Grasping and Manipulation Performance Measures and Benchmarking

Joe Falco, Karl Van Wyk, Elena Messina, Kenny Kimble
Intelligent Systems Division
National Institute of Standards and Technology

Agenda

- Overview of NIST Benchmarking work
  - Grasping and Manipulation (elemental level)
  - Robotic Assembly (functional/task level)

- Participant discussion of related work

- Formulation of a unified effort

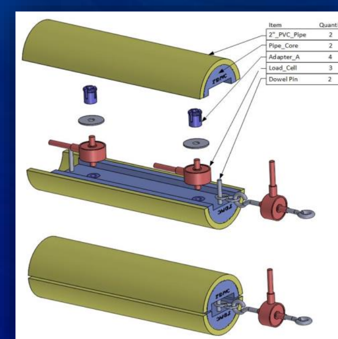
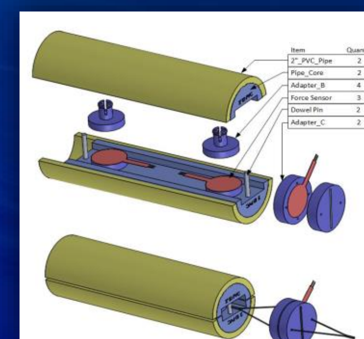
NIST Goals

- Develop metrics, test methods and artifacts with example datasets to characterize the performance of grasping and manipulation with emphasis on deployment for manufacturing tasks.
- Provide the robotics community with unbiased measurement methods for both elemental characteristics and function-level performance capabilities.
- Short Term: Provide researchers and developers insight for improving their hardware and software designs
- Long Term: Used to develop specifications that will help match capabilities to end-user manufacturing needs

NIST Testbed

- Hands/Grippers
  - SCHUNK Dexterous Hand II
  - ROBOTIQ 3-Finger Gripper
  - Wonik Robotics Allegro Hand
  - Empire Robotics VERSABALL Gripper
  - Soft Robotics Inc.
  - Conventional parallel grippers
- Tactile Sensors
  - Syntouch BioTac, BioTac SP, & Numatac
  - OptoForce 3D Force sensors
  - ATI Industrial Automation Nano17 F/T transducers
  - Weiss Robotics Tactile sensors
- Arms
  - KUKA LWR 4+
  - Universal Robots UR5, UR10
  - ABB YuMi
  - Rethink Robotics Baxter

