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Psychophysical Evaluation of Control Scheme Designed for Optimal Kinesthetic Perception in Scaled Teleoperation

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Abstract— **This paper focuses on psychophysical evaluation of the control scheme developed to optimize the kinesthetic perception during the scaled teleoperation. The control problem is formulated as a multi-objective constrained optimization. The objective function is a metric which quantifies the detection and discrimination capacity of the human operator. The constraints are position tracking accuracy and absolute stability of the scaled teleoperation. Two popular control architectures, i.e., the position-position and the force-position control architectures are considered in this paper. The method of limits is employed in this paper to conduct the psychophysical experiments and evaluation. Results show that the developed control scheme is more effective in increasing the detection and discrimination capacity of human subjects as compared to the traditional transparency-optimized control laws.**

I. Introduction

HAPTIC interaction with remote micro-scale environments for semi-autonomous systems require scaled information flow between a haptic master device on one side and a slave manipulator on the other. Such systems are more widely known as scaled teleoperation systems.

There has been extensive research about designing the controllers of scaled teleoperation systems based on different performance objectives. Lawrence discussed transparency as a performance objective in bilateral teleoperation systems and developed transparency optimized control law by virtue of which an operator can feel the exact impedance of the remote environment [1]. Cavusoglu *et al.* addressed task based performance optimization framework in which they defined fidelity as a more effective performance objective for teleoperation systems interacting with soft environments [2]. Controller optimization to improve haptic feedback fidelity was also investigated by estimating the impedance of the remote environment [3]. Gersem *et al.* studied the enhancement of the perception of environment stiffness by optimizing a bilateral controller to increase the relative changes in the stiffness [4]. Son *et al.* focused on enhancing kinesthetic perception to improve the detection and discrimination ability and argued that this is a more important performance objective for scaled teleoperation systems of soft tissues than that of transparency or fidelity [5].

This research focuses on the control scheme developed for remote microsurgical applications in [5] and performs psychophysical experiments to judge the effectiveness of the control design method. Experiments involving human subjects have been performed to explore whether force measurements can be helpful in improving the performance of tasks such as soft-tissue palpation and tissue stiffness discrimination [6]. Tonet *et al.* describes a study about the influence of visual position information on the capability of subjects to discriminate tissue stiffness [7]. The role of force and work cues in the compliance discrimination tasks have also been analyzed using psychophysical experiments [8]. Botturi *et al.* claim that the human haptic perception is different along different directions and suggest that perception can be enhanced by suitable scaling [9]. Allin *et al.* worked on finding the force discrimination threshold in the form of just noticeable difference (JND) for rehabilitation purposes [10]. Malysz and Sirouspour redefined the transparency objectives of bilateral teleoperation to include non-linear and linear time-invariant filter mappings between the master/slave position and force signals and performed psychophysics experiments to show that this modification enhances stiffness discrimination thresholds [11].

In this paper, psychophysical experiments have been conducted to check the effectiveness of the proposed control scheme [5] as compared to widely used transparency optimized control law. The method of limits has been used for implementing the experiments.

II. Kinesthetic Perception Based Control Scheme

A. System Modeling

The model of a generalized four channel scaled teleoperation system is schematically shown in Fig. 1. In this work, we have considered two channel schemes such as force-position (FP) control architecture and position- position (PP) control architecture which are special cases of the generalized architecture shown in Fig. 1. FP control architecture involves transmitting position information from the haptic master device to the slave manipulator while feeding back the force information from the slave side to the master. Therefore, for FP control architecture, $C_3 = 0$ and $C_4 = 0$. On the other

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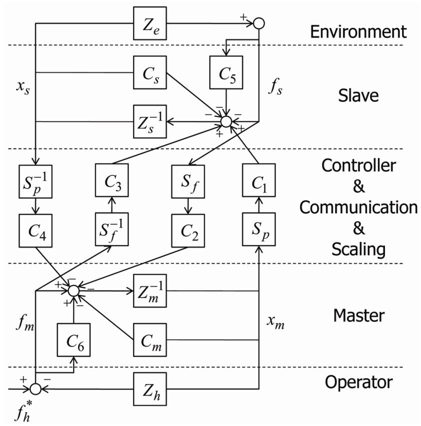

Fig. 1. Generalized four-channel scaled teleoperation system.

