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Preliminary Experiments of Kinesthetic Exploration in a 6 DOF Teleoperation System

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***Abstract*— A teleoperation system with kinesthetic feedback can provide operators with information so that they can make proper judgments as if they were in direct contact with the slave robot work environment. This paper presents the idea of testing the same haptics exploration tasks in both direct and teleoperation scenarios. This provides the advantage that lessons learned in experimental psychology can be used for future teleoperation systems' control and hardware design. One preliminary experiment is presented in this paper to demonstrate the concept. This experiment comprised of three sets of weight perception tasks. One set of direct hand exploration experiments were carried out first. Two sets of teleoperator based experiments, one with a basic two channel controller and the other with three channel controllers, were used to replicate the same set of experiments. Results from the experiments were compared and analyzed.**

I. Introduction

Teleoperators with kinesthetic feedback have seen applications in many areas, for example, outer space, deep ocean and high nuclear radioactive environment [13], [4], [7], [16]. An example of such teleoperation system is presented in [4]. Kinesthetics sensing is about the motion and force of muscles and joints while tactile sensing is about the touch between the fingers and the objects. Human direct hand kinesthetic sensing has been studied in experimental psychology for ages [1]. It would be very beneficial to apply some of the method used in earlier studies. Teleoperational weight perception has been studied in [16], its limitation is determined to be 3 lb (1.36 kg). A better kinesthetic feedback can improve the productivity of the system, a solution to improve the kinesthetic feedback in nuclear clean up was proposed in [13].

Teleoperation systems can extend the reach of human operators but it also compromises the sense of immersion. In other words, the teleoperation systems are not transparent to thet extent that humans can perceive as naturally as in the direct hand exploration. Many control architectures and control design methods have been proposed for teleoperation systems [18], [9], [8]. The most classic and robust one is the two channel position signal based PID controller, where only position signals from each side are transmitted to the other end, and the controllers compute the desired torque based on position error between the master and slave. Dynamics feedforward has been used in previous researches [12], but it is very notorious for amplifying the noise and an accurate modeling of the robot is required. Lawrence proposed his seminal four channel architecture where the force measurement terms are incorporated [10]. Hannaford summarized all possible control architectures and analyzed their transparency based on their transmitted impedance [15]. Psychophysics experiments are largely used in teleoperation control design [19]. Even though these analyses provided significant theoretical results, their data have not been compared with the direct hand kinesthetic exploration tasks. Also these transparency studies all focus on single degree of freedom systems. This paper considers a 6 DOF teleoperation system, which has far more application potentials.

Haptics refers to the sense of touch, including weight, temperature, inertia, stiffness perceptions and so on. It is one of the most classic research areas in experimental psychology. Haptics has two major sub-areas: kinesthetic [1] and tactile [11]. Previous research in experimental psychology has been conducted regarding kinesthetic exploration [1], but most is in tactile. Some methods and testing protocols will be used in this paper and extended to the teleoperation scenario in an effort to bridge the gap between these two areas [22]. There has been some research about the psychophysics evaluation of teleoperation systems [14] and [19], where researchers consider the environment as a virtual wall with stiffness and damping.

One of the first kinesthetic sensing tasks used in experiments is the weight and inertia perception. We adopted these experiment protocols as our major testing method. In teleoperation, many performance indices have been proposed by others [21]. Most of them are task dependent and difficult to generalize into other applications. Draper categorizes all the indices into two major categories in his human factor analysis paper [5].

II. Modeling and Control of Teleoperation Systems

The general control system architecture considered in this paper is given in Fig 1. C_1, C_2 and C_4 stand for the PID controller for the master robot, the PID controller for the slave robot and the force channel controller, respectively.