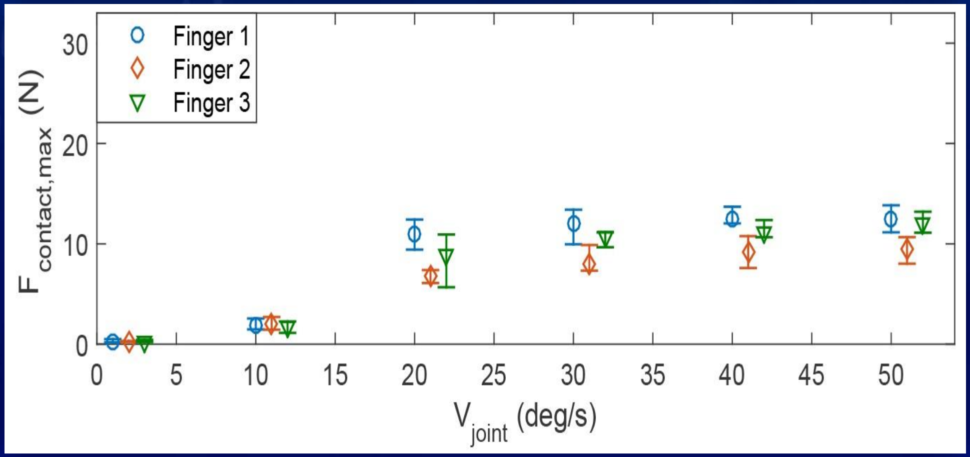
Elemental Test Methods

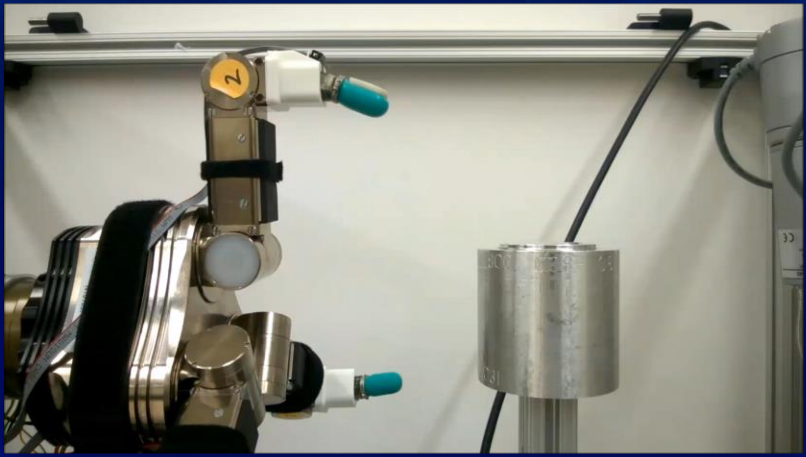
Test Method	*Measurement Instrument*
Finger Strength Touch Sensitivity Finger Force Tracking Force Calibration	
Grasp Strength Slip Resistance Grasp Efficiency Cycle Time	 
In-Hand Manipulation Object Pose Estimation	

http://www.nist.gov/el/isd/grasp.cfm

Touch Sensitivity

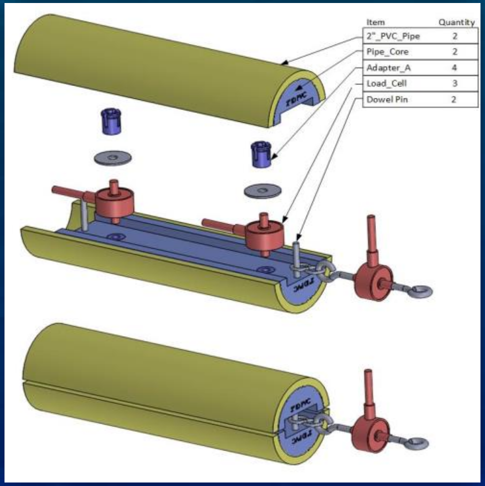
- What: A measure of the smallest, self-registered contact force exerted by a robotic finger on an object
- How: Measure maximum impact force at full finger extension at various joint speeds
- Why: Force dependent on speed, force maximized at full extension, minimize disturbance during object acquisition