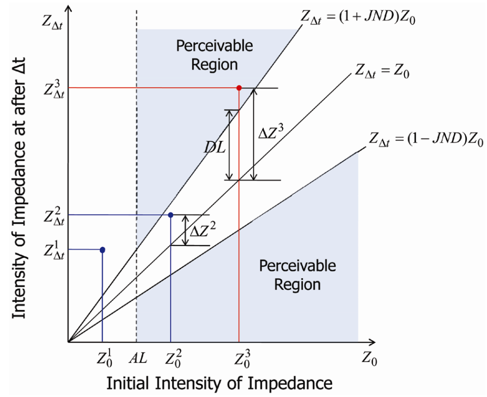

Fig. 2. Kinesthetic perception region.

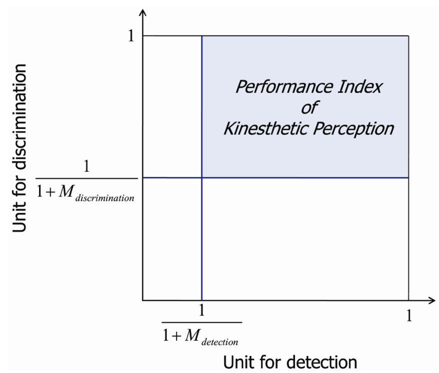

Fig. 3. Mapped region of metric for kinesthetic perception.

hand, if only position information is sent from both master as well as slave side, it is known as PP control architecture in which case $C_2 = 0$ and $C_3 = 0$. The human operator, who is modeled as second-order linear time invariant (LTI) impedance model $Z_h = M_h s + B_h + K_h / s$, interacts with the master device modeled as $Z_m = M_m s$. On the remote side, the slave manipulator, which is modeled as $Z_s = M_s s$, manipulates the environment also modeled as second-order LTI impedance model $Z_e = M_e s + B_e + K_e / s$. Here, M_i, B_i, and K_i $(i = h, e)$ are inertia, viscosity, and stiffness of the human operator and the environment respectively and M_m and M_s are the inertia of the master and slave robots respectively. Z_{to} is defined as the transmitted impedance to the operator. The exogenous input force of the human operator is denoted as f_h^*. The local position controllers of the master and slave robots are PD controllers modeled as $C_m = B_m + K_m / s$ and $C_s = B_s + K_s / s$, respectively where B_m and B_s are the velocity control gain parameters and K_m and K_s are the position control gain parameters. The local force controllers for slave and master are given by C_5 and C_6 respectively. S_p and S_f are defined as the position and force scaling factors respectively such as $x_s = S_p x_m$ and $f_m = S_f f_s$ where f_i and x_i $(i = m, s)$ are the force and the position of the master and slave respectively.

B. *Performance and Stability*

The control design method is a multi-objective constrained optimization problem. The objective function and the constraints are decided based on the following performance as well as stability criteria.

1) Performance Criteria

Two kinds of performance criteria were defined based on the control objectives of scaled teleoperation systems of soft tissues which are given as follows.

(1) Position tracking

Son *et al.* [5] argues that in microsurgical operations, position tracking is a more important performance criterion than that of force tracking or transparency as it would make the surgical operation more predictable and less strenuous for the surgeon located at a remote location. They defined a performance index for the position tracking as given in (1).

$$PI_{tracking} = \left\| W_{tracking} \frac{1}{h_{11}} \left(1 - \frac{h_{21}}{S_p} \right) \right\|_2 \tag{1}$$

where $W_{tracking}$ is a low-pass weighting function with a cut-off frequency $\omega_{c,tracking}$.

(2) Kinesthetic perception

Kinesthetic perception is also used as a more effective performance objective in remote microsurgical operations in which the ability to detect and discriminate varied environment impedances is given more importance than that of mere transparency or force tracking. A kinesthetic perception region is defined in this paper to indicate a set of perceivable impedance levels of the environment based on AL (*Absolute Limen*), DL (*Difference limen*), or JND. The kinesthetic perception region is illustrated in Fig. 2. For example, it is impossible to detect Z_0^1 because it is smaller than AL. In addition, $Z_{\Delta t}^2$ cannot be discriminated from Z_0^2 because ΔZ^2 is smaller than DL. It is, however, possible to perceive Z_0^3 and $Z_{\Delta t}^3$ because they satisfy the conditions of AL and DL. Therefore, the impedance transmitted to the human operator, Z_{to}, has to be located in the kinesthetic perception region to perceive the environment effectively. A larger area of kinesthetic perception region means better perception of the environment. The detection ability is enhanced by lowering the AL of the transmitted impedance while the discrimination ability is improved by lowering the DL or JND of the transmitted impedance. These result in the increase of the kinesthetic perception region. Finally, this enhanced kinesthetic perception region is mapped quantitatively onto a rectangular region by designing a metric whose value ranges from 0 to 1 as given in (2).

