Replicable Tests and Benchmarking for Robotic Assembly Operations

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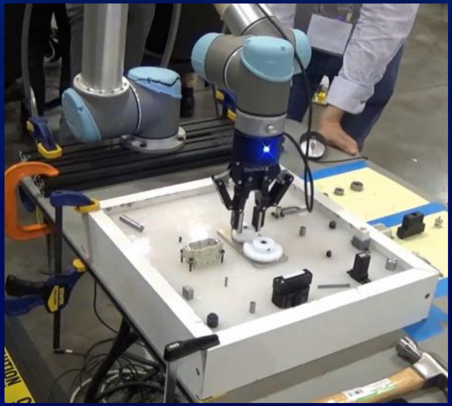
Goal

- Performance assessment and benchmarking
- Feedback for researchers
- Future technical specifications

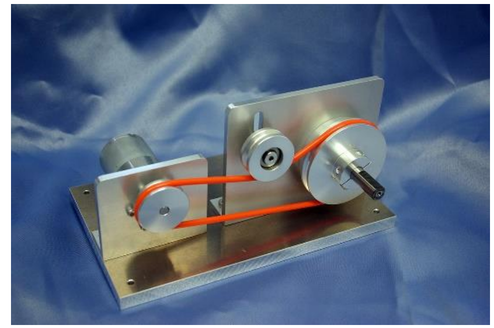
Community Interest

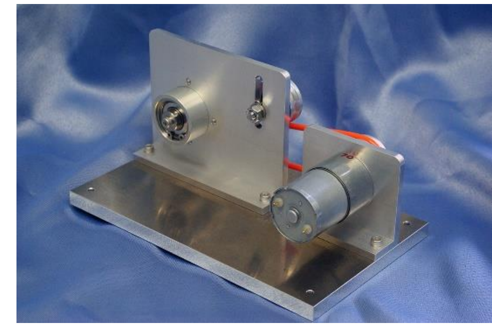
- Workshops
  - IEEE ICRA 2015 Benchmarking in Manipulation Research: The YCB Object and Model Set
  - IEEE ICRA 2015 Robotic Hands, Grasping, and Manipulation
  - IEEE CASE 2016 Robotic Hand Technologies and Performance
  - IEEE IROS 2017 Development of Benchmarking Protocols for Robot Manipulation
  - IEEE ICRA 2017 Reproducible Research in Robotics: Current Status and Road Ahead
- Competitions
  - Amazon Picking Challenge
  - DARPA Robotics Challenge
  - IEEE IROS 2016 Grasping and Manipulation Competition
  - IEEE IROS 2017 Grasping and Manipulation Competition
  - World Robot Summit (WRS) 2018/2020 Industrial Robotics Competition

