Enhancement in Operator’s Perception of Soft Tissues and Its Experimental Validation for Scaled Teleoperation Systems

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Abstract—This paper focuses on scaled teleoperation systems interacting with soft tissues and presents an optimal control scheme to maximize the operator’s kinesthetic perception of remote soft environments while maintaining the stability in macro–micro interactions. Two performance metrics are defined to quantify the kinesthetic perception of the surgeons and the position tracking ability of the master–slave system. Kinesthetic perception is defined based on psychophysics by using two metrics, which relate to the detection and discrimination of stimulus. This paper then employs a multiconstrained optimization approach to get an optimal solution in the presence of the stability-performance tradeoff wherein the objective is to enhance the kinesthetic perception while maintaining the tracking and robust stability for interactions between macro and microworlds. Simplified stability constraints for scaled teleoperation systems are designed based on Llewellyn’s absolute stability criterion for the optimization procedure, which provides easy and effective design guidelines for selecting control gains. Experiments with phantom soft tissues have been conducted using scaled force–position control architecture, scaled position–position control architecture, and scaled four-channel control architecture to verify the proposed control scheme. Results prove the effectiveness of this algorithm in enhancing the kinesthetic perception of surgeons for scaled teleoperation systems. Psychophysical experiments were then performed to compare our approach with similar contemporary research methods that further validated its efficacy.

Index Terms—Absolute stability, controller optimization, kinesthetic perception, psychophysics, scaled teleoperation.

I. INTRODUCTION

TELEOPERATION systems enable a human operator to control and manipulate a remote environment through a master–slave system. Its common applications include but are not limited to hazardous environments [1], space [2], underwater environments [3], production [4], and medicine [5]. Position and force scaling are often necessary between the master and the slave in many applications involving interactions between macro and microworlds [6], [7]. A teleoperation system with scaled-up power is efficient for manipulation and assembly of heavy materials and parts in production applications [8]. Position control accuracy can also be increased by scaling down the position in the microassembly and microsurgery [8]–[10].

This paper focuses on scaled teleoperation systems in general and telemicromanipulation applications in particular and devises a scheme to maximize its performance while maintaining the stability for macro–micro interactions. It is to be noted that the microsurgical applications in particular such as ophthalmology, otology, digit reattachment surgery, microvascular surgery, urology, and obstetrics, which require tasks and skills like micropositioning, making incisions, microdissections, and suturing small vessels, require precise detection and discrimination abilities in terms of force feedback for effective performance [11]–[13]. Hence, the enhancement of the human perception in general, including the detection and discrimination abilities, is very important for these applications. However, this aspect has been neglected in defining many such performance indexes that have been used in literature till now based on different considerations. Transparency has been used as a performance index in bilateral teleoperation systems according to which the environment impedance should be equal to the transmitted impedance to the operator for perfect transparency [14], [15]. Some other researchers who focused on interacting with hard and rigid environments used performance indexes similar to that of transparency [16]–[18]. For teleoperation systems interacting with soft environments, fidelity was proposed as a performance objective based on the claim that the information about the relative changes of environment impedance is more important for interactions with soft tissues than the environment impedance alone [19]. However, they tried to increase only the fidelity that measures the sensitivity of the transmitted impedance to changes in the environmental impedance and is different from the concept of the discrimination ability based on the concept of the Weber’s Law [40]. In addition, their work does not help to increase the detection ability for environments with very small impedance like that of microsurgical applications. Optimization methods were also adopted by Wang and Liu [20] to improve haptic feedback fidelity, but their method also does not guarantee the enhancement of the detection and discrimination abilities. Gersem et al. [21] only considered the...
enhancement of the sensitivity to environment stiffness and tried to increase the relative changes in the stiffness for teleoperation systems. But, the experimental results are suboptimal and not sufficient to support the claim of the enhancement of stiffness perception. The transparency objectives were redefined to enhance the stiffness discrimination threshold by including nonlinear and linear filtering between the master and the slave in [22] by Malysz and Sirouspour. According to their approach, the product of the position scaling factor and the force scaling factor, which is expressed as $k_p^{-1} k_f$ in their paper, has to be designed as greater than 1 to increase the discrimination ability. However, this decreases the stability robustness [23], [24]. Also, their work is only applicable when a force channel is used in bilateral controllers, but it is difficult to use slave-side force sensors in telesurgical or telemicrosurgical applications [25]. In addition, their approach did not guarantee the enhancement of the detection ability. Mitsuishi et al. developed a direction-dependent task-specific force-feedback augmentation modes for laparoscopic surgery and employed gain-scheduling algorithm for maximum force perception [26]. However, this method is specific to a particular surgical procedure. Tanner and Niemeyer developed a control scheme for interaction with rigid objects using wave variables to scale and shape high-frequency acceleration feedback independently of the low-frequency force-feedback, which eventually improves the user’s perception [27]. An approach to optimize the haptic device design parameters and mechanism dimensions has also been developed to maximize the transparency [28]. The effect of the virtual surface stiffness on the haptic perception including identification, detection and discrimination was studied in [29], which showed that performance improves in a nonlinear fashion as the maximum virtual surface stiffness increases in simulations. Another study on the effect of force saturation on the haptic perception also showed that performance improves nonlinearly as the maximum allowable virtual force increases in simulations [30]. Kammermeier et al. developed a systems theory-based mathematical model for human perception in multimodal telepresence and virtual systems, which can contribute to a more systematic planning and evaluation of human-in-the-loop experiments [31]. Wongwirat and Ohara presented a moving average-based adaptive method for haptic media synchronization to preserve the loss of haptic sequences for avoiding distortion of haptic information due to varying time delay [32]. Son et al. argued that the kinesthetic perception ability of a surgeon is more effective for medical applications of telerobotics, and hence proposed a performance metric for quantifying the detection and discrimination ability of human subjects [33].

