

# Comparative Peg-in-Hole Testing of a Force-based Manipulation Controlled Robotic Hand

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**Abstract**—This work demonstrates the first instance of a recently developed manipulation controller applied to a multi-fingered robotic hand for solving a peg-in-hole task. The active force control strategy was applied to a four-fingered, sixteen degree-of-freedom robotic hand with six-axis force-torque transducers at the fingertips. The robotic hand actively controlled the full Cartesian pose of the peg, enabling the tilting and aligning of the peg with the hole. Results indicate that the strategy is competitive with more typical search routines deployed on a robotic arm under impedance control.

**Keywords:** manipulation, grasping, performance testing

## I. BACKGROUND

Multi-fingered robotic grasping and manipulation is an active area of research that requires much advancement before the technology can be applied to real-world problems. At its core, grasping and manipulation operations can be mathematically casted by seeking to control the Cartesian pose of an object in the environment. Typical approaches to this problem are either kinematic [1] or kinetic in nature [2]. This work presents experimental results on a force-based manipulation controller that was recently developed [3], applied to a peg-in-hole task. Results are compared to more standard solutions to peg-in-hole that involve searching with the end-effector with a compliant or force-controlled arm [4].

## II. IMPLEMENTATION AND RESULTS

### A. Sensing and Control

The control architecture was successfully implemented on a four-fingered, sixteen degree-of-freedom robotic hand as shown in Fig. 1. The control architecture features a centralized manipulation controller and independent Cartesian force controllers for each finger. The sensing suite includes a touch-based object pose estimation algorithm, 3D fingertip force, 3D fingertip normal force direction, and 3D fingertip center of pressure. All sensing and control rates operated at a nominal 333 Hz.

### B. Robotic Systems and Strategies

Two robotic systems were tested: 1) a 7 degree-of-freedom, Cartesian position controlled arm with a four-fingered robotic hand (System 1), and 2) a 7 degree-of-freedom, Cartesian impedance controlled arm with a pneumatic, parallel gripper (System 2) as shown in Fig. 2. System 1 conducted the test with the hand actively controlling the

pose of the peg, and coordinating motions with the arm using the aforementioned sensing and control technology. Upon peg acquisition, the hand tilts the peg before an insertion attempt to induce peg-hole contact force profiles that guide the preliminary alignment. Afterwards, the hand vertically re-aligns the peg with the hole, and the hand and arm insert the peg, while minimizing peg-hole contact forces and peg pose control error. System 2 conducted the peg-in-hole test by coupling the arm's impedance properties with one of several search routines including spiral, random, and pseudorandom.

### C. Peg-in-Hole Test Method and Metrics

The test method consisted of three equally distanced holes at 35 cm apart. Non-chamfered peg and hole diameters were uniformly 14.8 mm and 15.1 mm, respectively. Peg and hole heights were 50 mm and 25 mm, respectively. The test initializes with two pegs placed into two holes. The goal is to consecutively transfer a peg into the open hole in a circular fashion. The planar hole location prior to every insertion attempt is intentionally misaligned by adding noise in both the X and Y directions, simulating perception error. Noise in both directions were drawn from two distributions: a Gaussian distribution with 1) zero mean and 1 mm standard deviation ( $\sigma_1$ ), and 2) zero mean and 1 mm standard deviation ( $\sigma_2$ ). The test was conducted for 60 attempted insertions, where the X-Y perception error was the same across both systems for all insertions.

The performance measures for this test involve statistically analyzing the insertion times across all systems. First, an autocorrelation coefficient of lag one ( $r_1$ ) is calculated for every data set to verify that the collected samples are statistically independent. Next, a Kolmogorov-Smirnov (KS) test is conducted to determine whether or not the distributions of two data sets are significantly different. The Levene test with the Brown-Forsythe statistic is used to determine if the variances ( $\sigma^2$ ) of two data sets are significantly different. Depending on this outcome, the appropriate variant of the t-test is applied to determine if there is a difference in the sample means ( $\mu$ ). Finally, the probability of success (PS) of inserting a peg is calculated, and the Kolmogorov-Conover algorithm [5] is used to determine if there exists a statistical difference between the PS of two systems. The statistical tests were conducted across the data sets at a 95% confidence level.

### D. Results

General remarks on the results reported in Tables I and II are three-fold. All data sets are sufficiently uncorrelated

with low  $r_1$  values, satisfying an underlying assumption for all subsequent statistical tests. The performance distribution of System 1 was different from all variants of System 2 as indicated by KS. The probability of inserting a peg for System 1 was statistically equivalent to all variants of System 2 despite the fact that System 1 experienced insertion failures, while System 2 did not.