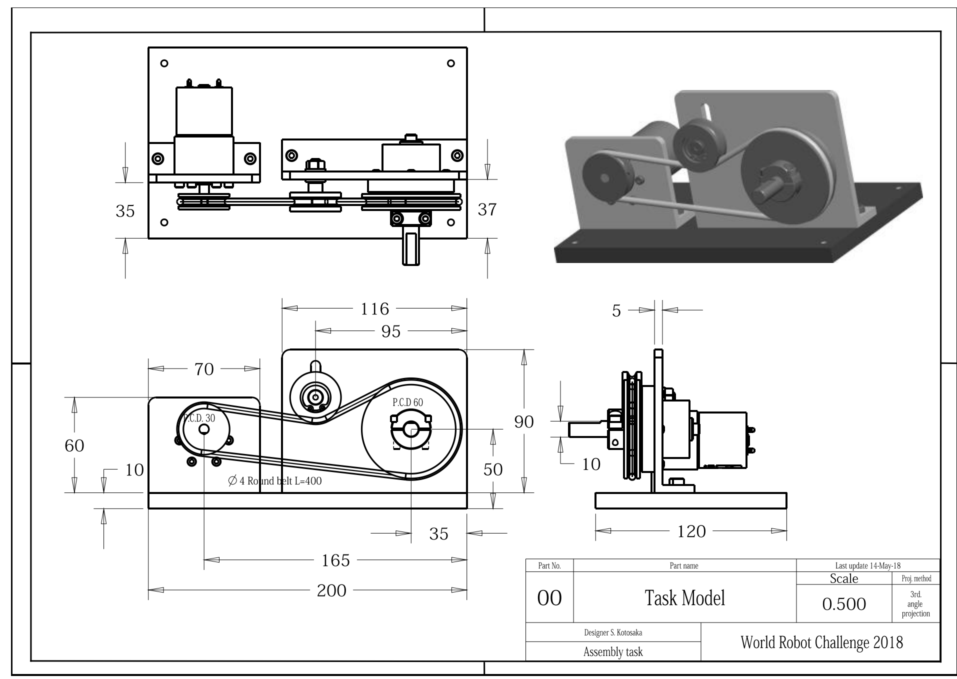


Assembly Task

- Assembly of belt-drive units
  - Day 3: 3 normal sets
  - Day 4: 2 normal set + 1 set incl. surprise parts
- Competition time:
  - Day 3: 45min. ×2 trials
  - Day 4: 60min. ×1 trial
- Surprise parts
  - CAD model is given 60 min. prior to the competition
  - Real parts are given 10 min. prior to the competition







Community Interest

- Technical Committees
  - IEEE RAS Technical Committee on Performance Evaluation and Benchmarking of Robotics and Autonomous Systems
  - IEEE RAS Technical Committee on Robotic Hand Grasping and Manipulation
- Existing Efforts
  - YCB object and model set
  - UC Berkeley Open Discussion
  - Advanced Robotics for Manufacturing (ARM) Institute
- Publications
  - IEEE RAM R-Article
- Testing Facilities
  - New England Robotics Validation and Experimentation (NERVE) Center

University of Massachusetts Lowell

New England Robotics Validation and Experimentation (NERVE) Center

- Manipulator testbeds for evaluating grasping, assembly, and human-robot collaboration performance with a suite of robotic arms, hands, and sensors of varying capabilities and characteristics
- Test methods and benchmarks from NIST, YCB Object and Model Set, new methods in development
- Developing metrics and evaluation methods for the Advanced Robotics for Manufacturing (ARM) Institute

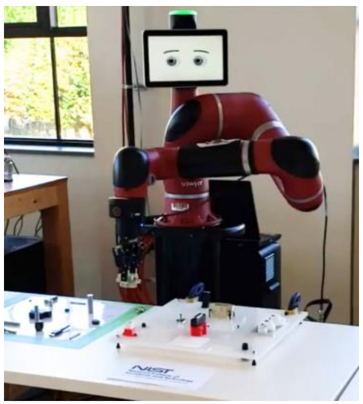
Soft Robotics

Right Hand Robotics

More to come!

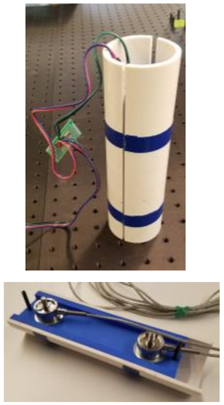
Wonik Robotics

Rethink Robotics



Rethink Robotic Sawyer with Robotiq 2-finger manipulating NIST assembly task board

Universal Robots UR5 with Robotiq 3-finger manipulating NIST grasping test artifact



Contact: Adam Norton, Assistant Director adam_norton@uml.edu

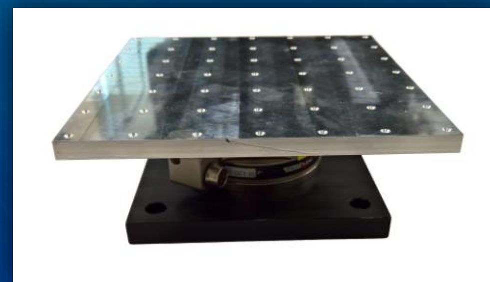
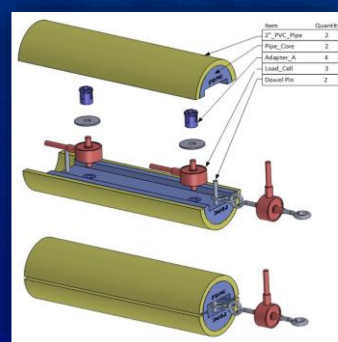
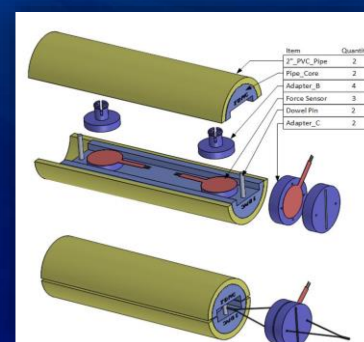
Problem Scope