$$PI_{perception} = \left(1 - \frac{1}{1 + M_{detection}}\right) \cdot \left(1 - \frac{1}{1 + M_{discrimination}}\right) \quad (2)$$

where $M_{detection}$ and $M_{discrimination}$ are the metrics for detection and discrimination and are shown in (3) and (4) respectively [5], [13]. It is schematically drawn as in Fig. 3.

$$M_{detection} = \left\| W_{perception} \frac{Z_{to}}{Z_e} \right\|_2 \quad (3)$$

$$M_{discrimination} = \left\| W_{perception} \frac{\Delta Z_{to} / Z_{to}}{\Delta Z_e / Z_e} \right\|_2 \quad (4)$$

where $W_{perception}$ is a low-pass weighing function and Δ operator denotes the change in any quantity. The reasons for using infinity norm instead of 2-norm operation given in [5] is because infinity norm concerns with the worst-case performance which should be the criteria in order to improve the threshold perception especially in microsurgical cases.

2) Analytical Stability Criteria

Analytical stability criteria have been developed using Llewellyn's absolute stability [12] for PP and FP control architecture and are given below [5].

Theorem 1: The position-position control architecture for a scaled teleoperation system is absolutely stable for all frequency range if $B_m \geq 0$, $B_s \geq 0$, and $K_m B_s - K_s B_m = 0$.

Theorem 2: The force-position control architecture for a scaled teleoperation system is absolutely stable for all frequency range if $K_s \leq 0$, $B_m \geq 0$, and $B_s = 0$.

However, the above Theorem 2 requires the slave damping to be 0 which might in-turn affect the performance. Hence, Son *et al.* came up with the following two corollaries for non-zero slave damping in which case the scaled teleoperation system would be stable not for all frequencies but for a range of frequencies suitable for remote microsurgical applications. The corollaries are given below.

Corollary 1: The force-position control architecture for a scaled teleoperation system with slave damping, i.e. $B_s \neq 0$, is absolutely stable for a range of real frequencies if $B_m > 0$, $B_s > 0$, and $S_p S_f M_s K_s \geq B_m B_s + S_p S_f B_s^2$.

Corollary 2: The force-position control architecture which satisfies Corollary 1 has more wide range of real frequencies for absolutely stability if $B_m >> B_s$.

C. Control Scheme

The controller design scheme is formulated as a multi-objective constrained optimization problem wherein the performance criteria of kinesthetic perception is taken as the objective function while the criteria of position tracking and analytical stability criteria are used as constraints [5]. It is mathematically shown as in (5).

$$\{C_i\} = \arg \inf_{\substack{PI_{tracking} < 1 \\ satisfy\ C_{stability}}} \sup\left(PI_{perception}\right) \quad (5)$$

where $C_{stability}$ is cumulatively given by Theorem 1, and Theorem 2 or Corollary 1 and 2 for the PP and FP control architectures, respectively. The optimization scheme in (5) gives the optimal result of the control gains $\{C_i\}$ taken as arguments by taking the infinum of the supremum of the weighted norm which represents the worst-case performance

III. Psychophysical Experiment Method

The psychophysical experiments have been conducted to verify the efficacy of the proposed kinesthetic perception based control scheme [5] as opposed to transparency based control scheme [1], [12].

A. Controller Design

The master device and the slave manipulator are modeled as a Phantom and a Phantom with a small surgical tool (300g), respectively. Therefore, $Z_m = 0.072s$ and $Z_s = 0.372s$. The initial values of the local position controllers of the master and slave are chosen proportionally based on the controller values given in [12] and then tuned by a grid search for all possible controller combinations which offer the required position tracking and analytical stability to get the values before optimization. The values of local position controllers were, therefore, selected as $C_m = 2.5 + 50/s$ and $C_s = 15 + 330/s$. The bilateral controllers were then selected based on transparency optimized law. However, the controller values for kinesthetic perception based control scheme were obtained after optimization using MATLAB based on the proposed multi-objective constrained optimization problem shown in (5) and nominal model of the virtual environment. The values were $C_m = 3.46 + 91.47/s$ and $C_s = 10 + 264.44/s$ for PP control architecture as well as $C_m = 3.73 + 100/s$ and $C_s = 18.42 + 332.13/s$ for FP control architecture. The bilateral controllers were then chosen accordingly. There are no local force controllers in either case.