An optimization scheme has, hence, been developed based on the performance index defined in [33] to maximize the perception ability of surgeons for macro–micro applications because of its importance, specifically in telemicrosurgical applications, as already discussed in the previous paragraph based on [11]–[13]. In telemicrosurgery, the position tracking ability of the slave robot is also of fundamental importance as high tracking performance can make the operation procedure less strenuous for the surgeons and more secure for the patients [19]. A quantitative metric for position tracking is also, therefore, defined and used as a performance criterion in this paper for the analysis of scaled teleoperation systems. Absolute stability approach is used to analyze the stability robustness of the system due to its less conservative nature than that of passivity [34], because it is well known that telesurgery is safer from the standpoint of stability issues when compared to sudden interactions with hard environments. A multiconstrained optimization approach is, then, employed to arrive at an optimal solution so that the kinesthetic perception is maximized while the position tracking and the stability are maintained. Simplified analytical stability criteria based on Llewellyn’s absolute stability method are used for the optimization purposes for reducing the number of parameters to be optimized, and hence reducing the complexity.

Popular bilateral control architectures including the two-channel scaled position–position (PP), two-channel scaled force–position (FP), and scaled four-channel (4C) controls are used to verify and implement the aforementioned control design approach. Experiments are then conducted with phantom soft tissues based on the proposed optimization procedure and results indicate the effectiveness of the algorithm in enhancing the kinesthetic perception of the surgeons for all three teleoperation control architectures. Psychophysics experiments are also performed based on [35] to check if the proposed performance objective can increase the detection and discrimination thresholds of human subjects, and the results are compared to the well-known contemporary control schemes presented in [19] and [22] for enhancing the operator performance, which further verifies its efficacy. It is also to be noted that this is the first time that psychophysical experiments have been performed to compare the performance of a control scheme for scaled teleoperation systems with that of other similar existing schemes in the literature.

## II. SYSTEM MODELING AND STABILITY

### A. Scaled Teleoperation System

Generalized control architecture of the scaled teleoperation system is shown in Fig. 1. The scaled teleoperation system shown in Fig. 1 consists of the master, the slave, a bilateral controller, and the scaling and communication channels. Relations among these components can be expressed using a hybrid matrix [17], [34]. The hybrid matrix is defined in

$$
\begin{bmatrix}
  f_m \\
  -\dot{x}_s
\end{bmatrix} = H
\begin{bmatrix}
  \dot{x}_m \\
  f_s
\end{bmatrix}
\begin{bmatrix}
  h_{11} & h_{12} \\
  h_{21} & h_{22}
\end{bmatrix}
\begin{bmatrix}
  \dot{x}_m \\
  f_s
\end{bmatrix}
$$

(1)

where $f_m$, $x_m$, and $\dot{x}_m$ denote the force, the position, and the velocity at the master, respectively, while $f_s$, $x_s$, and $\dot{x}_s$ are the force, the position, and the velocity at the slave, respectively.

The human operator and the environment, in this paper, are modeled as second-order linear time invariant (LTI) impedance models of $Z_h = m_h s + b_h + k_h / s$ and $Z_e = m_e s + b_e + k_e / s$, respectively. The $m_h$, $b_h$, and $k_h$ ($i = h, e$) represent the inertia, viscosity, and stiffness of the human operator and the environment, respectively, and $f_i^h$ denotes the intended force...
input of the human operator. Let \( M_m \) and \( M_s \) be the inertia of the master and slave robots, respectively. Also, let us suppose that \( B_m \) and \( B_s \) are the velocity control gain parameters and \( K_m \) and \( K_s \) are the position control gain parameters. Second-order LTI impedance models \( Z_m = M_m s \) and \( Z_s = M_s s \) are the master and slave impedances, respectively. \( C_m = B_m M_m / s \) and \( C_s = B_s M_s / s \) are the local position controllers of the master and slave robots, respectively, while \( C_5 \) and \( C_6 \) are the local force controllers for slave and master, respectively. For convenience, \( Z_{cm} = Z_m + C_m \) and \( Z_{cs} = Z_s + C_s \) are introduced. \( C_1 \) and \( C_4 \) are the two position controllers, while \( C_2 \) and \( C_3 \) are the two force controllers controlling the information flow between master and slave, respectively. The position and force scaling factors are defined as \( S_p \) and \( S_f \), respectively. Scaling laws for the position and the force are defined as \( x_A = S_p x_A \) and \( f_A = S_f f_A \), respectively. The control input to the master and slave is expressed as \( \tau_m \) and \( \tau_s \), respectively.

Impedance transmitted to the human operator, \( Z_{to} \), is derived using the hybrid matrix parameters as shown by

\[
Z_{to} = \frac{h_{11} + (h_{11}h_{22} - h_{12}h_{21})Z_e}{1 + h_{22}Z_e}.
\]

B. Stability

Passivity approach is a common method to analyze the stability of a system. It guarantees the system stability coupled with passive human operator and environment. The net energy is calculated, which is the difference between the input energy and the output energy, and the system is passive if this difference is positive.

The operator dynamics, though passive, is generally adaptive and changing, while the environment impedance is either unknown or inadequately modeled. Stability analysis based on the two-port network model of the scaled teleoperation system alone rather than the whole system including the operator and the environment is therefore more appropriate. When the two-port network of the teleoperation remains stable under all possible uncoupled passive terminations, the teleoperation system is said to be absolutely stable. Absolute stability is used in this paper to analyze and evaluate the stability robustness of the scaled teleoperation system. Absolute stability is a less conservative condition compared to passivity. Llewellyn’s criterion for absolute stability is expressed in terms of immittance matrix parameters as follows [34], [41], [42].