A. System Dynamics Modeling

For a robotic arm with n revolute joints in three dimensional workspace, all links are rigid and all torques are

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TABLE I: Summary of controllers used in the experiment

	C_1	C_2	C_4
Two channel controller	•	•	×
Three channel controller	•	•	•

applied at the joints, its dynamics are given by:

$$M(\theta_*)\ddot{\theta}_* + C(\theta_*, \dot{\theta}_*)\dot{\theta}_* + G(\theta_*) = \tau_* \qquad * = s, m \tag{1}$$

where θ is an $n \times 1$ vector that represents the configuration of the robot, $M(\theta)$ is a $6 \times n$ that represents the inertia matrix, $C(\theta, \dot{\theta})$ is a $6 \times n$ Coriolis matrix, $G(\theta)$ is an $n \times 1$ vector that represents the gravity and τ is also $n \times 1$ showing the torque applied at the joints. This equation describes dynamics of the "Slave Robot" and the "Master Robot" blocks in Fig. 1.

B. Control Architecture

The most commonly used controller for a bilateral teleoperation system is the two channel position-position controller. This control architecture will be used as a comparison group in our project, to show the superiority of the three channel controller.

$$\tau_* = K_*^p(\tilde{\theta}_* - \theta_*) + K_*^d(\dot{\tilde{\theta}}_* - \dot{\theta}_*) \qquad * = s, m \tag{2}$$

Where K^d and K^p represent the derivative and proportional gains of the system. Therefore, the close-loop dynamics of the manipulator are given by

$$\begin{aligned} &M(\theta_*)\ddot{\theta}_* + C(\theta_*, \dot{\theta}_*)\dot{\theta}_* + G(\theta_*) \\ &= K_s^p(\tilde{\theta}_* - \theta_*) + K_*^d(\dot{\tilde{\theta}}_* - \dot{\theta}_*) \\ &\qquad\qquad\qquad * = s, m \end{aligned} \tag{3}$$

We compared two types of control architectures in this project: a simple two channel controller as described in Eq. 3, and a three channel controller with force feedforward. As in Fig. 1 and Table I, the first type of controller is the case where C_4 is zeros, for the second type of controller, the only difference is that

$$C_4 = K_f \tag{4}$$

Which means that the master controller has an extra scaled force signal feedback to the operator. In the case where there is only two channel control, the force feedback is proportional to the position tracking error. So when the slave robot is handling a very heavy object, the tracking error between the slave and the master robots would be large, and therefore provide kinesthetic feedback to the operator that implies the weight information about the object. In the three channel controller case, the interacting force between the slave and the object is sent back to the master manipulator and added to the force feedback provided by the PID controller. This additional feedback signal provides extra information about the slave environment.

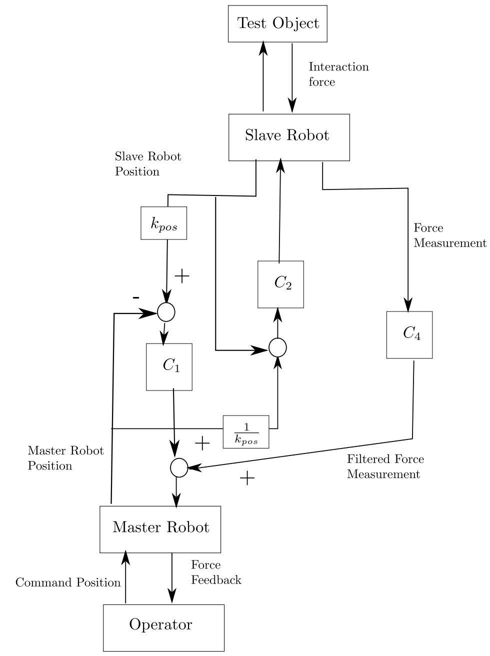


Fig. 1: Control architecture of the teleoperation system.

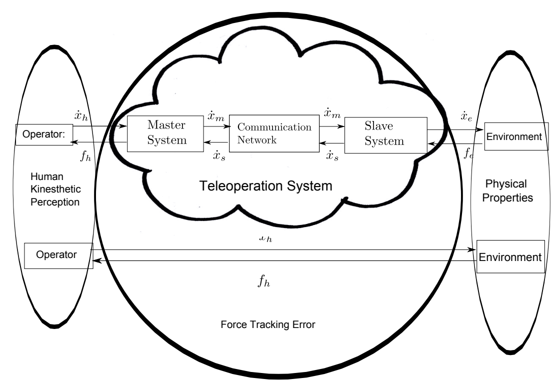


Fig. 2: Haptics exploration (up-Bilateral Teleoperaton; down-Direct)

III. Kinesthetic Exploration in Direct and Teleoperation Scenario

Kinesthetic exploration refers to the process of discovering and determining the kinesthetic properties of the objects in remote environment, as shown in Fig. 2. In the upper part of the picture, where the human interacts with the environment through the teleoperation system, the force feedback is subject to force tracking errors brought in by the teleoperation system, while in the lower part of the figure, the direct exploration case, there is no force tracking error.