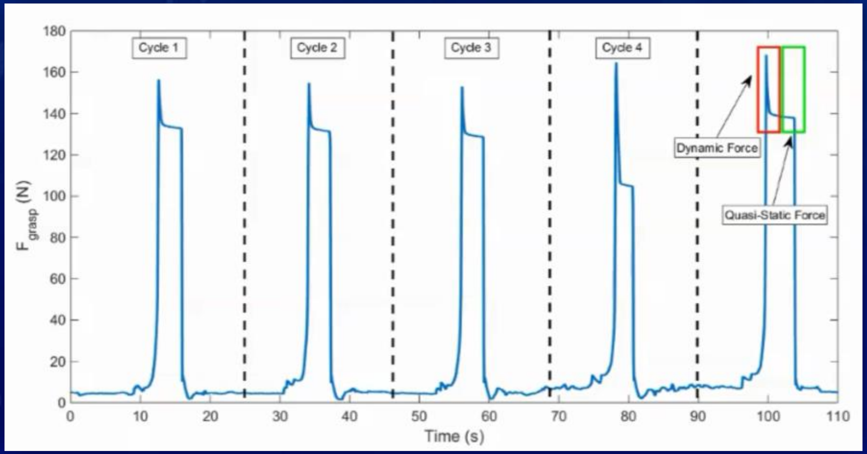




Grasp Strength

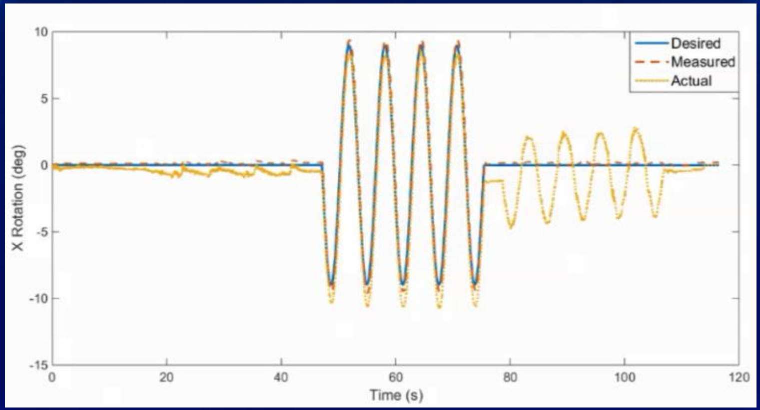
- <u>What:</u> The maximum force a robotic hand can impose on an object
- <u>How:</u> Artifact with intrinsic force sensing
- <u>Why:</u> Estimate payload

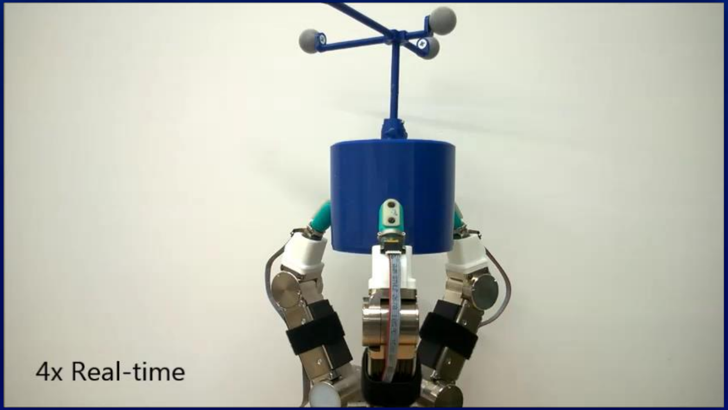




In-Hand Manipulation

- What: Measure of a robotic hand's ability to control the pose of an object
- How: MoCap system and objects with optical targets
- Why: Quantifies range-of-motion, frequency response, controller accuracy and repeatability, useful for functional-level tasks





Functional Performance Testing

- 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

https://www.nist.gov/programs-projects/performance-metrics-and-benchmarks-advance-state-robotic-assembly

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, fitting 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 board