1) \( h_{11} \) and \( h_{22} \) have no poles in the right half plane.
2) Any poles of \( h_{11} \) and \( h_{22} \) on the imaginary axis are simple with real and positive residues.
3) For all the real values of \( \omega \), we have

\[
\Re(h_{11}) \geq 0,
\Re(h_{22}) \geq 0
\]

\[
2\Re(h_{11})\Re(h_{22}) - \Re(h_{12}h_{21}) - |h_{12}h_{21}| \geq 0.
\]

The last condition in (3) can be expressed as (4).

\[
\eta = -\cos(\angle h_{12}h_{21}) + 2\frac{\Re(h_{11})\Re(h_{22})}{|h_{12}h_{21}|} \geq 1.
\]

Stability robustness is analyzed and evaluated by defining \( \eta \) as the stability index [42].

III. PERFORMANCE CRITERIA

A. Kinesthetic Perception

1) Kinesthetic Perception Region: There are two types of thresholds for perception, which include the detection and discrimination of a kinesthetic stimulus (\( \phi \)). First, the absolute threshold (AL for Absolute Limen) is defined as the smallest amount of stimulus to produce a sensation in a detection task and is represented as follows:

\[
\phi_{detectable} = \{ \phi_k | \forall k > 0, \phi_k \geq AL \}.
\]

The second is the difference threshold (DL for Difference Limen), which is defined as the smallest amount of stimulus change required to produce a change in sensation in a discrimination task. The linear relationship between DL and the stimulus intensity is known as Weber’s law [40]. It is defined in

\[
c = \frac{\Delta \phi}{\phi_0} = \frac{DL}{\phi_0}.
\]

Here, \( \phi_0 \) is the initial intensity of the stimulus, \( \Delta \phi \) is the smallest discriminable change of the stimulus intensity, and the constant \( c \) is referred to as the JND, the just noticeable difference. Equation (7) shows the discriminable stimulus from the initial intensity based on the JND.

\[
\phi_{discriminable} = \{ \phi_k | \forall k > 0, \phi_k \geq (1 + JND)\phi_0 \text{ or } \phi_k \leq (1 - JND)\phi_0 \}.
\]

Lower AL and JND values imply that detection and discrimination are relatively easier.

Impedance of the environment \( Z_e \) is the most important stimulus to perceive the dynamic changes in the environment in telesurgery involving interaction with soft tissues [19]. The
kinesthetic perception region is illustrated in this paper in Fig. 2 [33] to indicate a set of perceivable impedance levels of the environment based on AL, DL, and JND. For example, it is impossible to detect $Z_1^{\lambda}$, because it is smaller than AL. In addition, $Z_2^{\Delta}$ cannot be discriminated from $Z_0^{\Delta}$, because $\Delta Z$ is smaller than DL. However, it is possible to perceive $Z_0^{\Delta}$ and $Z_1^{\lambda}$, because they satisfy the conditions of AL and DL. Therefore, the impedance transmitted to the human operator $Z_{\text{to}}$ 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.

2) Enhancement of Kinesthetic Perception: Two methods are introduced to enhance the kinesthetic perception of the operator in the scaled teleoperation system as follows:

a) Detection Enhancement Method: Enlargement of the kinesthetic perception region in relation to the AL, i.e., the detection threshold, by increasing the transmitted impedance

If the impedance of the environment $Z_e$ is smaller than the AL of the impedance of the environment $AL_e$, as illustrated in Fig. 3(a), then $Z_e$ cannot be detected. Now, if the impedance transmitted to the operator $Z_{\text{to}}$, can be made larger than $AL_e$ by introducing $\lambda$, which satisfies $\lambda \geq AL_e/Z_e > 1$ such that $Z_{\text{to}} = \lambda Z_e$, $\lambda \neq 1$, this implies that the detection threshold of transmitted impedance to the operator $AL_{\text{to}}$ would be decreased $1/\lambda$ times of $AL_e$. Hence, the perceivable region can be enlarged, as illustrated in Fig. 3(a).

b) Discrimination Enhancement Method: Enlargement of the kinesthetic perception region in relation to the JND, i.e., the discrimination threshold, by increasing the relative change of the transmitted impedance

As shown in Fig. 3(b), if the relative change of the environment impedance $Z_e/\Delta t/Z_e$ is smaller than the JND for the environment impedance $JND_e$, then $Z_e/\Delta t$ cannot be discriminated from $Z_e$. Now, if the relative change of the transmitted impedance $Z_{\text{to}}/\Delta t/Z_{\text{to}}$ can be increased until it is larger than $JND_e$, i.e., $Z_{\text{to}}/\Delta t/Z_{\text{to}} = \sigma(Z_e/\Delta t/Z_e)$, where $\sigma$ satisfies $\sigma \geq JND_e/(Z_e/\Delta t/Z_e) > 1$, this implies that the discrimination threshold for the transmitted impedance to the operator $JND_{\text{to}}$ would be decreased $1/\sigma$ times of $JND_e$. Hence, the perceivable region is enlarged, as illustrated in Fig. 3(b).