A. Kinesthetic Exploration in Direct Haptics Scenario

Weight perception is one of the most basic sensing capabilities that researchers in the human factor analysis domain have investigated. Shape, inertia tensor and location of center of gravity all play roles in it. In previous experiments, the human subjects are usually blind folded from the experimental objects. Also, the objects often have identical handles so that there are no tactile sensing clues [1]. We adopted these two means to improve our experiments.

The dynamics of the test object shown in Fig. 3 can be modeled as a pure mass/inertia component, of which its motion is governed by:

$$m\ddot{x} = F \tag{5}$$

$$I\dot{\omega} + \omega \times I\omega = \tau \tag{6}$$

The reason for using this type of testing object is that we considered teleoperation operations in nuclear and deep sea exploration tasks where the most common interaction between the slave robot and the master robot is the grasping/lifting process. This test object is sufficient to emulate the remote handling tasks that we are interested in.

B. Teleoperation Kinesthetic Exploration and Force Tracking

The gap between the teleoperation exploration and direct hand exploration is the position and force tracking error. The force tracking error is the result of the dynamics of the teleoperation system, and therefore, different control architecture can bring different force tracking errors.

Position tracking has also been considered as a more important factor in previous researches [20]. However inremote operation tasks, the systems usually have vision feedback, where the position offset can be compensated by the operator. Also, in the teleoperation system we used in our experiments, the position tracking error has very low due to the fact that our slave robot is low friction, and it is cable-driven and therefore has very low backlash.

Instead of having Eq. 5 and Eq. 6 in the direct haptics exploration case, the force feedback in teleoperation haptics exploration is given as:

$$f = f_{ext} + k_p(x_d - x_s) + k_d(\dot{x}_d - \dot{x}_s) \tag{7}$$

where K_f is the force scaling factor and f_{ext} is the torque/force measurement. The ideal case for f_{ext} is

$$f_{ext} = \begin{bmatrix} F \\ \tau \end{bmatrix} \tag{8}$$

where F and τ are given in Eq. 5 and 6. However, the readings of the force/torque sensor are usually noisy and need to be filtered. The advantage of having a PID term in Eq. 7 is that it can help stabilize the system [2].

IV. Experiment Methods

The experiment presented here is the first one of a series of experiments. In this experiment, haptics exploration tasks were studied in both teleoperation and direct interactions. Weight perception was used as the kinesthetic exploration task. The operator interacted with test objects that look identical. They then would answer questions about the weight of test objects. It took approximately half an hour for the subjects to complete the experiments.

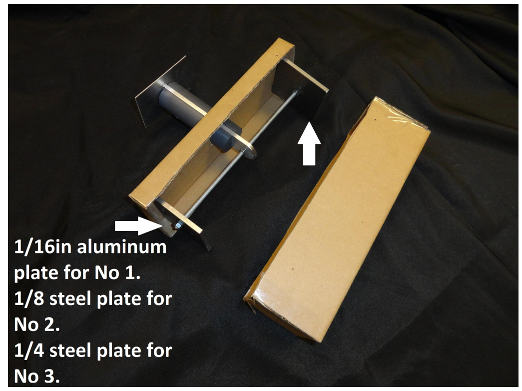


Fig. 3: A Test object with its cardboard box open

TABLE II: Test object

No.	Weight (Unit:kg)	Normalized Weight (W_n)
1	0.6030 (W_a)	6.865
2	0.8774 (W_a)	9.987
3	1.2909 (W_a)	14.70
Comparison	0.8784 (W_c)	10.00

