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Analysis of human Peg-in-Hole Executions in a Robotic Embodiment using uncertain Grasps

Thiusius Rajeeth Savarimuthu*, Danni Liljekrans*, Lars-Peter Ellekilde*,
Ales Ude†, Bojan Nemec† and Nobert Krüger*
∗ Maersk Mc-Kinney Moller Institute, University of Southern Denmark
† Jožef Stefan Institute, Department of Automatics, Biocybernetics, and Robotics, Slovenia

Abstract— **In this paper, we perform a quantitative and qualitative analysis of human peg-in-hole operations in a tele-operating setting with a moderate degree of dexterity. Peg-in-hole operation with different starting configurations are performed with the aim to derive a strategy for performing such actions with a robot. The robot is a 6 DoF robot arm with the dexterous 3 finger SDH-2 gripper. From the extracted data, we can distill important insights about (1) feasible grasps depending on the peg's pose, (2) the object trajectory, (3) the occurrence of a particular force-torque pattern during the monitoring of the action and (4) an appropriate insertion strategy. At the end of the paper, we discuss consequences for using these insights for deriving algorithms for robot execution of peg-in-hole actions with dexterous manipulators.**

I. INTRODUCTION

Programming by Demonstration (PbD) [1], [2], [3] has proven to a be powerful tool to teach robots to perform complex tasks. An important issue of PbD is the level on which the knowledge transfer is performed. A relatively straightforward way is the transfer of trajectories which can be relatively easily done in constrained environments as frequently occurring in a production context, for example by directly moving the robot such that it performs the task in the specific context (kinesthetic guidance). However, the establishment of sufficiently constrained environments comes with an engineering cost and a good part of nowadays production research tries to loosen the requirements of such constraints. One important research direction is the utilization of a higher degree of dexterity than usually occurring in nowadays industrial grippers [4]. With a larger degree of dexterity, the robot can adapt to a larger variety of situations and but it also increases uncertainties in the assembly process since usually the control over the object is weaker than in nowadays used industrial grippers.

Once operating in less constrained environments (e.g., unknown object poses) and/or using embodiments with a high degree of dexterity, a direct approach of trajectory learning is not feasible anymore. The reasons for that are twofold: First, the trajectory depends on the starting configuration (e.g., the pose of the objects). Second, even when a pose can be determined with a high precision and a trajectory can be adapted accordingly, using dexterous gripper devices, the force control over the object is weaker. This is in particular due to slip caused by in general lower forces applied as well as the non exact matching of finger and object shape. Hence, when using dexterous grippers, a strategy that is able to deal with such uncertainties needs to be derived. In this paper, we analyze peg-in-hole operations of humans performed in the embodiment of the robot (i.e., in a tele-operating like setting) with a 'moderate' degree of dexterity. 'Moderate' refers to a still low number of fingers and joints of the used SDH-2 hand (see figure 2) compared to the, e.g., human hand.

The tele-operating control is rather intuitive allowing the user to 'act naturally', hence allowing to transfer former human experience and intelligence into the tele–operated process. By that, we are able to characterize the strategies humans apply to deal with uncertainties connected in particular to the uncertainties connected to the dexterity of the embodiment. We even show that the human makes constructive use of this dexterity by, e.g., purposefully using slip when this is of advantage for the assembly process.

In assembly tasks there are two primary subtasks. One is the grasping of objects and the other is the actual physical interaction of objects in an assembly operation. Adult humans have learned and posses intuitive skills in both grasping and performing the actual assembly tasks. The aim of the current paper is to analyze and utilize human assembly skills for robot control in the context of peg-in-hole operations with dexterous devices in the tele–operating setting shown in figure 2. By analyzing (1) the way humans grasp the object, (2) execute trajectories and (3) make use of force-torque information occurring during the execution, we will derive a strategy which can also be used to automate the task on a robot.