B. Experimental Setup

Two kinds of psychophysical experiments have been conducted. One of them is the test of detection ability while the other is the test of discrimination ability. The experimental setup is shown in Fig. 4. The human subject manipulates the master device which is a PHANToM Premium in this case. The virtual slave manipulator is interacting with a virtual wall as the environment. The teleoperation setup is implemented using Visual C++ and GUIs for detection test and discrimination test have been made to interact with the virtual environment as shown in Fig.

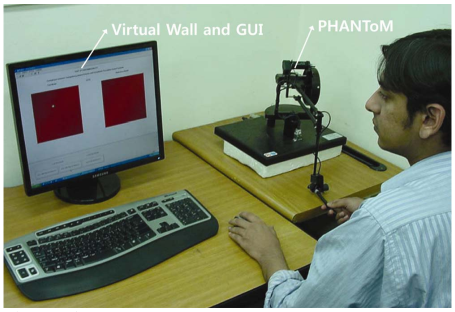

Fig. 4. Experimental setup.

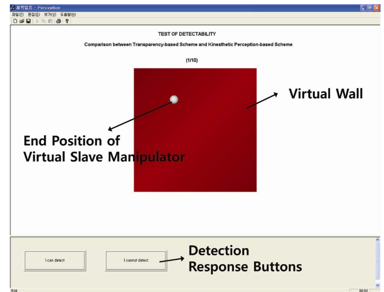

Fig. 5. Graphical user interface for the test of detection ability.

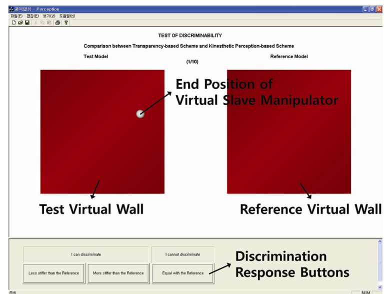

Fig. 6. Graphical user interface for the test of discrimination ability.

5 and 6, respectively. For the detection test, as shown in Fig. 4, there is one virtual wall and the subjects are asked to respond according to whether they can detect the wall or not. The default color of the wall is red but it turns blue as soon as the end-effector of the virtual slave manipulator touches the wall. The discrimination test, however, has two virtual walls. The subjects are asked to discriminate between these two walls based on the haptic information that is fed back to the subject. The haptic update rate was fixed at 1 kHz for the PHANToM haptic device. The experiments were designed according to within-subject design for cost efficiency and maintaining uniformity.

C. *Test of Detection Ability*

The test of detection ability is designed in such a way that a human subject who is holding the PHANToM is asked to interact with the virtual wall which is known as the *Test Model* and respond as to whether he or she can detect the impedance of the environment. Each subject has to perform the experiments for five different *cases* where each case is divided into two *series* such as ascending series and descending series. The five *cases* differ according to the different lower limits for the ascending *series* and different upper limits for the descending *series* and the variable step sizes which vary from *case* to *case* so as to rule out any possibility of intelligent guesses. Also, the *cases* and the *series* are all randomized so as to minimize the human response bias. The points at which the response changes from *Cannot Detect* to *Can Detect* for ascending series or vice-versa for descending series are marked as transition points. The method of limits is used to calculate the AL for the subjects [13].

D. *Test of Discrimination Ability*

The GUI for the test of discrimination ability has two virtual walls, one of which is called the *Test Model* and the other *Reference Model*. Each subject is asked to respond if he or she can discriminate between the test model and the reference model. Every subject has to perform the experiments for five different *cases* in which the reference models have five different environment impedances. The reference model impedances are chosen uniformly such as $Z_e = 1 + 100/s$, $Z_e = 1 + 200/s$, $Z_e = 1 + 300/s$, $Z_e = 1 + 400/s$, and $Z_e = 1 + 500/s$. For each of these reference models there are two kinds of *series* known as ascending *series* and descending *series* which is similar to that of test of detection. The method of limits is also used to calculate the JND for the subjects [13].