When the systems conducted the test with perception error  $\sigma_1$ , System 1 did not outperform any System 2 variants, but did perform similarly to System 2 with random search in both mean and variance of insertion times, and the likelihood of insertion. System 2 with pseudorandom search outperformed all others in mean and variance of insertion times. When conducted with perception error  $\sigma_2$ , System 1 outperforms System 2 with spiral search in mean and variance of insertion times, while performing similarly to System 2 with random search. Again, System 2 with pseudorandom search outperforms all others in mean and variance of insertion times.

Encouragingly, the results indicate the beginnings of a much more generalized robot system with multi-fingered manipulation outperforming a simpler, specialized system. Although not discussed here, an ancillary benefit for System 1 include peg-hole interactions forces of less than 0.5 N, whereas System 2 created visible scarring on both the peg and outer surface of the hole. Furthermore, System 1 can be immediately adapted to objects of widely different geometries, while System 2 is more limited.

### III. FUTURE WORK

Future efforts include testing the robotic hand and control strategy on a more diversified set of insertion, fastening, and assembly operations using standard parts when available. Manipulation controller response can also be further improved.

### DISCLAIMER

Certain commercial equipment, instruments, or materials are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

### REFERENCES

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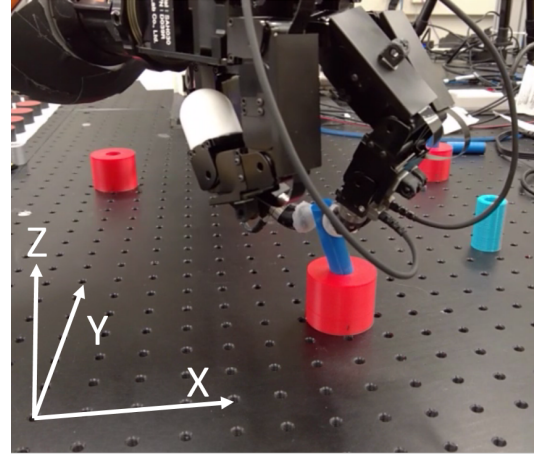


Fig. 1. System 1 with robotic hand completing a peg insertion.

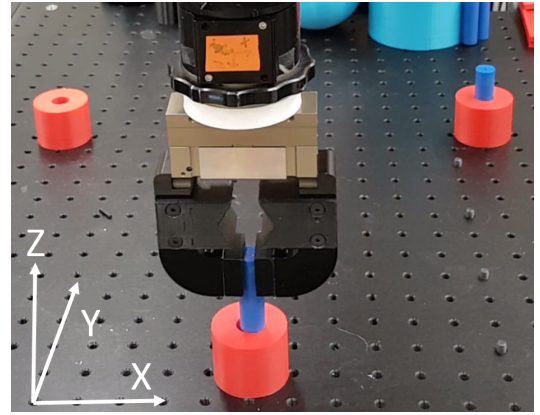


Fig. 2. System 2 with parallel gripper completing a peg insertion.

TABLE I

PERFORMANCE MEASURES OF ROBOTIC SYSTEMS ON PEG-IN-HOLE TASK WITH PERCEPTION ERROR  $\sigma_1$ . (\*) INDICATES STATISTICALLY SIGNIFICANT DIFFERENCE WHEN COMPARED TO SYSTEM 1.

System	$r_1$	KS	$\mu$ (s)	$\sigma^2(s^2)$	PS (%)
1	-0.01		11.70	40.57	85.4
2, Spiral	0.15	*	7.19*	12.79	95.2
2, Random	-0.04	*	8.01	59.92	95.2
2, Pseudo-random	-0.04	*	3.11*	8.84*	95.2

TABLE II

PERFORMANCE MEASURES OF ROBOTIC SYSTEMS ON PEG-IN-HOLE TASK WITH PERCEPTION ERROR  $\sigma_2$ . (\*) INDICATES STATISTICALLY SIGNIFICANT DIFFERENCE WHEN COMPARED TO SYSTEM 1.

System	$r_1$	KS	$\mu$ (s)	$\sigma^2(s^2)$	PS (%)
1	0.08		18.31	107.3	87.6
2, Spiral	0.07	*	37.13*	399.6*	95.2
2, Random	-0.01	*	15.62	417.72	95.2
2, Pseudo-random	-0.11	*	8.2*	50.25*	95.2