A. Design of the Test Objects

A test object used in the experiment is shown in Fig. 3. It was made up of three parts: the handle, the extra weight and the cardboard box around them. The handle was where the subjects would grasp. On top of the handle, there was a piece of sheet aluminium, The purpose of that was to make it easier for the robot to grasp the test object. Every time the robot grasps the test object, the gripper is manipulated in to the position when the palm is perpendicular to the ground and the fingers are open. And then, the handle is placed against the palm with the top piece of sheet aluminum is on the edge of the palm to provide some supporting force. Then the robotic fingers are closed to provide gripping force. These combined mechanisms ensured a firm grasp. A threaded rod passed through a hole at the bottom of the handle and was bolted down in its midpoint. The extra weights were fastened on the two ends of the threaded rod. Every test object is mounted inside a cardboard box, and all the boxes had identical appearances. Also, since the material of the handles are identical, there was no appreciable tactile sensing difference between the objects. The normailized weight is defined according to Eq. 9.

$$W_n = \frac{W_a}{W_c} \times 10 \tag{9}$$

Where W_a is the actual weight shown in the second column of Table II. W_c is 0.8784 kg, the actual weight of the comparison objects, as shown in the last row, second column in Table II. The purpose of this normalization is to eliminate bias from the subjects' previous experience.

There are three testing methods used: direct haptics exploration, teleoperation haptics exploration with a two channel controller, teleoperation haptics exploration with a three channel controller. In the direct haptics exploration, the subjects manipulated the test objects directly using their dominant hand, so the force the participants experienced was exactly the amount of force needed to manipulate the objects, as shwon in Fig. 5. In the teleoperation experiments, the participants manipulated the object through a teleoperation system shown in Fig. 4. In every section, three test objects were used, so for each participant there were nine trials in total.

The perception time was also recorded as a performance index. In direct hand exploration tests, perception time was the interval from when the subject picked up the object until they gave answers to our questions. In teleoperation exploration tests, the perception time was the time interval between the force feedback was enabled and the participants gave answers. The subjects were unaware that the time they spent was a type of data we were collecting, but before the experiment started, they were all informed that the process would be video taped.

B. Procedure and Instructions

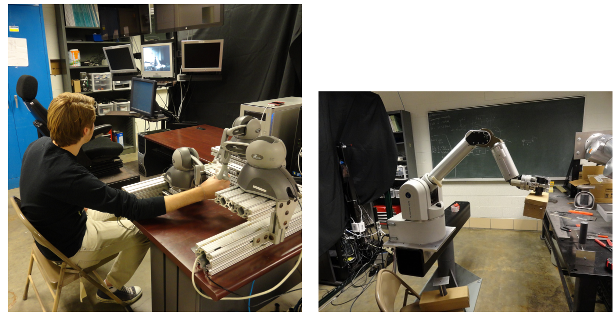
In the experiment, the participants were asked to come in and sit comfortably on the chair next to the table where the direct haptic exploration was going to take place. An introduction about the experiments was given to the participants by the examiner. Then the direct hand exploration experiment started. The subjects were first given the comparison object to manipulate. They were told that the weight of this object was ten and that they needed to remember this weight. It was then taken away from the participant and a test object was presented to them. They then picked up the test object and manipulated it before telling the examiner the weight of the test object. This process repeated two more times for the other two test objects. Then the direct hand exploration experiment ended. The order of the test objects presented to the participants were based on a computer generated random sequence.

Before the teleoperation kinesthetic tasks started, the subjects were given two minutes of recess while the examiner setup and initialized the robot. At the beginning of the two channel controller teleoperation exploration section, the subjects were given a brief introduction about the system. Then the experiment started. The experiments shared the same procedure as the direct hand experiments. They were given the comparison object every time before the test object to review.

After finishing the two channel control section, the robot went back to its home position. The participants were given a two minutes recess while the examiner made changes to the controller. Then the same procedure was carried out again one more time.