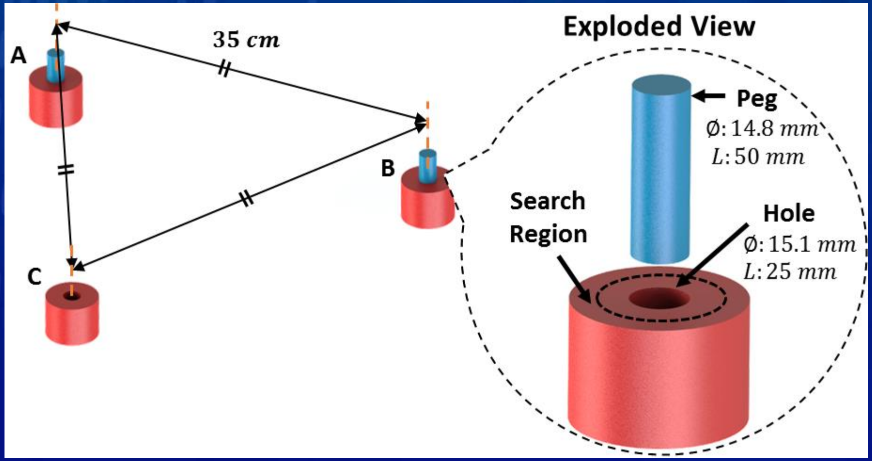
Data Analytics

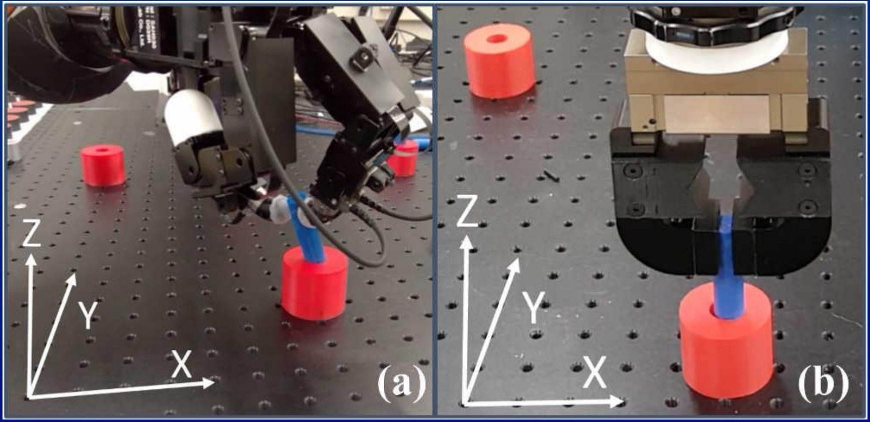
- Ordinal or Attribute Data
  - Detecting statistical difference in datasets – Kolmogorov-Conover
  - Check for differences as a whole or on a per rank basis
  - Primary performance measure: probability of success (PS)
- Continuous Data
  - Detecting statistical difference in datasets – Kolmogorov-Smirnov
  - Check for differences between sample means and variances
  - If no detectable differences, difference exists somewhere else (skewness, kurtosis)
- Matlab, R

http://www.nist.gov/el/isd/software.cfm

Example Peg-in-Hole

- 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

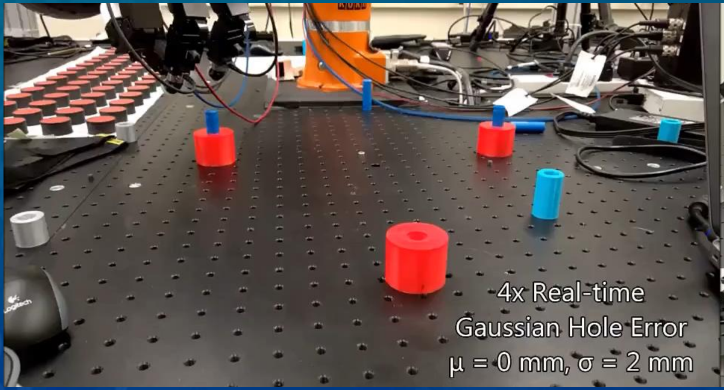




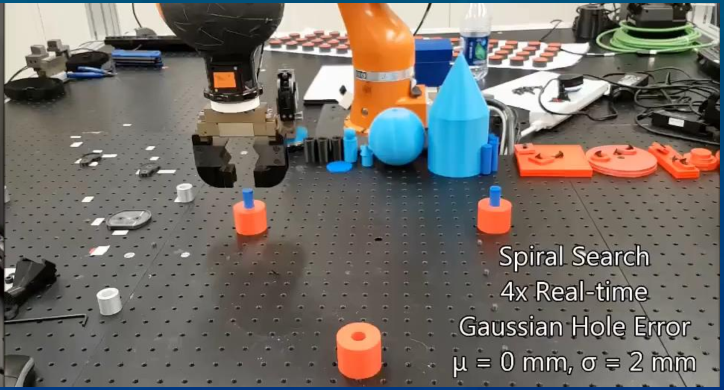
System 1 System 2

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,* DOI: 10.1109/TRO.2018.2791591.