3) Performance Index of Kinesthetic Perception: To compare the kinesthetic perception region quantitatively, two types of performance metrics are defined. First, the metric related to AL is defined in

$$M_{\text{detection}} = \left\| W_{\text{perception}} Z_{\text{to}} \right\|_2$$

where

$$Z_{\text{to}}/Z_e = \frac{h_{11} h_{22} - h_{12} h_{21} + h_{11} Z_e^{-1}}{1 + h_{22} Z_e}$$

(8)

where $W_{\text{perception}}$ is a low-pass weighing function. The cut-off frequency $\omega_{\text{c,perception}}$ of $W_{\text{perception}}$ also depends on the specific application of the teleoperation system. Equation (8) represents the performance index for the detectable region, i.e., the detection ability.
A performance index for the position tracking is defined quantitatively as in

$$PI_{\text{tracking}} = \left\| W_{\text{tracking}} \frac{1}{h_{11}} \left( 1 - \frac{h_{21}}{S_p} \right) \right\|_2$$ \hspace{1cm} (12)

where $W_{\text{tracking}}$ is a low-pass weighting function with a cut-off frequency $\omega_c$. $\omega_c$ is to be less than 8 Hz. $\omega_c = 2$ Hz is sometimes considered reasonable in microsurgical applications because the surgeons carry out the surgery with very slow and carefully controlled movements [38], [39].

IV. PERFORMANCE OPTIMIZED CONTROL

In this section, a performance optimized control scheme is proposed to maximize the target performance while maintaining the system stability for scaled teleoperation systems. The multi-constrained optimization control scheme has the metric of kinesthetic perception defined in the previous section as the objective function, while the index of position tracking performance as one of the constraints. Simplified stability conditions are also found out based on the Llewellyn’s absolute stability criteria to be used as the other constraints for the optimization procedure so that the overall system stability is maintained.

A. Analytical Stability Criteria

Analytical stability criterion is derived for PP, FP, and 4C control architectures using Llewellyn’s absolute stability criteria. We assume that $Z_m = M_m s$ and $Z_s = M_s s$ are the master and slave impedances, respectively where $M_m$ and $M_s$ are the inertia of the master and slave robots, respectively. Also, $C_m = B_m + K_m s$ and $C_s = B_s + K_s s$ are the local position controllers of the master and slave robots, 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.

1) Position–Position Control Architecture: In the PP control architecture, it is known that $C_2 = C_3 = 0$, which nullifies the use of any force sensor. Assuming $C_3 = 0$ and $C_6 = 0$ while $C_1 = C_s$ and $C_4 = -C_m$ with no time delay based on transparency optimized control law, we propose the following theorem.

Lemma 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 $K_m B_s - K_s B_m = 0$.

Proof: The aforementioned proof is based on the impedance matrix representation of the teleoperation system wherein all the five conditions of absolute stability given by the Llewellyn’s criteria, as shown in Section II-B, are satisfied one by one. The hybrid matrix terms are, however, substituted by the corresponding impedance matrix terms. The detailed proof is completely mathematical and can be understood easily from the authors’ previous work in [33].

2) FP Control Architecture: In the FP control architecture, $C_3 = C_4 = 0$. Let us assume that $C_6 = 0$ and $C_0 = 0$ while $C_1 = C_s$ and $C_2 = 1 + C_6 = 1$ with no time delay based on
transparency optimized control law. We propose the following theorem.

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

Proof: This proof is also based on the impedance matrix representation of the teleoperation system wherein all the five conditions of absolute stability given by the Llewellyn’s criteria, as shown in Section II-B, are satisfied one by one. The hybrid matrix terms are, however, substituted by the corresponding impedance matrix terms. The detailed proof is completely mathematical and can be understood easily from the authors’ previous work in [33].

Corollary 1: The FP 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 $S_p S_f M_K K_s \geq B_m B_s + S_p S_f B_s^2$.

Proof [Refer 33]: The aforementioned corollary has been considered because, in general, the slave damping will never be completely nullified. However, the resultant criteria, with non-zero slave damping, are no longer valid for all frequencies.

Corollary 2: The FP control architecture, which satisfies Corollary 1, has more wide range of real frequencies, which is absolutely stable if $B_m \gg B_s$.

Proof [Refer 33]: The aforementioned corollary was found to make the teleoperation system absolutely stable for a wider range of frequencies.

3) 4C Control Architecture: For the 4C control architecture, we assume $C_5 = 0$ and $C_6 = 0$ while $C_2 = 1 + C_6 = 1$ and $C_3 = 1 + C_5 = 1$ from transparency optimized control law and obtain the following theorem.

Lemma 3: The 4C control architecture for a scaled teleoperation system is absolutely stable for all frequency range if the following hold true.

Case (1) $M_m = S_p S_f M_s$:

$$
K_m + S_p S_f K_s \geq 0 \\
B_m + S_p S_f B_s \geq 0.
$$

Case (2) $M_m > S_p S_f M_s$:

$$
K_m + S_p S_f K_s \leq 0 \\
B_m \leq 0 \\
B_m + S_p S_f B_s = 0.
$$

Case (3) $M_m < S_p S_f M_s$:

$$
K_m + S_p S_f K_s \leq 0 \\
B_m \geq 0 \\
B_m + S_p S_f B_s = 0.
$$

Proof: The aforementioned proof is based on the hybrid matrix representation of the teleoperation system wherein all the five conditions of absolute stability given by the Llewellyn’s criteria, as shown in Section II-B, are satisfied one by one. The detailed proof is completely mathematical and can be understood easily from the authors’ previous work in [33].

V. EXPERIMENTAL RESULTS

A. Experimental Setup

The experimental setup, as shown in Fig. 5, was prepared using two 1-degree-of-freedom mechanical devices as the master haptic device and the slave manipulator.