- Performance assessment and benchmarking
  - Arms
  - Grippers/hands
  - Sensors
  - Algorithms
  - Implementation/integration
  - Objects
  - Tasks/tests
  - Metrics
  - Performance comparisons

Hand/Gripper

- Enhancing end-effector adaptability
- Unify R&D performance measurement
- Unify technical specifications
- Rollout of enhanced behaviors

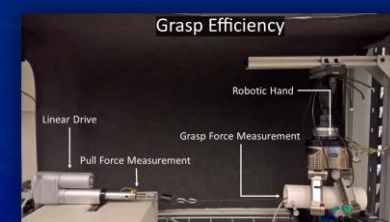
Hand/Gripper Tests

Test Method	***Measurement Instrument***
Finger Strength Touch Sensitivity Finger Force Tracking Force Calibration	
Grasp Strength Slip Resistance Grasp Efficiency Cycle Time	 
In-Hand Manipulation Object Pose Estimation	

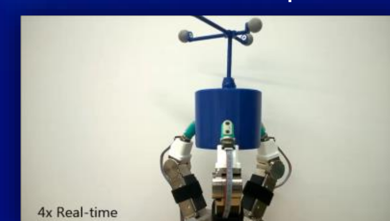
Touch Sensitivity

Grasp Strength

Grasp Efficiency



In-Hand Manipulation



Documentation

- NIST SP: Proposed Standard Terminology for Robotic Hands and Associated Performance Metrics
- NIST SP: Performance Metrics and Test Methods for Robotic Hands
- J. Falco, K. Van Wyk, S. Liu, S. Carpin, "Grasping the performance: facilitating replicable performance measures via benchmarking and standardized methodologies", *IEEE Robotics and Automation Magazine,* 2015.

https://www.nist.gov/el/intelligent-systems-division-73500/robotic-grasping-and-manipulation-assembly

Assembly Performance Tests

- Quantify performance of a robotic system completing a task
- Tests target assembly operations: pick-place, insertion, fastening, meshing, wire harnessing, pulley belt routing
- Whole system-system testing
- Component testing

Test Design

- Assembly Operations
- Design for Assembly (DFA)
  - Human performance factor analysis
  - Parameterizes objects
  - Handling times
  - Insertion times
- Guide design space
- Direct human comparison

MANUAL INSERTION-ESTIMATED TIMES (s)

Key: Part added but not secured

		After assembly no holding down required to maintain orientation and location (3)				Holding down required during subsequent processes to maintain orientation at location (3)			
		Easy to align and position during assembly (4)		Not easy to align or position during assembly		Easy to align and position during assembly (4)		Not easy to align or position during assembly	
		No resistance to insertion	Resistance to insertion (5)	No resistance to insertion	Resistance to insertion (5)	No resistance to insertion	Resistance to insertion (5)	No resistance to insertion	Resistance to insertion (5)
		0	1	2	3	6	7	8	9
Addition of any part (1) where neither the part itself nor any other part is finally secured immediately: Part and associated tool (including hands) can easily reach the desired location	0	1.5	2.5	2.5	3.5	5.5	6.5	6.5	7.5
Part and associated tool (including hands) cannot easily reach the desired location: Due to obstructed access or restricted vision (2)	1	4	5	5	6	8	9	9	10
Due to obstructed access and restricted vision (2)	2	5.5	6.5	6.5	7.5	9.5	10.5	10.5	11.5

Part secured immediately

		No screwing operation or plastic deformation immediately after insertion (snap/press fits, circlips, spire nuts, etc.)		Plastic deformation immediately after insertion						Screw tightening immediately after insertion	
				Plastic bending or torsion			Riveting or similar operation				
					Not easy to align or position during assembly			Not easy to align or position during assembly			
		Easy to align and position with no resistance to insertion (4)	Not easy to align or position during assembly and/or resistance to insertion (5)	Easy to align and position during assembly (4)	No resistance to insertion	Resistance to insertion (5)	Easy to align and position during assembly (4)	No resistance to insertion	Resistance to insertion (5)	Easy to align and position with no torsional resistance (4)	Not easy to align or position and/or torsional resistance (5)
		0	1	2	3	4	5	6	7	8	9
Addition of any part (1) where the part itself and/or other parts are being finally secured immediately: Part and associated tool (including hands) can easily reach the desired location and the tool can be operated easily	3	2	5	4	5	6	7	8	9	6	8
Part and associated tool (including hands) cannot easily reach desired location or tool cannot be operated easily: Due to obstructed access or restricted vision (2)	4	4.5	7.5	6.5	7.5	8.5	9.5	10.5	11.5	8.5	10.5
Due to obstructed access and restricted vision (2)	5	6	9	8	9	10	11	12	13	10	12