For this, we realize the tele-operating setting as indicated in Fig. 2 and perform a total of 170 executions of peg-in-hole operations with different combinations of starting conditions. In one experiment (see figure 1, experiment 1), a larger peg was used thereby making the difference between peg diameter and hole very small leading to a tight fit. The peg-in-hole operation with that object thus involved quite some difficulty in sliding the peg into place. The experiments with the smaller size peg (see figure 1, experiment 2–5) includes a lying starting pose and also trials performed by novice users with limited training.

In the context of defining a robot control strategy, such a tele-operating setting has at least one advantage compared to

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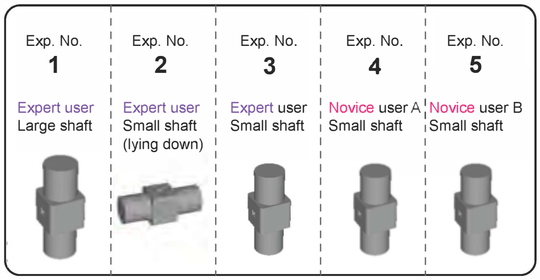


Fig. 1. Overview of the five experiments performed.

Fig. 2. The tele–operating setup with the hand-mounted sensor and the Universal Robots arm.

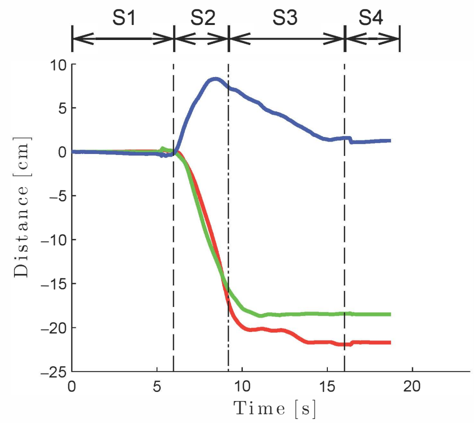


Fig. 4. Position data for peg (offset to start in zero). The red, green and blue shows x, y and z position data of the peg respectively. The vertical black lines define the boundaries for the segments in Fig. 5.

a free execution of assembly tasks by humans with their own embodiment: The human skills are executed already in the embodiment that the execution has to be performed in. Hence the mapping to the robot should be easier than for example when the human uses his/her five finger hand which would need to be mapped to the three finger hand of the robot. We found that the human user rather quickly learns to operate in the tele-operating setting.

In summary, we made three important findings:

F1 **Grasping:** When standing, the peg was in general grasped with the three finger ball grasp as indicated in Fig. 3a, while when lying it was grasped with a two finger pinch grasp as indicated in Fig. 3e. In the first case, the grasp was very stable which allowed optimal force control. This optimal grasp was not executable in a situation when the peg was lying. In this case, the object was grasped side-ways (and slightly tilted, approximately 20 degrees from vertical), which allowed for a peg-to-hole insertion with sufficient space for operation.

F2 **Approach:** In the approaching phase, the angle distance relation shows that users tilts the peg in its approach in a rather systematic way.

F3 **Insertion:** The insertion phase is guided by the occurrence of a sideways force that aids the human in maintaining a correct position of the peg relative to the hole. This particular force-event is recognizable prior to the angle-alignment between the peg and hole, in particular for the peg with a tight fit due to the increased necessity for a proper alignment.

The paper is structured as follows. In section II, we give a brief overview of the state of the art in learning by demonstration with focus on peg-in-hole operations. In section III, we describe the tele-operating setting in more detail and present our experiments. In section IV, we analyze the data generated by the human operators and distill from the analyzed data a qualitative strategy that can be transferred into a robot control strategy.

