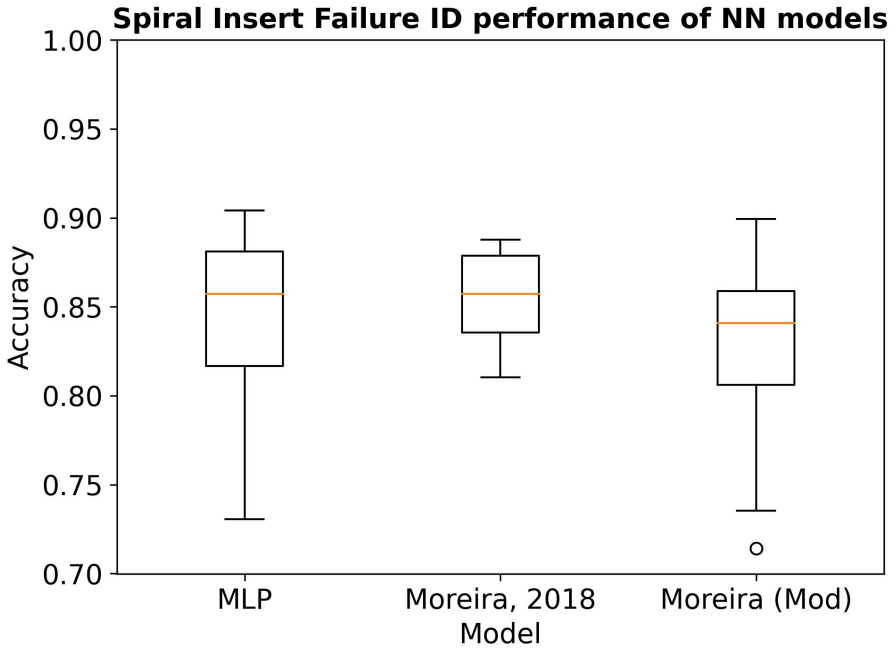
- MLP
  - Input: 128 Units
  - Output: 2 Units, fully connected
- Moreira, 2018
- Moreira, Modified
  - Replaced the first 1D conv. layer with a 2D conv. across FT channels



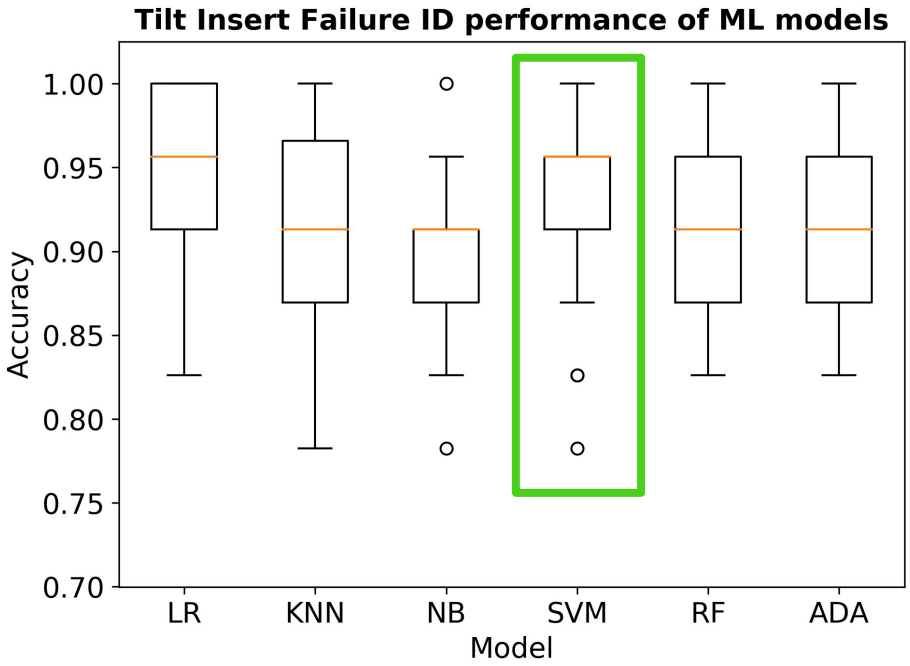
Moreira, Guilherme R., Gustavo JG Lahr, Thiago Boaventura, Jose O. Savazzi, and Glauco AP Caurin. "Online prediction of threading task failure using convolutional neural networks." In *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 2056-2061. IEEE, 2018.