National Instruments Motion Controller was used together with Maxon Motor Driving Circuit to control the master and slave manipulator through a wire-driven mechanism. The control algorithm is implemented using MATLAB SIMULINK, and Real-Time Windows Target Workshop is used to connect MATLAB SIMULINK with the control hardware. ATI six-axis force/torque sensors, Mini40 and Nano17, are attached to the master device and the slave manipulator, respectively. A 16-bit A–D interface is used to input voltages from the force–torque sensors. The human operator perceives the environment by pushing the handle tip of the master device. The sampling time of the experimental system is 1 kHz.
Phantom tissues were used as the viscoelastic soft tissue environment, as shown in Fig. 6. The characteristics of the phantom tissues are analyzed by measuring the interacting force and position. Fig. 7 shows the stiffness characteristics of the phantom tissue. Although the stiffness of tissues is nonlinear, the stiffness of every phantom tissue is calculated under the assumption of linearity for simplicity. Results are $Z_{T1} = 522.31 \text{ N/m}$, $Z_{T2} = 452.04 \text{ N/m}$, and $Z_{T3} = 716.88 \text{ N/m}$ for the phantom tissue 1, the phantom tissue 2, and the phantom tissue 3, respectively.

The dynamics of the device is expressed as

$$F_h(t) = Ma(t) + Bv(t) + F_c \text{sgn}(v(t))$$

(17)

where $M$, $B$, and $F_c$ are inertia, damping, and Coulomb friction of the device, respectively, and these parameters are unknown. These unknown parameters are estimated using the measured input force of the human operator $F_h(t)$ and the position $x(t)$. The estimation result is shown in Table I. With these estimated parameters, feedforward compensation of Coulomb friction is implemented. 95% of Coulomb friction is compensated using this feedforward compensator. More specifically, the position scaling factor has been designed as 0.5 for the experiments with the phantom tissues and as 1 for the psychophysical experiments given in the next section. The force scaling factors have been chosen accordingly such that the product of the scaling factors is always maintained at unity for enhanced stability [23], [24]. Finally, a local PD controller of the master and the slave is designed based on [17] and fine-tuned manually. The tuned controllers are $C_m = 33.72 + 722.52/s$ and $C_a = 3.6372 + 77.94/s$ for the master haptic device and the slave manipulator, respectively. All experiments were performed using the phantom tissue 1, 2, and 3. And all experimental results are illustrated using the average values for the phantom tissue 1, 2, and 3.

### B. Kinesthetic Perception With Optimized Control

1) Controller Optimization: A steepest descent algorithm has been used to optimize the problem [36]. C++ programming language has been used for more effective computation of the optimization algorithm and was interfaced with MATLAB. Finally, controller optimization results, based on (20), are shown in Table II.

2) Kinesthetic Perception: Experimental results on the detection ability of the 4C, PP, and FP control architecture for the phantom tissues 1, 2, and 3 are listed in Table III. The detection ability is enhanced for all the control architectures after controller optimization as is evident by the increase in the value of $Z$. The 4C controllers show the best enhancement, which is computed using $Z_{t10}$. The 4C and the PP and FP control architectures show comparatively lower enhancement among the three controllers. Improvement in the metric for the detection ability is plotted for different control architectures in Fig. 8 using Table III. The enhancement is, however, consistent for all the three soft-tissue environments even though their comparative enhancement may vary.

Table IV shows the experimental results of the discrimination ability.
TABLE III

EXPERIMENTAL RESULTS ON ENHANCEMENT OF DETECTION ABILITY

<table>
<thead>
<tr>
<th>Controller</th>
<th>Environment</th>
<th>Before Optimization</th>
<th>After Optimization</th>
<th>Mean Enhancement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tissue 1</td>
<td>196.03</td>
<td>297.49</td>
<td>52.71%</td>
</tr>
<tr>
<td></td>
<td>Tissue 2</td>
<td>205.90</td>
<td>311.20</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tissue 3</td>
<td>229.14</td>
<td>355.00</td>
<td></td>
</tr>
<tr>
<td>4C</td>
<td>Tissue 1</td>
<td>187.06</td>
<td>236.0637</td>
<td>27.60%</td>
</tr>
<tr>
<td></td>
<td>Tissue 2</td>
<td>199.77</td>
<td>215.3984</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tissue 3</td>
<td>215.54</td>
<td>317.1571</td>
<td></td>
</tr>
<tr>
<td>PP</td>
<td>Tissue 1</td>
<td>246.45</td>
<td>308.6577</td>
<td>25.55%</td>
</tr>
<tr>
<td></td>
<td>Tissue 2</td>
<td>240.67</td>
<td>295.176</td>
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</tr>
<tr>
<td></td>
<td>Tissue 3</td>
<td>248.84</td>
<td>320.129</td>
<td></td>
</tr>
</tbody>
</table>

TABLE IV

EXPERIMENTAL RESULT ON ENHANCEMENT OF DISCRIMINATION ABILITY

<table>
<thead>
<tr>
<th>Controller</th>
<th>Environment</th>
<th>Before Optimization</th>
<th>After Optimization</th>
<th>Mean Enhancement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tissue 1 and 2</td>
<td>+5.03</td>
<td>+4.61</td>
<td>14.46%</td>
</tr>
<tr>
<td></td>
<td>Tissue 1 and 3</td>
<td>+16.89</td>
<td>+19.33</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tissue 2 and 3</td>
<td>+11.29</td>
<td>+14.07</td>
<td></td>
</tr>
<tr>
<td>4C</td>
<td>Tissue 1 and 2</td>
<td>+6.79</td>
<td>+8.75</td>
<td>202.06%</td>
</tr>
<tr>
<td></td>
<td>Tissue 1 and 3</td>
<td>+15.22</td>
<td>+14.35</td>
<td></td>
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<tr>
<td></td>
<td>Tissue 2 and 3</td>
<td>+7.89</td>
<td>+8.24</td>
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<tr>
<td>PP</td>
<td>Tissue 1 and 2</td>
<td>-2.34</td>
<td>-4.37</td>
<td>146.53%</td>
</tr>
<tr>
<td></td>
<td>Tissue 1 and 3</td>
<td>+0.97</td>
<td>+3.72</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tissue 2 and 3</td>
<td>+3.39</td>
<td>+8.45</td>
<td></td>
</tr>
</tbody>
</table>

VI. PSYCHOPHYSICS EXPERIMENTS

A. Method

1) Participants: 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.