II. State of the Art

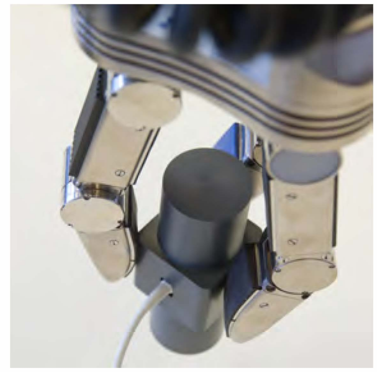
Executions of peg-in-hole operations is one of the classic problems in the domain of robotics and a great deal of research has gone into solving this problem in a general way [5]. In an industrial context, peg-in-hole is considered to represent a large class of assembly tasks [6] which increases the incentive to solve the problem generically. Peg-in-hole can be seen as a "solved problem" in case that the starting conditions are fully known and optimized force control can be achieved. This however can not be assumed in a general setting with significant uncertainties of object pose (when, e.g., extracted by vision) and in particular when using dexterous grippers with only limited force control leading to, e.g., slip in the assembly process. Actually, as we will show, humans use effects such as slip purposefully in the insertion phase when operating in the tele-operating system.

In this paper, we investigate a human peg-in-hole strategy using a tele–operation approach. Tele–operation has been used by others in the context of learning robotic movements, e.g., [7] where tele–operation of a robot is used to learn a reach-grasp-pull-retract task from human demonstration using Hidden Markov Models (HMMs). During a number of repeated experiments, the system monitored the internal states of the robot and they were able to extract a canonical representation of the task from six demonstrations.

Another example of tele–operation is described in [8]. A dexterous 3-finger hand was tele–operated with the purpose of grasp learning. They experienced difficulties in controlling

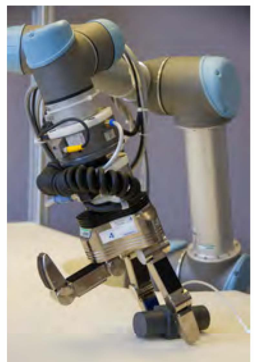
(a) Three finger ball grasp.

(b) Two finger pinch grasp.



(c) Three finger cylinder grasp.

(d) Three finger ball grasp



(e) Two finger pinch grasp.

(f) Three finger cylinder grasp.

Fig. 3. Grasp configurations for grasping the peg. Subfigures (a)-(c) shows grasps used for a peg standing up. Subfigures (d)-(f) shows grasps for a peg lying down.

the dexterous hand, due to different degrees of freedom than those of the human hand. The operator used his pinkie to control the spread of the gripper's fingers but it was not intuitive although perhaps necessary for some tasks.

In relation to learning peg-in-hole operations, although not in a learning-by-demonstration context, [9] investigated the influence of passive compliance in the learning of peg-in-hole tasks. They found that learning is achieved faster with a passive compliance setup. A three joint robot system was used for peg-in-hole in a 2D scenario. Passive compliance is best known from humans, where muscles act on external forces by adaption. Dedicated compliance devices will not be used in our paper, however the platform has a small degree of passive compliance in a $100mm$ thick layer of foam on the experiment platform table (see figure 2). This foam deforms under occurring forces and the deformation can be observed visually by the operator.

As opposed to passive compliance, active compliance does not use a dedicated compliance device but rather utilize force feedback in the controller. This can be done either using impedance or a hybrid controller. The hybrid control combines pure position and pure force control, where the position and force controlled subspaces are orthogonal. In [10], it has been shown that the stability of the tele–operated task can be significantly improved by applying impedance control to the tele–operated robot arm.

In the work presented in [11], a lightweight robot is programmed by the human using kinesthetic guidance. Here the purpose is to teach the robot the trajectory for the execution of a piston into a engine block. During teaching, the teacher physically grasps the robot close to TCP and move around with it. By changing the stiffness of different links, the system designer can guide the teacher to move the robot in the desired joints or directions. E.g., if the robot is supposed to learn positions and not orientations, the stiffness for the orientation control can be increased and hence be made more difficult to manipulate for the teacher. The work [11] shows that peg-in-hole task can be learned, however under the condition that there are no or only a very little degree of uncertainties. Furthermore in [11] the object (piston) is pre-grasped and only the actual insertion is learned. In our paper, we also investigate the grasping which we found to be related to the concrete the peg-in-hole task.