For both these experiments, six subjects of different backgrounds and gender, falling under the age group of 21 to 29 years, are chosen to maintain the generality of the experiments. Two of them are from technical background with no knowledge of haptics or psychophysics, while the others are familiar with haptics. Five of the subjects are males while one is female. All of the subjects were right-handed by self-report. All the ten *trials* (five cases multiplied by two series) are repeated for kinesthetic perception based control scheme and transparency based control scheme to obtain the comparison and verify the efficacy of the developed scheme. These are repeated for two kinds of scaled teleoperation control architecture such as PP and FP controller. Therefore, each subject has to perform forty trials for the detection experiment as well as another forty trials for the discrimination experiment. It is to be noted that the subjects could visually detect the contact between the virtual wall and the virtual slave due to the change of color of the wall during contact and could hear the PHANToM motor noise. These visual and auditory effects were present for all parts of the experiments and hence do not affect the comparison of experimental results because our objective is not to find the exact AL and JND of human subjects but to compare the performance of various control schemes using the indices of AL and JND under the same conditions. It is also to be noted that the human subject responds according to the force feedback from the PHANToM which depends not only on the impedance of the environment but also on the insertion depth and velocity of the PHANToM end-effector. However, these aspects are left to the intuition of the human subject to make the response more human-centric. Also, the choice of grip of the PHANToM as well as the choice of the right or left hand is left to human subject's intention and feeling for maximum

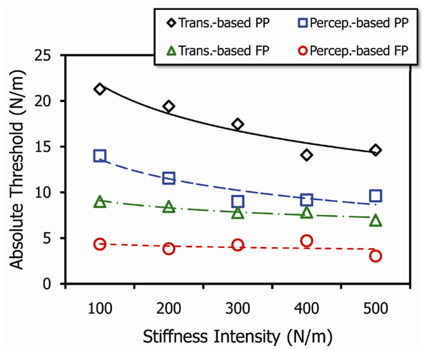

Fig. 7. Variation of AL with environment stiffness intensity.

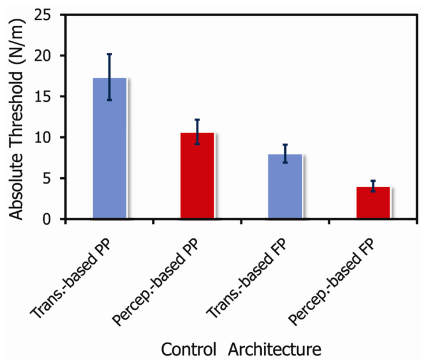

Fig. 8. AL with control architecture.

perception. The subjects were given a detailed tutorial about the experiment and were given a small training session with the PHANToM in the beginning. The forty trails for detection experiment took almost one and a half hours while the forty trials for the discrimination experiment took almost three hours. Subjects were given a 10 minutes break after every 10 trails.

IV. Experimental Results

A. Test of Detection Ability

The results for the detection experiment are summarized in Figs. 7 and 8. It can be seen in the Fig. 7 that as the environment stiffness increases, the mean AL for six subjects decreases irrespective of control architectures or control schemes. It means that as the environment becomes stiffer, human operator can detect the environment in a better way. However, the decrease is more for PP controller than that of FP. In any particular architecture, the transparency based control scheme shows steeper decrease as compared to that of kinesthetic perception based control scheme.

Figure 8, on the other hand, is obtained by computing the average and standard error of the AL for all stiffness intensities to get an overall behavior of various control schemes which shows the efficacy of the kinesthetic perception based control scheme in increasing the detection ability of human beings. It can be noticed that, irrespective of control schemes chosen, FP control architecture always shows better detection ability than that of PP. Also, for each of these control architectures, the kinesthetic perception based control scheme always enhances the detection ability by lowering the AL as compared to that of transparency based control scheme. It is, however, interesting to note that even though PP control architecture is optimized based on kinesthetic perception based control scheme, its detection ability is lower than that of FP control architecture tuned based on transparency based scheme. Quantitatively, there is an 38.61% enhancement in the detection ability for PP control architecture and 49.64% enhancement for FP as shown in Table I. However, the enhancement depends on the initial controller values chosen before optimization and can always vary. One-way ANOVA tests have also been performed at significance level of 95% the results of which are also given in Table I. It can be seen that the p-value for the enhancement of detection ability for PP control architecture is approximately 0.039 ($F(1,58) = 4.463$) while the p-value for the enhancement in FP is around 0.003 ($F(1,58) = 9.752$) which shows that the enhancement of the detection ability is highly significant.