2) Apparatus: Two types of psychophysics experiments including the test of detection ability and the test of discrimination ability have been performed. The experimental setup is shown in Fig. 10. The human subject manipulates a haptic master device, which is the PHANToM Premium used in these experiments, while a virtual slave manipulator is interacting with a virtual environment instead of real environments for effectively performing the psychophysical experiments using a large number of environments with varied impedances. The environment model impedance is selected based on various soft-tissue models including that of the stomach and the colon [43], [44].

There is one virtual wall for the detection test, as shown in Fig. 11(a), and the subjects need to respond whether they can...
detect the wall or not. The color of the wall changes from red to blue when the virtual slave contacts the virtual wall. There are, however, two virtual walls for the discrimination test and the subjects need to differentiate these based on the haptic feedback information. The PHANToM haptic device is updated at the rate of 1 kHz. The experiments have been designed according to within-subject design for cost-efficiency and maintaining uniformity.

3) Controller Design: The master device impedance is mathematically expressed as \( Z_m = 0.072 s \), which is similar to that of the PHANToM, while the slave manipulator is modeled as a PHANToM with a small surgical tool (300 g) whose impedance is given by \( Z_s = 0.372 s \) [45]. The experimental method requires the design of controllers for both the transparency optimized control law as well as the kinesthetic perception-based scheme for their mutual comparison purposes.

The initial values of the local position controllers of the master and slave are chosen proportionally based on the controller values given in [42] and then tuned by a grid search for all possible controller combinations that 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 multiobjective constrained optimization problem shown in (16) and the nominal model of the virtual environment. The values were \( C_m = 3.46 + 91.47/s \) and \( C_s = 10 + 264.44/s \) for the PP control architecture as well as \( C_m = 3.73 + 100/s \) and \( C_s = 18.42 + 332.13/s \) for the FP control architecture. The bilateral controllers were then chosen accordingly. There are no local force controllers in either case [35]. As already mentioned earlier, the position scaling factor has been designed as 1 for these experiments. The force scaling factors have been chosen accordingly such that the product of the scaling factors is always maintained at unity for enhanced stability [23], [24].

4) Procedure: Psychophysics experiments are performed to verify the efficacy of the proposed kinesthetic perception optimized control scheme and is then compared with two other previous control schemes by Cavusoglu et al. [19] (hereafter referred to as scheme 1) as well as by Malysh and Sirouspour [22] (hereafter referred to as scheme 2). The metrics for the optimization schemes are the ones used in the corresponding manuscripts. Therefore, for the scheme 1 [19], we used the optimization scheme with their performance index \( \|W_s \frac{\partial Z_m}{\partial x} \| / Z_m / Z_s \) \( s \). And for the scheme 2 [22], we used the nonlinear force scaling with filtered position mapping shown in the first experimental part of their paper [22], i.e., \( k_p(x) = x \) and \( k_f(x) = 0.75 f \tanh((f/4)^2) + 0.25 f \). For the experiments with our own scheme, we have used our proposed optimization metrics given in Section III. However, all these three schemes, which have been optimized using their own performance indexes, are compared on the same grounds based on the widely accepted metrics of detection ability such as the AL and discrimination ability such as the JND. In each of these three experiments involving the three control schemes, every subject has to perform ten trials wherein each case is divided into two series, such as the ascending series and the descending series, as defined in the method of limits [40]. The five cases are different because each has different lower limit, different upper limit, and variable step size to avoid any possibility of intelligent guesses. Also, the cases and the series are all randomized so as to minimize the human response bias.

These three experiments using the three control schemes are randomly repeated for two kinds of teleoperation control architecture such as the PP and the FP controllers to avoid any bias. Therefore, each subject has to perform all total 60 trials for the experiment to test the detection ability as well as another 60 trials for the experiment to test the discrimination ability.

It is to be noted that the subjects could visually detect when the virtual slave contacted the virtual wall because of the color change of the wall during contact and could also 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 indexes 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 process seem natural and 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 on the intention of the human subject based on the feeling of maximum perception of the subject to reduce the number of human factors to be analyzed.

The subjects were given a detailed tutorial about the experiment in the beginning and were provided a small training session with the PHANToM to get them familiarized with that. For the test of detection ability, the total 60 trials took almost two and a half hours and subjects were given a 10 min. break after every ten trials. The total 60 trials, for the test of discrimination ability, took almost 4 h, and subjects were given at least 10 min break after every ten trials.

B. Experiment 1: Test of Detection Ability

1) Method: In the test of detection ability, human subjects are asked to interact with the virtual wall known as the test model, using the PHANToM haptic master device after which they need to give their response based on whether the environment impedance is detectable or not.