The objective of this paper is to use tele–operation in order to acquire insights about how a human performs the peg-in-hole action in such a context. The aim is, based on these insights, to qualitatively describe a strategy that can be transferred to a robot control program. To our knowledge – although peg–in-hole actions have been investigated in a learning by demonstration context (see, e.g., [11]) – this paper is the first investigation of human peg-in-hole strategies that utilizes a dexterous hand in a tele-operation setting.

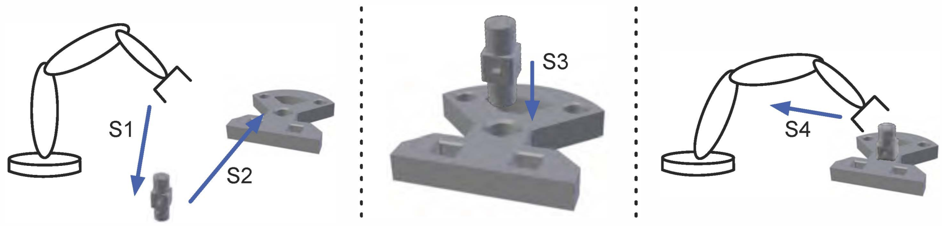
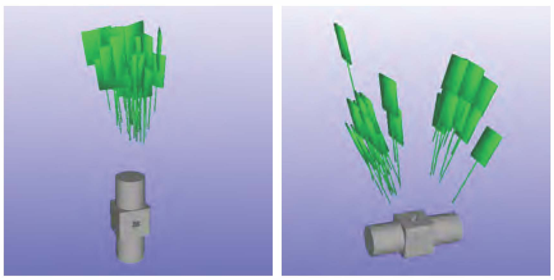


Fig. 5. Four segments of a trial. In S1 the gripper is moved closer to the peg such that it can be grasped. In S2 the peg approaches the hole. In S3 the peg is inserted and finally in S4 the gripper retracts from the peg.



(a) Grasps for the standing peg. (b) Grasps for the lying peg.

Fig. 6. Stick-figures showing how the peg was grasped from a standing and a lying position respectively.

III. METHOD

This section is divided into two subsections. First, an overview is given in subsection III-A which describes the setup and the experiments. Subsequently, the actual findings are described in subsection III-B in terms of the three findings F1–F3 discussed in the introduction: F1) Grasping, F2) Approach and alignment and F3) Insertion. A more detailed report on the setup, experiments and findings can be found in [12].

Two pegs with different diameters were used with the same hole-object for this work. The peg's diameters are $40mm$ and $42.4mm$ and the hole's diameter is $43mm$. The larger object poses a substantially more difficult problem, with a slack of only $0.6mm$. Besides working with this more difficult problem, experiments were also performed with the smaller peg from an initial lying position. Furthermore, to compare the experiments performed by an expert user, who has worked substantially with the system, two novice users who were trained for 10 minutes each, also carried out experiments as well. In total, five experiments were conducted (see Fig. 1): expert trials with the large peg (1) and expert trials with the normal peg from a lying position (2). In these two experiments, the peg and hole objects were moved to a random starting position between each trial. Trials in which both pegs, hole and robot start from a fixed starting position were also performed. These trials were done by the expert user (3) and two novice users (4 and 5). The numbers in parenthesis correspond to the numbers in Fig. 1.

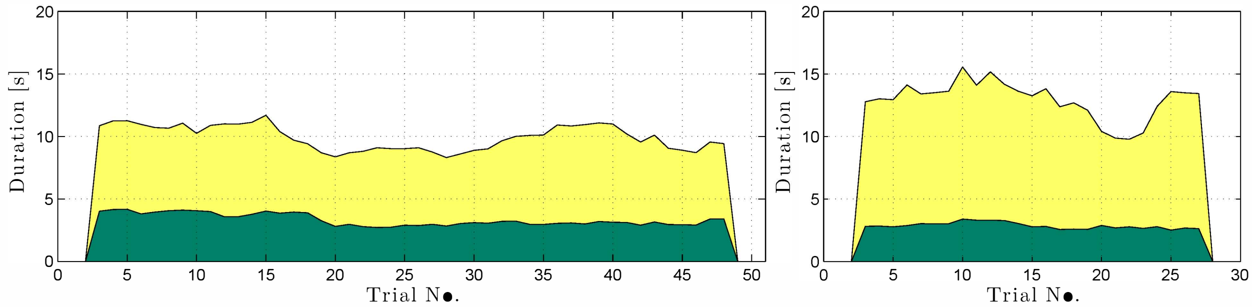
A. Overview, experiments and segmentation