Separate operation

		Mechanical fastening processes (part(s) already in place but not secured immediately after insertion)				Non-mechanical fastening processes (part(s) already in place but not secured immediately after insertion)				Non-fastening processes	
		None or localized plastic deformation				Metallurgical processes					
							Additional material required				
		Bending or similar process	Riveting or similar processes	Screw tightening or other processes	Bulk plastic deformation (large proportion of part is plastically deformed during fastening)	No additional material required (e.g. resistance, friction welding, etc.)	Soldering processes	Weld/braze processes	Chemical processes (e.g. adhesive bonding, etc.)	Manipulation of parts or sub-assembly (e.g. orienting, fittings or adjustment of part(s). etc.)	Other processes (e.g. liquid insertion, etc.)
		0	1	2	3	4	5	6	7	8	8
Assembly processes where all solid parts are in place	9	4	7	5	12	7	8	12	12	9	12

Geoffrey Boothroyd, Peter Dewhurst, and Winston Knight. *Product Design for Manufacture and Assembly. CRC press, 1994.*

Performance Metrics

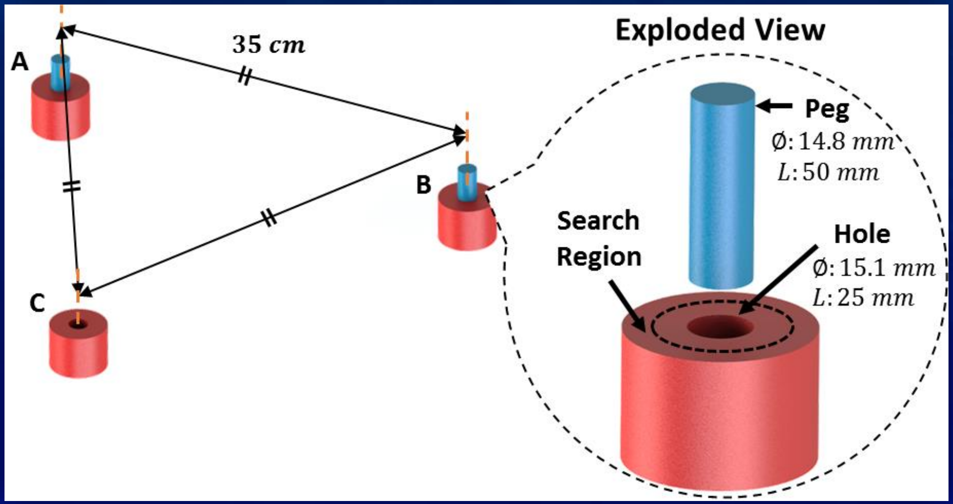
- Modes
  - Disassembly
  - Assembly
- Primary metrics
  - Speed → completion time
  - Reliability → probability of success
- Granularity
  - Per-part/operation
  - Whole

Data Analytics

- Ordinal or Attribute Data
  - Primary measure – probability of success
  - Discontinuous distribution – Kolmogorov-Conover
- Continuous Data
  - Primary measure – time
  - Distribution – Kolmogorov-Smirnov
  - ANOVA – Levene, Brown-Forsythe
  - Means – Snedecor-Cochran
- Matlab, R

Peg-in-Hole Test

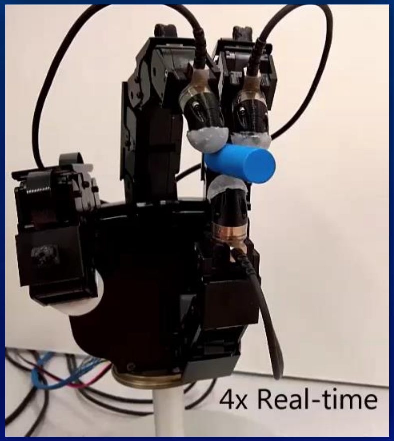
- Functional test method to measure the performance of robot systems at basic insertions
- Triangular design facilitates cyclical testing
- Peg-hole parameters, spacing based on human data