Example Peg-in-Hole



System 1



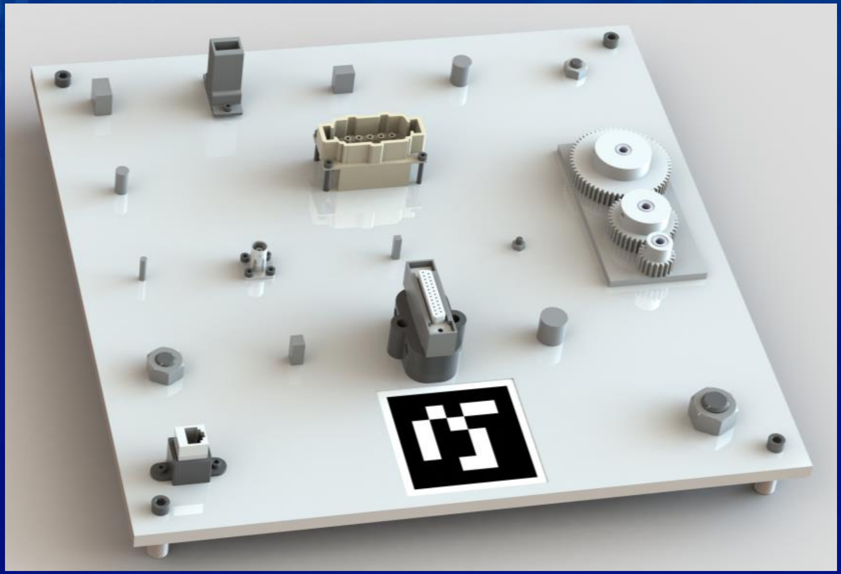
System 2

Robotic System	Correlation	KS	μ (s)	σ^2 (s)	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

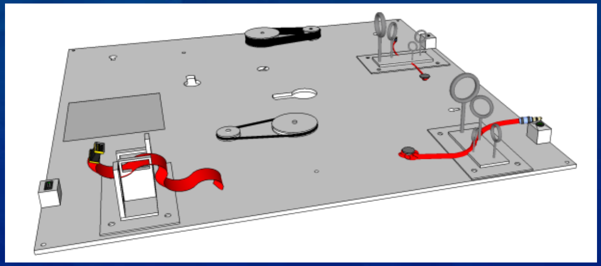
*Indicates statistical significance in comparison with System 1.