The approach to investigate human peg-in-hole strategies taken in this work has been to let a human demonstrator control the 6DoF robot arm UR5 from Universal Robots [13] with the dexterous gripper SDH–2 mounted (see Fig. 2 and the video [14]). Note that a force torque sensor is mounted between the robot flange and the SDH–2 hand. Hence the peg-in-hole experiments is performed in the robot embodiment. The motion of the demonstrator's hand is captured using the trakSTAR 6D motion tracking system[1]. The motion is then directly transferred to the robot end-effector allowing for an intuitive control. The human operator can choose between three different grasp types (see Fig. 3) before an experiment is initiated. The chosen grasping strategy is then controlled binarily (open/close) with the demonstrator's index-finger, where an additional tracking sensor is mounted. The three types of grasps (see Fig. 3) cover 1) a three finger ball grasp, 2) two-finger pinch grasp and 3) three-finger cylinder grasp. The grasps are shown for standing pegs (top row) and lying pegs (bottom row) in Fig. 3) before an experiment is initiated. The chosen grasping strategy is then controlled binarily (open/close) with the demonstrator's index-finger, where an additional tracking sensor is mounted. The three types of grasps (see Fig. 3). These grasp types were tested in pilot experiments to investigate the most stable and intuitive grasps for both standing and lying pegs. It was found that after a number of trials, the three finger ball grasp was chosen by a human operator for standing pegs while the 2-finger pinch grasp was chosen for lying pegs. These two grsaps were thus used in the subsequent experiments. The platform table, where the experiments are performed, is covered by a layer of foam used for protection. The visually perceived compliance of the foam can, however, also bn used for an indirect force-feedback method as will be described later.

An experiment trial consist of four phases or segments as shown in Fig. 5. The segments are S1: approach the peg with gripper, S2: move peg towards hole, S3: insert peg and S4: release peg and retract gripper. The segmentation of the acquired data is subsequently done automatically when the gripper closes (S1 to S2), the center of the peg is $100mm$ from the top of the hole (S2 to S3) and when the peg is released by the gripper (S3 to S4).

The position of the peg during a typical trial is shown in Fig. 4, where the blue line shows that when S2 starts, the peg is lifted (z-value), and the red and green lines show that the peg is moved from one position to another on the platform

[1] http://www.ascension-tech.com/medical/trakSTAR.php



(a) Normal peg, 50 trials (b) Large peg, 30 trials

Fig. 7. Trial durations (segment 2 in green and segment 3 in yellow) for easy and difficult problem respectively. Durations have been averaged (window size 5 trials).

(x- and y-values). The peg is only moving in the phases S2 and S3 due to the segmentation described above.

B. Findings

F1 Grasping: One contribution of this work is the acquisition of experimental task specific grasp data. The grasps are visualized with stick-figures. Each stick in Fig. 6 represents one grasp. The plate on the stick-figures represents the orientation of the gripper along its longitudinal axis. The stick-figures in Fig. 6a are from experiments with the three finger ball grasp as shown in Fig. 3a and the stick-figures in Fig. 6b are from grasps as shown in Fig. 3e.

An angle of the grasp relative to the lying peg of between 10-15 degree, as shown in Fig. 6b, was used in the context of both grasping and subsequently inserting the peg (see also F3 below).

F2: Approach: Durations for segment S2 (approach) and S3 (insertion) for experiments with the normal peg and the large peg are shown in Fig. 7. As expected, the approach phase is comparable for the two different pegs. However, the insertion phase in case of a lying peg is substantially longer due to the increased difficulty of the problem.