Systems

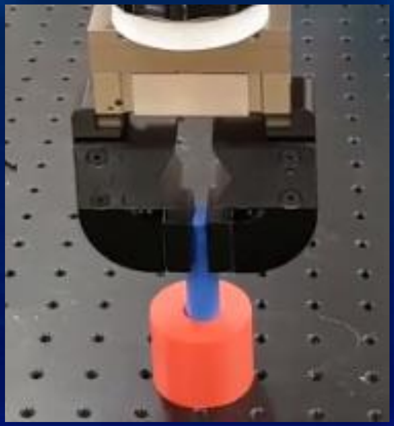
System 1

+

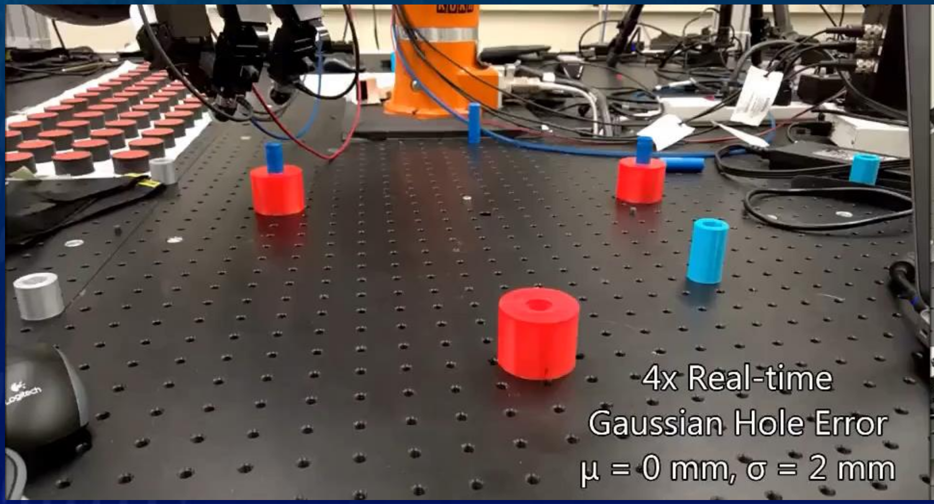


System 2

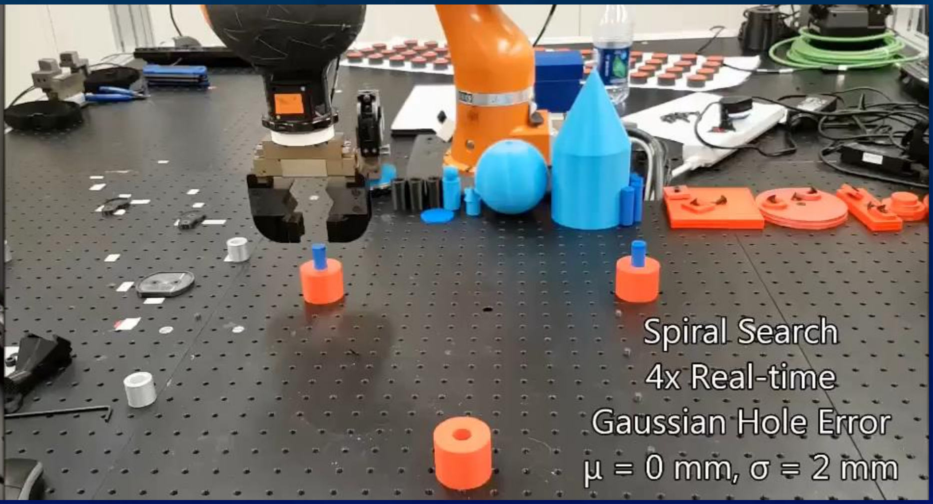
+



Peg-in-Hole Testing



System 1



System 2 *Spiral*

Comparative Results

Offsets ~ $N(0,\sigma_2)$, $\sigma_2 = 2$ *mm*

Robotic System	Correlation	KS	μ (s)	σ^2 (s^2)	PS (%)
System 1	0.01		18.31	107.3	87.6
System 2 *Spiral*	0.07	*	37.13*	399.6*	95.2
System 2 *Random*	-0.01	*	15.62	417.72*	95.2
System 2 *Quasi-Random*	-0.11	*	8.2*	50.25*	95.2