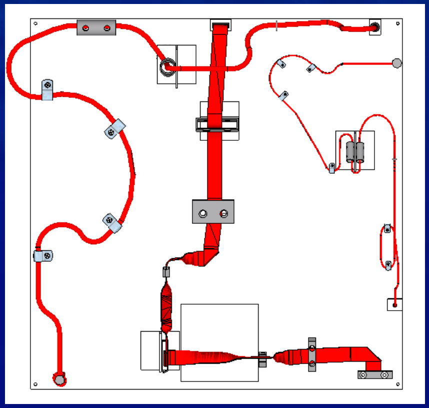
Task Boards

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



Task Board #1

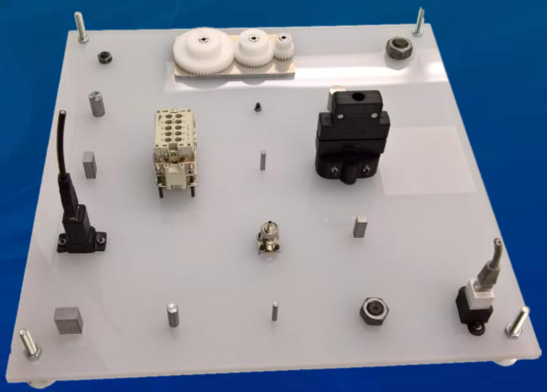


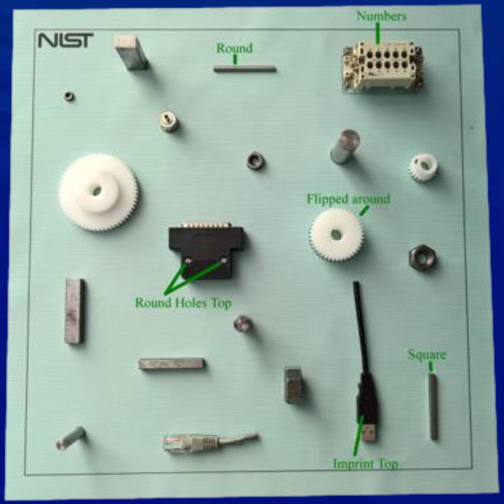


Concepts

Task Board #1

- Focuses simple insertions, nut threading, gear meshing, plug connections
- Design intersection
  - Spans DFA tables
  - Real components
  - Low-cost
  - Internationally replicable
- IROS 2017 competition
- Distribution





Documentation

- Grasping and Manipulation
  https://www.nist.gov/programs-projects/performance-metrics-and-benchmarks-advance-state-robotic-grasping
- Robotic Assembly
  https://www.nist.gov/programs-projects/performance-metrics-and-benchmarks-advance-state-robotic-assembly
- Working Publications – (*NIST Special Publication Format)*:
  Terminology document – Proposed Standard Terminology for Robotic Hands and Associated Performance Metrics
  Test method document – Performance Metrics and Test Methods for Robotic Hands

Publications

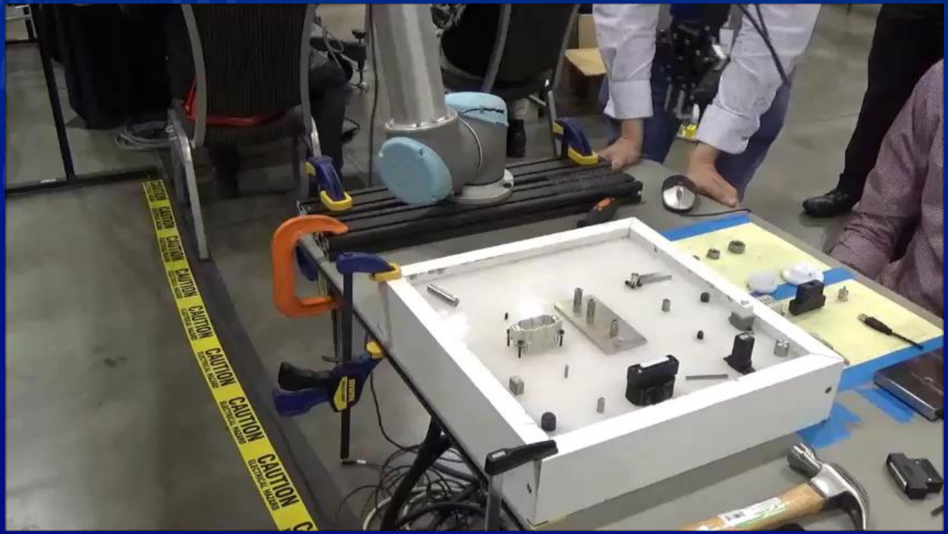
- K. Van Wyk, M. Culleton, J. Falco, K. Kelley, "Comparative Peg-in-Hole Testing of a Force-based Manipulation Controlled Robotic Hand", *IEEE Transactions on Robotics, 2018,* DOI: 10.1109/TRO.2018.2791591.
- J. Falco, K. Van Wyk, S. Liu, S. Carpin, "Robotic Grasping: Facilitating Replicable Performance Measures via Benchmarking and Standardized Methodologies", *IEEE Robotics and Automation Magazine*, December 2015.
- Stefano Carpin, Shu Liu, Joe Falco, Karl Van Wyk, "Multi-Fingered Robotic Grasping: A Primer," *arXiv* 1607.06620, online.
- Shneier, Michael, et al., "Measuring and Representing the Performance of Manufacturing Assembly Robots", *NIST Interagency/Internal Report (NISTIR)-8090*, 2015.
- J. Falco, J. Marvel, R. Norcross, K. Van Wyk, "Benchmarking Robot Force Control Capabilities: Experimental Results", *NIST IR 8097*, January, 2016.
- Falco, J., Marvel, J., Messina, E., A Roadmap to Progress Measurement Science in Robot Dexterity and Manipulation, NISTIR 7993, May 2014.
- Falco, Marvel, J., Messina, E., Dexterous Manipulation for Manufacturing Applications Workshop, NISTIR 7940, June 2013.