A main contribution of this work is the observation of the tilt-angle of the peg during the approach phase. This phenomenon is shown in Fig. 8 for the expert user and one novice user. For all trials the key alignment between the peg and the hole occurs at the $50mm$ mark on x-axis in Fig. 8.

The peg's tilt-angle, at the point where the peg-tip is just at the top of the hole, is shown for all five experiments in the boxplot in Fig. 9. In effect, the boxplot presents the same data as shown in Fig. 8, but only at the $50mm$ mark for all five experiments. The two plots in Fig. 8 correspond to experiment (3) and (4) in Fig. 9 respectively. In Fig. 9 we see that the angle of the peg just before the insertion point is consistently above 10 degrees for the expert trials with the small peg (experiment (2) and (3)) and approximately 8 degrees for the large peg (experiment (1)). Also or the novice trials (experiment (4) and (5)), we notice a consistency in the angle.

Insertion: The tilt-angle plots in Fig. 8 shows both the approaches, but also the insertion strategy. For the large peg (i.e., the difficult problem), another strategy was observed

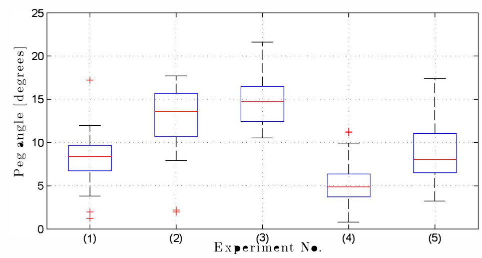


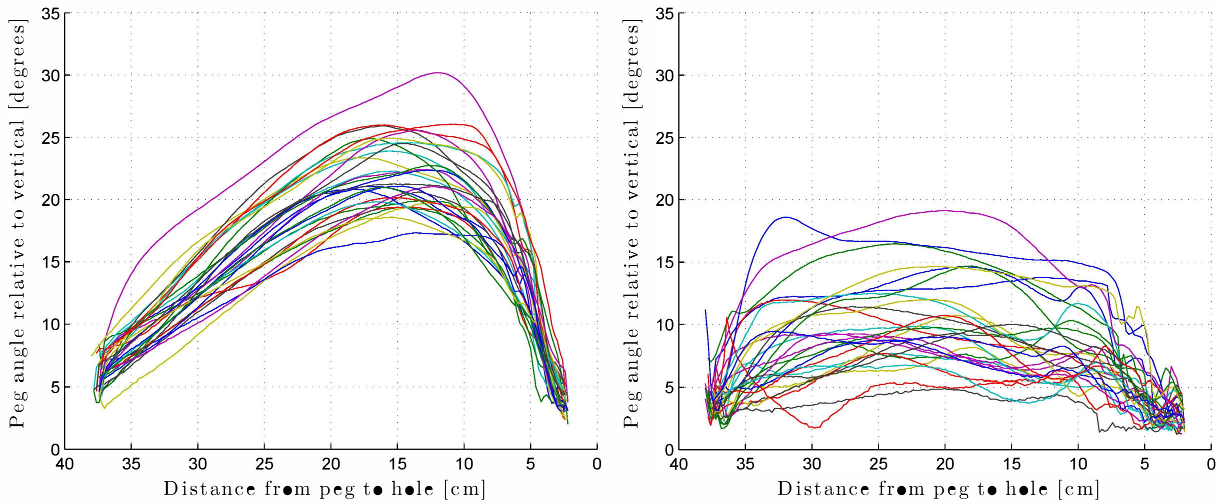
Fig. 9. Box plot showing the distribution of peg-angle at the time when the end of the peg reaches the hole. Expert trials are number 1, 2 and 3. Random starting positions are for trials 1 and 2, and fixed starting positions are for trials 3 to 5.

at the insertion phase, which is deduced from Fig. 10. This Figure shows the tilt-angle in the top, the downwards force in the middle and the sideways force in the bottom. All forces are measured using the force/torque sensors mounted between the robot and the hand.