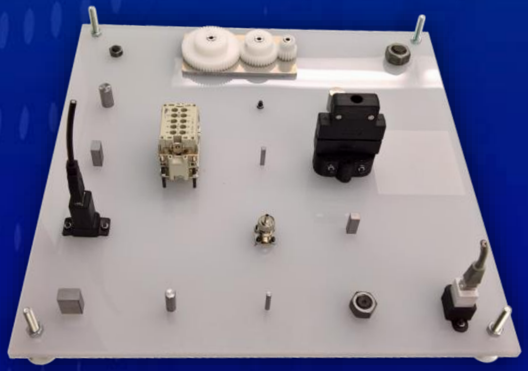
*Indicates statistical significance in comparison with System 1 after 60 trials.

K. Van Wyk, M. Culleton, J. Falco, K. Kelley, "Comparative Peg-in-Hole Testing of a Force-based Manipulation Controlled Robotic Hand", *IEEE Transactions on Robotics,* 2018.

Assembly Task Boards

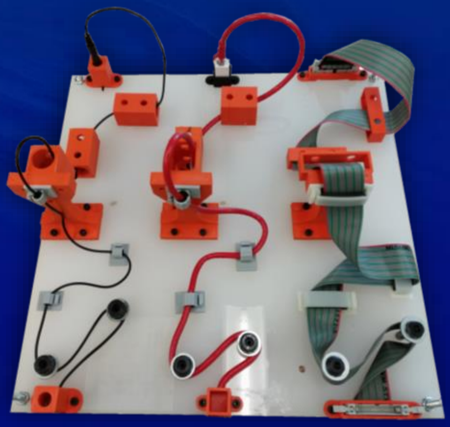
- Series of themed boards
- Each instance focuses on particular assembly facets
- Design with reference to DFA
- Low-cost, internationally replicable
- Realistic components

Task Board #1



Task Board #2

Task Board #3



Test Method

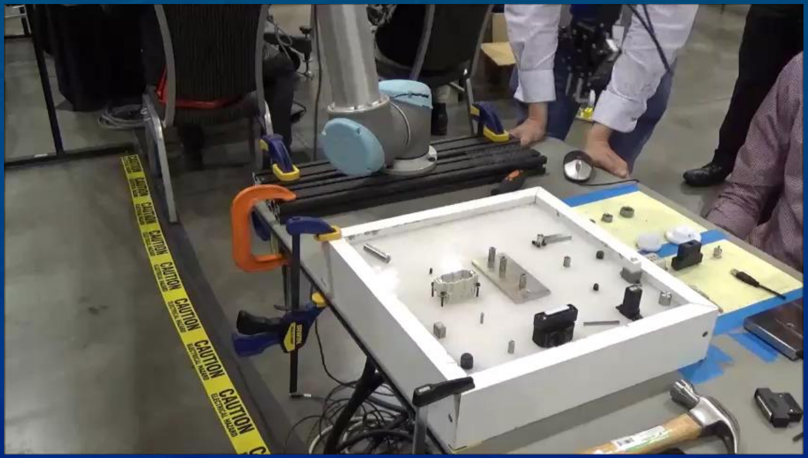
- Setup per trial
  - Option 1: randomly place task board and predesigned kit
  - Option 2: randomly place task board and parts (box shake)
- Execution
  - Disassembly: move-grasp-disassemble-transport components to target kit/bin
  - Assembly: move-grasp-transport-assemble components to target task board
- Considerations
  - Task board, bin, kit not fixed
  - Several trials per desired confidence, resolution
  - No restriction on order of solution

Test Metrics

- Operation- and object-centric
  - Completion time and pass/fail
    - Move-grasp-transport sequence
    - Assembly sequence
    - Move-disassemble sequence
    - Transport-place sequence
- Mode- and board-centric
  - Completion time
  - Percent complete

Thoughts

- Overfitting
  - Part variations
  - Operation variations
  - Variable initial conditions
  - Variety of task boards
- Difficulty
  - IROS 2017 GMC



Questions/Feedback

https://www.nist.gov/el/intelligent-systems-division-73500/robotic-grasping-and-manipulation-assembly

- Datasets
- Gripper/hand test methods
- Assembly test methods
- Replication documentation
- IEEE RHGM TC meeting notes and presentations