C. System Testbed

A 7 DOf Whole Arm Manipulator (WAM) made by Barrett Technology was used as the slave robot. A customized designed 6 DOf master controller was used as the master robot, as shown in Fig 4. The WAM was a cable driven, low friction and low backlash 7 DOF robot. The master controller consists of four Phantom haptic devices, its design



(a) Master Side (b) Slave Side

Fig. 4: Teleoperation Exploration

Fig. 5: Direct Hand Exploration

and control algorithm is given in [17]. This design enables 6 DOF force/torque feedback while maintaining a large range of workspace. Two control computers of the robots were connected through Ethernet. One camera on the slave side was directly connected to a monitor on the master side to provide vision feedback for the subjects. A large piece of black cloth hanging between the slave robot and the master side prevent the subjects from directly seeing the slave side. This was to ensure that the subjects receive viewing the test object only from the monitors to mimic the actual teleoperation scenario.

When we implemented the three channel controller according to Eq. 7, a new issue emerged. The force/torque sensor reading from the slave robot had a high frequency noise. When it is reflected to the master controller, there was an audible, high pitch noise from the actuators of the master controller, so we implemented a digital first order low pass filter to sensor measurement value, as shown in Eq. 10. Its cutoff frequency was set to 5 Hz, because when converted to frequency domain, most of the human motion is under 5 Hz. [6]

$$\tilde{f}_{ffd}(k) = \alpha f_{ffd}(k) + (1-\alpha) * \tilde{f}_{ffd}(k-1) \tag{10}$$

Where α is the low pass filter constant, f_{ffd} is the measurement value sent from the slave robot to the master robot and $\tilde{f}_{ffd}$ is the filtered measurement value. The result is shown in Fig. 6. Another issue was the f_{ffd} was given with respect to the robotic hand coordinate frame, which must be transformed into the world coordinate frame. This was

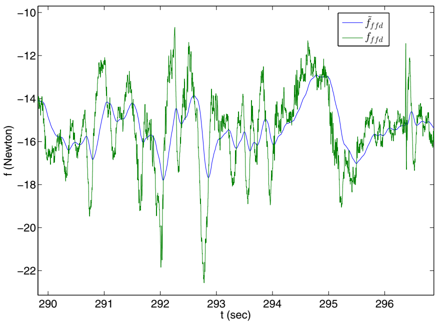


Fig. 6: Filtered force/torque sensor data and unfiltered force/torque sensor reading

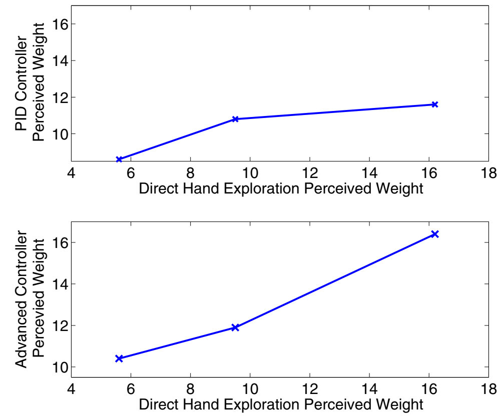


Fig. 7: Perceived weight Vs. Actual weight in direct hand (top), two channel control (Middle) and three channel controller (bottom)

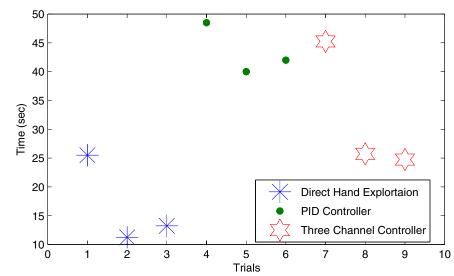


Fig. 8: Perception Time Vs. Trials

achieved by multiplying the coordinate transformation matrix ${}^0_7R$, which can be derived through robot forward kinematics. Also the force feedback was scaled down to ensure that the desired force did not exceed the capacity of the haptic devices.

$$f_{ext} = K_f {}^0_7R \tilde{f}_{ffd} \tag{11}$$
$$C_4 = K_f = 0.5 \tag{12}$$
$${}^0_7R = {}^0_7R(\theta_1, \theta_2, \theta_3, \theta_4, \theta_5, \theta_5, \theta_6, \theta_7). \tag{13}$$

Where K_f is the force scaling factor, and ${}^0_7R$ is the coordinate transformation between the gripper frame and the world frame and is a function of the robot configuration as shown in Eq. 13 and θ_1 θ_7 are all joint angle value of the robot. Therefore, combining Eqs. 10 to 13, results in C_4 block in Fig. 1.