It was observed that in 75% of trials with the large peg, that a small increase in sideways force occurs before the peg is aligned with the hole. In Fig. 10, the alignment is present at $52mm$ and the sideways guidance force is present from $59mm$ to $53mm$. Note that this particular force-pattern can be used to distinguish between a successful and an unsuccessful match between the peg and the hole.

An interesting observation in relation to the force-control was that users reported that an intuitive understanding of the relation between applied force and the compliance/compressibility of the foam which aided the insertion of the large peg. A large force applied with the peg would press the hole-object to move into the foam. The angle and way the hole-object is pressed into the foam indicates the direction of the force which could then be adjusted by the human. Hence this effect provides a force-feedback system.

A final contribution of the teleoperated approach is a demonstration of the users ability to utilize slip in the system. During insertion of the peg that was initially lying, the gripper is in a tilted pose (see figure 6b), a pose also less prone to collide with the platform. We observed that the operator utilized slip once the peg has just touched the hole, such that the gripper could be rotated towards a more vertical



(a) Expert operator with small peg.

(b) Novice operator C with small peg.

Fig. 8. Peg tilt-angle as a function of distance to the hole for trials in Experiment Set 2. Colouring is done to separate trials. The graphs stop before $x = 0mm$ because the distance is measured between the top of the hole and the center of the peg, which can never align completely.

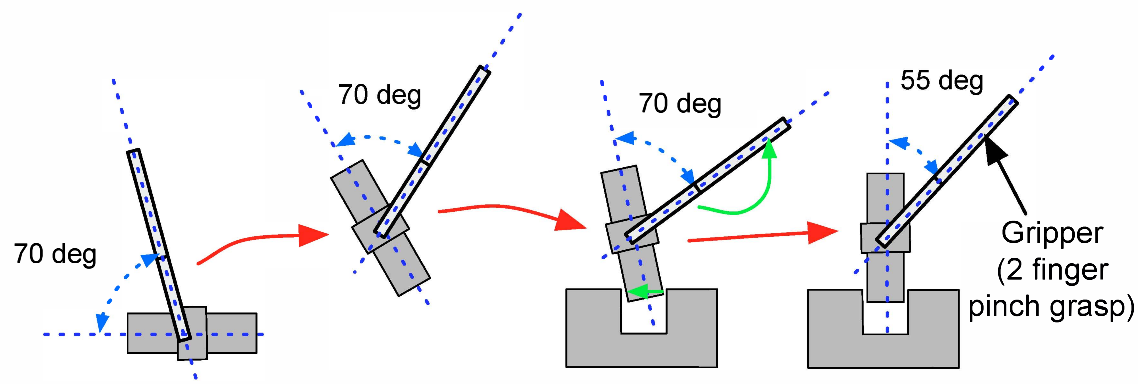


Fig. 11. Strategy observed in experiments with the lying peg. By rotating the gripper as illustrated by the top green arrow, and utilising the reaction contact force between the hole and the peg as illustrated by the small green arrow, the angle between the gripper and the peg decreases.

pose. This is shown in Fig. 11.

Comparing the angle between the gripper and the peg over the duration of a trial, the pattern as displayed in Fig. 12 emerges. The data shown starts when the gripper is initially moved in a trial and ends when the peg is released by the gripper. Fig. 12 indicates an initial angle of 80-110 degrees, which is when the peg is lying down and the gripper is approximately vertical, depending on the ending position from the previous trial. Next, the peg is grasped and the relative angle is constant (with slight tilt) for the period when approaching the hole. Finally, slip between the peg and gripper is utilized and the angle decreases before the peg is released.