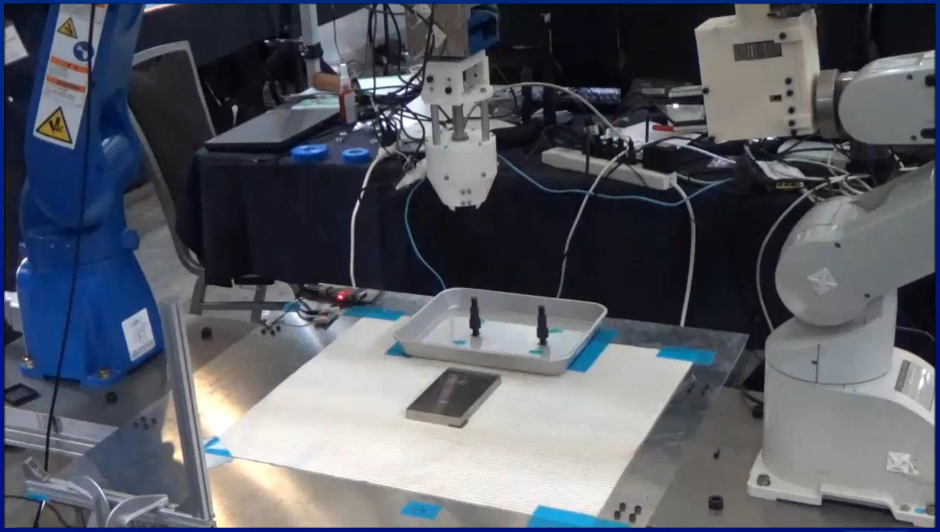
Competitions

- Mechanism for introducing benchmarking concepts to the research community in a competitive environment
- IROS 2016 household tasks with some manufacturing tasks introduced
- IROS 2017 dedicated manufacturing track
- World Robot Summit (WRS) Industrial Robotics 2018
- IROS 2019 - TBD
- WRS Industrial Robotics 2020
- European Robotics League

IROS 2017

- Robotic Grasping and Manipulation Competition: Manufacturing Track https://www.nist.gov/el/intelligent-systems-division-73500/robotic-grasping-and-manipulation-competition-manufacturing





WRS 2018

- WRS 2018 World Robot Challenge (WRC) Industrial Robotics Category
http://worldrobotsummit.org/en/wrc2018/industrial/

Related Work

- Yale-CMU-Berkley (YCB) Object Benchmarks for Robotic Manipulation
- Advanced Robotics for Manufacturing (ARM) Institute
- Berkeley led open discussion of robot grasping benchmarks, protocols and metrics
- UMass Lowell – NERVE Center
- Other?

Formulation of Unified Effort

- Propose unifying efforts with regular meetings under IEEE RHGM TC
- Periodic NIST hosted online
  - What is an appropriate frequency?
  - Sub-focus areas/sub-working groups could meet independently
- Yearly face-to-face at an IEEE robotics conference
- Consensus on tests, metrics, analyses will facilitate benchmarking
- Working publications as precursors to standards efforts
- Competitions