D. *Participants*

Five individuals, aged from 24-30, volunteered to be the participants in these experiments. All of them are right-handed and two of them are females. None of them have participated in any experiments on this setup before.

V. Experiment results and discussion

A. *Experiment Results*

The results presented here are preliminary for the concept proposed. The perceived weights were recorded and their average and standard deviations were computed. The ideal perceived weight would be exactly equal to the actual weight of the test object, so the ideal curve would be a 45 degree straight line that passes the origin. As shown in Fig. 7, the perceived weight in PID and three channel controller teleoperation exploration cases were plotted against the perceived weight we derived from the direct haptic exploration case. In the upper plot in Fig. 7, the subjects cannot tell the difference between the test objects. This is due to the fact that the position tracking error between the master and the slave robots was so low, the force feedback was very close to zero, as shown in Fig. 9. In the lower plot, where the force feedback channel is enabled, the performance improved greatly, especially for the heavy object. This result has significant improvement from the results in [16].

The perception time also confirms our theory. In Fig. 8, trials 1-3 shows the perception time for the three trials in direct hand exploration, trials 4-6 show the time spent on the two channel controller time and trials 7-9 show the time spent on the three channel teleoperation experiments. Note for each section of the experiment, the first trials (trials 1, 4 and 7) always take longer than the rest. This is because that the subjects needed time to get used to the experiment setup. The second and third trial used in three channel controller case(trials 8 and 9) are significantly shorter than that of the two channel controller case (trials 5 and 6). This shows that the three channel controller provides better weight perception than the two channel controller, but is still worse than the direct haptics exploration.

B. *Discussion*

The goal for a kinesthetic teleoperation system is to provide a sense of immersion that the operator perceives as if it is direct contact interaction. The results in this paper show that the performance of current teleoperation systems are still not enough to provide that level of feedback. Both the hardware and control design of the system pose limitation to the performance.

In this experiment, the role of the controller design shows great influence on the results. The more real force feedback provided to the operator the better the result becomes. This

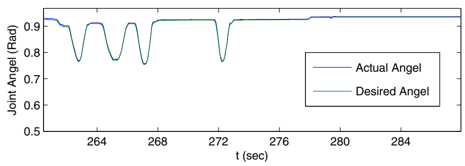


Fig. 9: Position Tracking of joint 2 or WAM

shows that by enhancing the control algorithm, it is feasible to improve the psychological based performance indexes. This is consistent with earlier research results that enhancing the control system can improve the system transparency [8], [10].

The capability of the hardware also has a huge effect on the results of the experiment. For example, when there is a slow and heavy slave robot, the position tracking errors can be large. This error makes the force/torque reading from the slave a heavily delayed signal and therefore, inaccurate. The inertia of the slave robot then gets reflected to the master robot. The subjects did poorly when they are given light test objects, because it was difficult to discern the difference.

Human factors are also important in the teleoperation experiments [3], which is also confirmed by the results of our experiments. For example, females tended to over rate the weight of the objects and males were more likely to under estimate the weight of the objects. Another important factor about human subjects is the fatigue issue. People get tired and then start overrating weights as the experiment proceeds, so a proper resting period in the experiment is crucial for the results. Also, the expertise of the subjects in related areas can also play a very important role. Someone who is familiar with the experiment setup can produce much better results than a person naive in the experiment. A general walk through and training about the experiment is desirable.

VI. Conclusion

In this paper, teleoperational and direct kinesthetic exploration were investigated. Different controllers for the teleoperation system were used in the experiments. A weight estimation experiment was considered. The result suggested that the controller with a better transparency provided better performance. Several factors were discussed and analyzed. This is the first of a series of experiments that explore and quantify the kinesthetic exploration capabilities, so there are a lot of open questions that may be promising research topics, such as the inertia and center of gravity exploration. Another interesting topic would be comparing the hardware systems using the same controller and experiment protocol.

Acknowledgment

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