For the ascending series of each case, the starting impedance (lower limit) of the test model is generally much lower than the detection ability of any normal human being and hence is undetectable initially. After the subject clicks the button to record his response as to whether he or she can detect the current impedance of the test model, the test model impedance is increased and the subject is asked to respond again. This process goes on till the environment impedance reaches an upper limit and somewhere in the middle of this procedure; the subject starts to detect the impedance of the environment as the environment impedance crosses the absolute threshold of that subject.

On the other hand, for the descending series of each case, the initial impedance (upper limit) is way over the detection threshold of a normal human being, and hence initially the subject feels the environment to be quite stiff. The test model impedance is, however, decreased in variable steps as the subject gives response. This process goes until a lower limit is reached and in the middle of this process at some point, where the environment impedance becomes lower than this absolute threshold, the subject can no longer feel the environment, although he is in contact with the environment.

The points at which the response changes from Cannot Detect to Can Detect for ascending series and the points where the response changes from Can Detect to Cannot Detect for descending series are marked as transition points. The method of limits is then used to calculate the AL for the subjects [40].

2) Result: Six subjects completed the test of detection ability using the PHANToM, while interacting with the virtual wall. The experimental results of every subject using all the controllers are summarized in Fig. 12. This figure shows that as the environment stiffness increases, the mean AL for all six subjects decreases irrespective of control architectures or control schemes. It signifies that human operator can better detect the environment as the environment becomes stiffer.

However, the decrease for FP controller is less than that of the PP control architecture for both the kinesthetic perception-based control scheme and scheme 1, but the case is opposite for scheme 2. It is also interesting to note that for both control architectures (PP and FP), as the environment stiffness increases, the scheme 1 always shows steeper decrease in the absolute threshold as compared to that of kinesthetic perception-based control scheme and scheme 2.

3) Discussion: Fig. 13 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, the FP control architecture always shows better detection ability than that of the PP. Also, for each of these control architectures, the kinesthetic perception-based control scheme always enhances the detection ability by lowering the AL more than that of the schemes 1 and 2. It is, however, noteworthy that even though the PP control architecture is optimized based on the kinesthetic perception-based control scheme, its detection ability is lower than that of the FP control architecture based on schemes 1 and 2.

One-way ANOVA tests are useful tools in this regard, because these tests can statistically determine if the means of several groups of data are equal or not, and hence can be used for comparison purposes. This is achieved by quantitatively comparing the p-value, which is the probability of obtaining the test statistic. Therefore, these tests have also been performed at significance level of 95%, the results of which are given in Table VI. Quantitatively, when the kinesthetic perception control scheme is used, there is a 71.20% enhancement in the detection ability for the PP control architecture from that of scheme 1 and a 66.74% enhancement from that of scheme 2, while a 49.53% enhancement for the FP control architecture from that of scheme 1 and 61.19% from that of scheme 2, as shown in Table VI. However, the enhancement is sensitive to the initial controller values chosen. It can be seen that the p-value for the enhancement of detection ability for the PP control architecture is approximately 0.0000019 for scheme 1 and 0.000033 for scheme 2, while the p-value for the enhancement in the FP
C. Experiment 2: Test of Discrimination Ability

1) Method: There are two virtual walls such as the test model and the reference model for the test of discrimination ability. 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 similar to that of the test of detection ability, 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 are similar to that of the test of detection ability.

For ascending series, the initial impedance of the test model is much lower than that of the reference model. After the subject clicks his response, the test model impedance is increased while the reference model impedance is kept same and the response is given again. This process goes on until an upper limit is reached. At some point in this process, the human response changes from \textit{less stiff than reference model} to \textit{equal}. This point is marked as lower limen ($L_l$). After some more time, a point would come when the response changes from \textit{equal} to \textit{more stiff than reference model} and this point is marked as upper limen ($L_u$). The series is stopped when an upper limit is reached.

For descending series, the initial impedance of the test model is, however, much higher than that of the reference model. As the subject clicks his or her response, the test model impedance is decreased while the reference model impedance is kept same. During the experimental procedure, the response changes from \textit{more stiff than reference model} to \textit{equal} and \textit{equal} to \textit{less stiff than reference model} at some points of time. These response transition points are termed as $L_u$ and $L_l$, respectively. The series is stopped when a lower limit is reached. The method of limits is used to calculate the JND for the subjects [40].

2) Result: The test of discrimination ability was also completed by the same subjects, the results of which are summarized in Fig. 14. This figure shows the variation of the JND with increasing environment stiffness. The JND is expressed as percentage in this study. As the environment stiffness increases, the JND decreases, as shown in Fig. 14. The decrease is more for the PP architecture than that of the FP irrespective of the control schemes chosen. In any particular architecture, the scheme 1 usually shows steeper decrease as compared to that of kinesthetic perception-based control scheme and scheme 2; however, the difference is not so prominent for the PP control architecture.

3) Discussion: Fig. 15 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 show the efficacy of the kinesthetic perception-based control scheme in increasing the discrimination ability (in the form of the JND) of human beings. It can be noticed, similar to the test of detection ability, that irrespective of control schemes chosen, the FP control architecture always shows better discrimination ability than that of the PP architecture. Also, for each of these control architectures, the kinesthetic perception-based control scheme always enhances the discrimination ability more by lowering the JND as compared to that of the schemes 1 and 2. It is, however, interesting to note that even though the PP control architecture is optimized based on the kinesthetic perception-based control scheme, its discrimination ability is lower than that of the FP control architecture tuned based on schemes 1 and 2.

