Perception-centric Force Scaling in Bilateral Teleoperation

D. Botturi, M. Vicentini, M. Righele\textsuperscript{a}, C. Secchi\textsuperscript{b}

\textsuperscript{a}University of Verona, Strada le Grazie 15, 37134 Verona, Italy
\{botturi, vicentini, mrighele\} \texttt{@metropolis.sci.univr.it}
\textsuperscript{b}University of Modena and Reggio Emilia, via G. Amendola 2, Morselli Building, 42122, Reggio Emilia, Italy cristian.secchi@unimore.it

\section*{Abstract}
In this work we propose a control architecture that leads to an intrinsically stable bilateral teleoperation system, where the telepresence of the user is improved in terms of remote force discrimination. We identify, through a set of psychophysical experiments, a variable force scaling matrix that improves the operator’s feeling of the remote environment. We show that it is possible to build a passive control scheme that embeds this perception-centric scaling. Finally, an experiment is presented to validate the results proposed in the paper.

\textit{Key words:} telepresence, passive bilateral teleoperation, psychophysical experiments

\section*{1. INTRODUCTION}

The force feedback provided by a haptic device is usually defined as the sensation of weight or resistance felt by a human operator \cite{1}. It requires a device that produces a force to the operator such as the one of the interaction with a real object, allowing a person to feel the weight of virtual objects, or the resistance to motion they create.

Several works are relevant to the quantitative measures of human biomechanical, sensorimotor, and cognitive abilities that affect the design of force-reflecting haptic interfaces. One of the most common measures is related to the Just Noticeable Difference (JND), which is the minimal difference between two stimuli (force $F$ vs. $F + \Delta F$ where $\Delta F$ is the force variance) that leads to a change in the human perceptual experience and that is detectable...
by a human being.

The JND percentage value for pinching motions between finger and thumb was found to be around 7% of the reference force [2]; in a force matching experiment about the elbow flexor muscles, a JND ranging between 5% and 9% was observed [3]. The JND was found to be relatively constant over a range of different base force values between 2.5 and 10 N, and essentially independent of reference force and displacement [4]. In previous works, such as [5, 6], results in human force perception for the design of haptic devices are presented but they are focused on finger capabilities or the described experiments primarily investigate haptic environments.

The authors, in [7], proposed a perception experiment aimed at exploring differences in ability of a person to discriminate a wide range of force intensities applied to different directions. A link between the way in which the user perceives the force and the intensity and the direction of the stimulus was observed and identified.

A bilateral teleoperation system can be interpreted as an haptic device, where the virtual object is replaced by the remote environment. Human factors and a quantitative evaluation of the cognitive abilities of the user in the detection of the force that is fed back at the master side are getting more and more important in the design of bilateral control strategies (see, e.g. [8]).

In many interesting scenarios, accuracy in the interaction with the remote environment is a critical goal. Thus, it is necessary that the user be able to distinguish small variations of the force fed back at the master side. For example, in telesurgery, low intensity signals are very common but not well perceived [9] and, therefore, some processing of the force feedback would be necessary to enhance the perception and, consequently, the performance of the teleoperation system.

The problem of enhancing the capability of the user to discriminate variations of the compliance of the remote environment is considered in [8, 10]. In [8] the parameters of a 2-channel control systems are optimized in order to maximize the sensibility of the user, while in [10] a 4-channel control architecture is considered and the controllers are optimized to make the user more sensible to the variation of stiffnesses falling into a desired, tunable, range. Both approaches consider linear teleoperation systems and a linear (ideal spring) model of the remote environment.

In this work, which is an extended version of [11], we show how to use the results of the perception experiments reported in [7] for building a variable (both in time and in direction) force-dependent scaling matrix that allows to
improve the ability of the user in the discrimination of force variations. Before using the scaling matrix in a bilateral teleoperation setup, it is necessary to prove that a safe (i.e. stable) behavior is guaranteed.

Passivity theory has been widely used for the control of bilateral telemanipulators since it allows to guarantee a stable behavior of the system thanks to impedance control techniques.

Port-Hamiltonian systems can be used for the design of passivity based bilateral teleoperators since they provide a clear energy-based representation of all physical systems [12]. In particular, it is possible to model a passively controlled teleoperation system as two passive port-Hamiltonian systems exchanging information along a communication channel.

Thus, we will address the problem of embedding the variable, force-dependent scaling matrix for the class of port-Hamiltonian based teleoperators in order to represent a wide class of real systems and for taking advantage of the port-Hamiltonian structure for the passivity analysis. Finally, we report experimental results on a 6DOF master-slave bilateral teleoperation system. These results show that the embedding of the force dependent scaling matrix actually improves performance in terms of detectable force variation without causing unstable behaviors.