TABLE I
QUANTITATIVE EVALUATION OF AL

Control Architecture	Enhancement Ratio	p-value
PP	38.61%	0.039
FP	49.64%	0.003

B. Test of Discrimination Ability

The results of the discrimination test are shown in Figs. 9 and 10. Figure 9 shows the variation of JND with increasing environment stiffness. JND is expressed as percentage in this work. As the environment stiffness increases, the JND decreases as shown in Fig. 9. The decrease is more for PP architecture than that of FP. In any particular architecture, the transparency based control scheme shows steeper decrease as compared to that of kinesthetic perception based control scheme.

Figure 10, on the other hand, is obtained by computing the average and standard error of the JND for all stiffness intensities to get an overall behavior of various control schemes which shows the efficacy of the kinesthetic perception based control scheme in increasing the discrimination ability of human beings. It can be noticed similar to the test of detection ability that, irrespective of control schemes chosen, FP control architecture always shows better discrimination ability than that of PP. Also, for each of these control architectures, the kinesthetic perception based control scheme always enhances the discrimination ability by lowering the JND as compared to that of transparency based control scheme. It is, however, interesting to note that even though PP control architecture is optimized based on kinesthetic perception based control scheme, its discrimination ability is lower than that of FP control architecture tuned based on transparency based scheme. Quantitatively, there is an 36.14% enhancement in the discrimination ability for PP control architecture and 32.38% enhancement for FP as shown in Table II. However, similar to that of the test of detection ability, the enhancement depends on the initial controller values chosen before optimization and can always vary. One-way ANOVA tests have also been performed at significance level of 95%, the results of which are also given in Table II. It can be seen that the p-value for

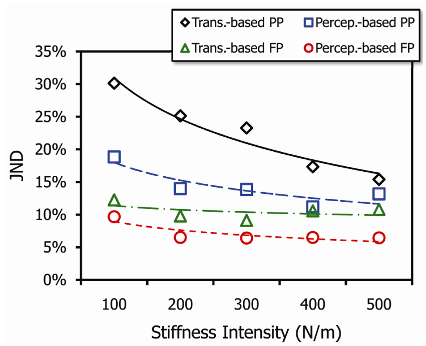

Fig. 9. Variation of JND with environment stiffness intensity.

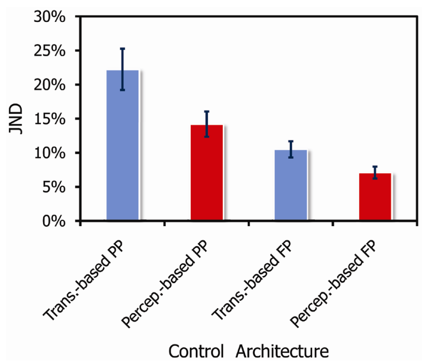

Fig. 10. JND with control architecture.

TABLE II
QUANTITATIVE EVALUATION OF JND

Control Architecture	Enhancement Ratio	p-value
PP	36.14%	0.028
FP	32.38%	0.025

the enhancement of discrimination ability for PP control architecture is approximately 0.028 (F(1,58) = 5.113) while the p-value for the enhancement in FP is around 0.025 (F(1,58) = 5.285) which shows that the enhancement of the discrimination ability is highly significant.

It is to be noted that, the proposed control scheme enhances the detection ability for FP more than that of PP but increases the discrimination ability of PP more than that of FP. Also, for FP architecture, the enhancement in detection ability is more than that of discrimination ability, but for PP, the enhancement for detection and discrimination are almost comparable.

V. CONCLUSION

A psychophysical evaluation is conducted to show the merits of the new control scheme designed for optimal kinesthetic perception during the scaled teleoperation. The test is conducted by comparing the developed control scheme with the widely-used transparency-optimized method. The experiment results show that the new method performs better than the transparency-based control scheme. There is 38.61% enhancement in the detection capacity and 36.14% enhancement in the discrimination capacity for the position-position control architecture. The improvements are 49.64% and 32.38%, respectively for the force-position control architecture.

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