### TABLE VI

<table>
<thead>
<tr>
<th>Control Architecture</th>
<th>Enhancement Ratio</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scheme 1</td>
<td>71.20%</td>
<td>1.9789E-6</td>
</tr>
<tr>
<td>Scheme 2</td>
<td>66.74%</td>
<td>3.3223E-5</td>
</tr>
<tr>
<td>FP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scheme 1</td>
<td>49.53%</td>
<td>0.0011</td>
</tr>
<tr>
<td>Scheme 2</td>
<td>61.19%</td>
<td>2.3049E-6</td>
</tr>
</tbody>
</table>

is around 0.0011 for scheme 1 and 0.0000023 for scheme 2, which shows that the enhancement of the detection ability by using the newly proposed kinesthetic-based control scheme is highly significant.
Quantitatively, when the kinesthetic perception control scheme is used, there is a $47.12\%$ enhancement in the discrimination ability for the PP control architecture from that of scheme 1 and a $47.72\%$ enhancement from that of scheme 2, while a $48.03\%$ enhancement for the FP control architecture from that of scheme 1 and $27.67\%$ from that of scheme 2, as shown in Table VII.

However, the enhancement is sensitive to the initial controller values chosen. One-way ANOVA tests have also been performed for this case at significance level of 95%, the results of which are also given in Table VII. It can be seen that the $p$-value for the enhancement of discrimination ability for the PP control architecture is approximately 0.0009 for scheme 1 and 0.0005 for scheme 2, while the $p$-value for the enhancement in FP is around 0.00051 for scheme 1 and 0.0494 for scheme 2, which shows that the enhancement of the discrimination ability by using the newly proposed kinesthetic-based control scheme is highly significant.

It is to be noted that the proposed control scheme enhances the detection ability for PP more than that of FP for both schemes 1 and 2, but it enhances the discrimination ability for PP more than that of FP for scheme 2, only while for scheme 1, the discrimination ability is enhanced more for FP than that of PP. Also, for scheme 1, the enhancement in detection ability is more than that of the discrimination ability for PP, but the enhancements for FP are more or less comparable. On the other hand, for scheme 2, the enhancement in detection ability is more than that of the discrimination ability for both PP and FP. It is to be noted that the work by Malysz and Sirouspour [22] is only applicable when a force channel is used in bilateral controllers. This is bolstered by the fact that scheme 2 shows worse result in the PP control than in the FP control for the experiments regarding the enhancement of discrimination ability.

Hence, scheme 2 using the PP control shows similar results with that of scheme 1 using the PP control, while scheme 2 using the FP control shows superior discrimination ability than that of scheme 1 using the same control. This means that scheme 2 does not have a clear advantage over scheme 1 when there is no force feedback channel from the slave to the master.

Also, it should be noted that the enhancement of detection ability is much higher when compared to discrimination ability for both the two schemes, because both these schemes did not consider the improvement of the detection ability in their control.

On the whole, it can be said that the FP control architecture shows better perception performance than that of the PP control architecture. This, however, has a disadvantage for telesurgical or telemicrosurgical applications because of the difficulty of using force sensors in these areas as already mentioned in Section I [25]. The PP control architecture, on the other hand, generally shows better stability than do the FP control architecture. This shows that there is stability-perception tradeoff between the PP and the FP, and the ultimate choice depends on the specific application characteristics.
This paper aimed at maximizing the perception of human operators for macro–micro interactions with soft tissues by employing an optimization scheme for scaled teleoperation systems wherein the proposed metric for kinesthetic perception is used as the objective function, while the tracking and stability criteria are used as the constraints to address the tradeoff between the stability and the performance. This scheme is then verified using experiments with phantom soft tissues for the PP, FP, and 4C control architectures, and its effectiveness is validated by comparing with similar control schemes existing in the literature using psychophysical methods.

Experimental results show that the 4C control architecture has the highest decrease of tracking error of 38.31% and largest enhancement of detection ability by 52.71%, while the FP architecture actually has an increase of 25.55% of the detection ability, which is the least among the three. Interestingly enough, the highest enhancement of the discrimination ability is for the PP architecture, which is 209.34%, while 4C has the lowest enhancement of only 14.68%. The cumulative effect of the detection and discrimination ability is seen in the kinesthetic perception results, which show the highest enhancement for FP while 4C has the lowest improvement.

Psychophysical experiment results show the effectiveness of the kinesthetic perception-based control scheme as compared to the well-known schemes 1 and 2. When the proposed control scheme is used, the detection ability is enhanced by 71.20% from scheme 1 and by 66.74% from scheme 2, while the discrimination ability is increased by 47.12% from scheme 1 and by 47.72% from scheme 2 for the PP control architecture. For the FP control architecture, there is a 49.53% enhancement in the detection ability for scheme 1 and 61.19% for scheme 2, while a 48.03% improvement for scheme 1 and a 27.67% improvement for scheme 2 in the discrimination ability.

All the earlier results validate the efficacy of the proposed control scheme. However, it is to be noted that the master and the slave have been modeled using only inertia terms to derive the analytical stability criteria. In practical cases, however, a general nonlinear dynamic model, including velocity-dependent terms and position-dependent terms, have to be considered to increase stability robustness, which is our future topic of research. One possible solution to this problem can be achieved by using appropriate disturbance observers, which can cancel the unmodeled terms and can give expected behavior with the inertia terms only. In addition, we plan to add an adaptive control scheme to the proposed control to anticipate sudden significant changes in the environment impedance. However, for telemicrorosurgical or telesurgical cases, where surgeons operate with carefully controlled motions, sudden significant changes in the environment impedance might be very rare. Design choices for a proper human–machine master interface [47] or a slave end-effector tool [48] for such teleoperation systems also play a very important role in their performance; however, these are outside the scope of our research, and we assume that our control algorithms are applied in an optimally designed master–slave setup.

VII. CONCLUSION

References