IV. Discussion and Transfer to the Robot System

Summarizing the findings presented in this paper, the following contributions are made:

1) Task specific grasp data has been acquired experimentally. It shows the use of a three finger grip with tight force control in case of a standing peg while a lying peg - which is not graspable by such a three finger grip – is grasped with a two finger grasp in a tilted way to prevent collisions between gripper and platform in the insertion phase (see Fig. 6b).
2) The particular relation between the peg's tilt-angle and the distance to the hole shows a distinct strategy (see Fig. 8).
3) The force-picture that emerges, when the sideways force is used for guiding the peg into the hole indicates a second aspect of a human strategy (see Fig. 10). Also in the context of insertion of a peg lying on the table, we have shown the the human operator uses the slip between the peg and the gripper (see Fig. 11) to rotate the gripper to a more convenient pose when insertion the peg.

The first finding is easily applicable in a non tele–operated setting. The grasping data can be used directly by grouping them and taking e.g. an average which is then used directly for grasp recommendations for the robot system. The peg-tilt pattern can also be easily used to define a generic control strategy for example by defining a target tilt of the peg is

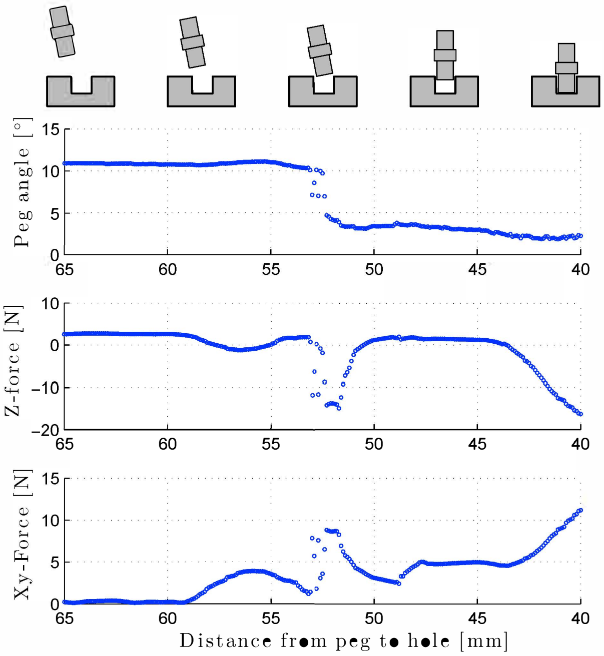


Fig. 10. Peg angle, z-force and the 2-norm of xy-forces from a trials with the large peg. The distance shown on the x-axis is from the top of the hole to the center of the peg. The pose of the peg relative to the hole is illustrated above the figure. Each peg/hole illustration corresponds to the scenario at the x-value where they are shown.

12 degrees when the peg tip is at the hole. The tilt can then be interpolated over the distance from the initial peg-position and to the target position. Rather interesting is also the observed utilization of slip. When using dexterous hands, slip will definitely occur and can be used constructively in the PiH operation. Finally, the force-pattern can be used to verify a position-relation between the peg and the hole. If the peg is not inside the hole when the sideways force is applied, the force picture will be different.

These are important finding for designing control strategies for a robot. In our current research, we aim to integrate these findings in a concrete robot control program for performing PiH actions with dexterous hands.

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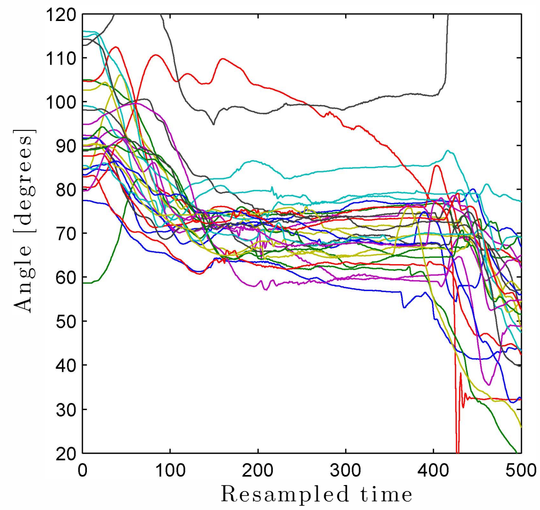

Fig. 12. Angle between longitudinal axis of peg and gripper for segments S1, S2 and S3.

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