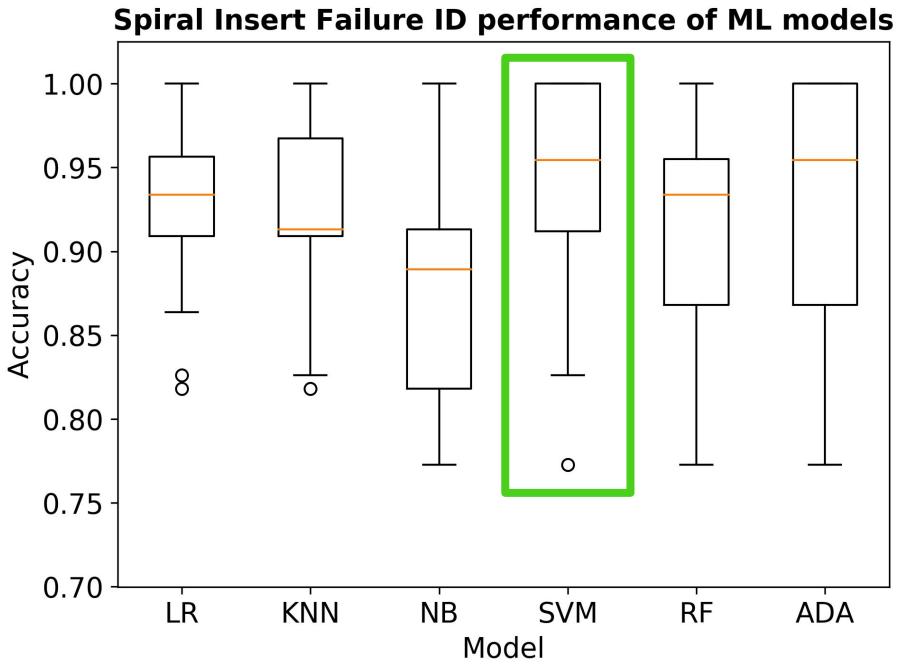
Neural Networks Model Performance



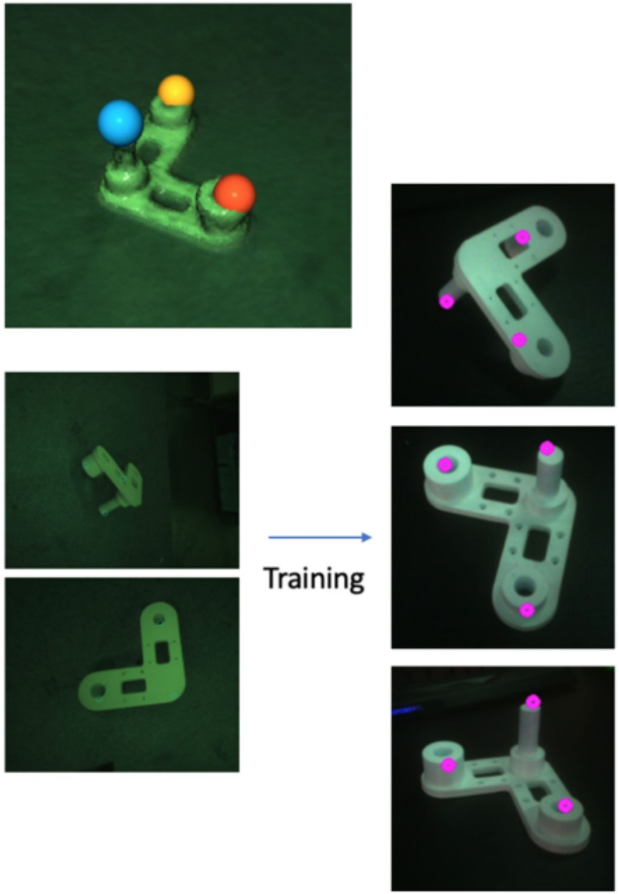


Machine Learning Model Performance





Future Work



- Immediate
  - *Learn* to identify tasks failures as they happen
- Medium Term
  - *Learning* BTs that select the appropriate recovery behavior for each failure type.
  - Use machine vision to determine if task pre/post-conditions are met
- Long Term
  - Efficiently manage simultaneous plans (BTs) based on likelihood of success and available resources