The contribution of the paper is threefold. Firstly, the determination of a scaling matrix starting from perceptual data is a new approach to force augmentation. Also the use of different scaling functions for each axis direction is a novelty and its motivation comes from the human perception
capabilities. Secondly, thanks to the port-Hamiltonian approach, it is possible to consider also nonlinear teleoperation systems. No assumptions on the dynamics of the operator and of the remote environments are needed other than their passivity. This allows to also consider environments with nonlinear dynamics such as plastic effects or non-constant stiffnesses. The third contribution concerns the design of the control strategy embedding the variable scaling. The problem of force scaling, both constant and variable, in teleoperation has been faced by several authors but it is usually assumed that the scaling is linear and uniform, namely that the same scaling factor is applied to all the components of the force. Furthermore, in case of variable scaling, some assumptions on the teleoperation system are made in order to prove stability [13, 14, 15, 16, 17, 18]. A noticeable difference is the approach reported in [19] where nonlinear force/position monotonic scaling mappings are taken into account. Because of the nature of the scaling matrix used in the paper (variable, non uniform, non monotonic) and of the general class of teleoperators we want to consider (both linear and nonlinear), it is not possible to exploit results proposed in the literature and, therefore, a new control strategy has been developed.

The paper is organized as follows: we briefly describe in Section 2 the psychophysical experiments results and the resulting force scaling matrix, while in Section 3 the port-Hamiltonian formalism and the port-Hamiltonian based bilateral teleoperation are presented. Section 4 shows how it is possible to embed the force dependent scaling in port-Hamiltonian based teleoperation in a stable way in case of negligible communication delay. Section 5 presents a validation protocol used to confirm our claims with a real bilateral teleoperation setup. Section 6 highlights conclusions and future works.

2. PERCEPTUAL-BASED SCALING MATRIX

The goal of this section is to verify whether the human capabilities in force perception can be actually enhanced by using an adequate scaling matrix for force-feedback in haptic environments, obtained from perceptual-based experiments.

2.1. Force Perception Thresholds

In a previous work [7] we defined an experimental design to measure the capability of the human hand in terms of force perception. The experimental work consisted in analyzing how force is fed back to the user using a 6 DOF
Figure 2: Force threshold vs. reference force for one prototypical direction. The yellow surface represents a hypothetical manipulation of the force signal considering as scale factor an exponential functions fitted from perceptual data, in order to reach a constant threshold along the stimuli continuum (green line).

haptic device, depicted in Fig. 1. The goal of that work was to understand which is the force range better perceived by the human hand/arm system.

In Fig. 2 the force threshold is plotted versus the reference force for one prototypical direction. We observed a non linear relationship between the reference stimuli and the JND. Considering low reference stimuli, the force stimulus and the perceptual threshold appeared to be associated inversely: the lower the force applied, the higher the JND%.

Our findings indicate an average JND of 15 - 20%; but this threshold is not constant along the stimuli continuum, and it also differs among the different cartesian directions.

That is, we found evidences that the perceptual threshold for forces larger than 5 N can be assumed as constant, with an average value of about 15% of the reference force [20]. Descriptive analysis suggested the presence of asymmetries in force and torque perception. We hypothesized that, along each translational or rotational direction, given a positive or negative direction, non symmetrical thresholds can be perceived. Our results are closer to the ones reported in recent works [21] which found that force perceptual threshold is inversely related with the reference force. In general, a researcher could
Table 1: Estimated parameters for Eq. 1 fitted on perceptual data.

<table>
<thead>
<tr>
<th>Direction</th>
<th>$F &gt; 0$</th>
<th>$F &lt; 0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x$</td>
<td>$k_1$</td>
<td>$c_1$</td>
</tr>
<tr>
<td></td>
<td>0.230</td>
<td>14.425</td>
</tr>
<tr>
<td>$y$</td>
<td>0.218</td>
<td>16.538</td>
</tr>
<tr>
<td>$z$</td>
<td>0.260</td>
<td>14.355</td>
</tr>
<tr>
<td>roll</td>
<td>0.0268</td>
<td>142.310</td>
</tr>
<tr>
<td>pitch</td>
<td>0.213</td>
<td>26.318</td>
</tr>
<tr>
<td>yaw</td>
<td>0.0824</td>
<td>54.980</td>
</tr>
</tbody>
</table>

expect a similar asymptotic trend in force perception: literature [22, 23] reports the JND% as constant only for medium values, while it increases for low intensities.

In order to better account for data variability, in [11] we fitted the experimental data with several exponential functions. We identified a perceptual scaling function that maps the JND% behavior:

$$\alpha(F) = \begin{cases} 
1 + e^{k_1(-F+c_1)} & \text{if } F > 0 \\
1 + e^{k_2(F+c_2)} & \text{if } F < 0
\end{cases}$$

where $F$ is the unscaled force (or torque) signal along a specific direction, $k_1$, $k_2$ are parameters referred to the human sensorial threshold, $c_1$, $c_2$ are parameters referred to the accuracy of the calibration of the experimental setup and are dependent on the human capability for a specific configuration. By customizing the parameters from the findings of the previous experiment (see Table 1), this equation led to a different scaling function for each direction, in order to exploit the differences that we have found along cartesian directions.

Those results justify a deeper study on a new force scaling concept related to the master device at hand and to the type of application in an actual teleoperation scenario. A suitable signal processing is needed to improve the force feedback and moreover the operation performance, without compromising the stability of the teleoperation system.

2.2. Signal processing

A suitable signal processing can enhance the ability to discriminate different stimuli by increasing the differences between them, letting a user to perceive under-threshold differences. This can be done by amplifying the force signal with a non constant scaling such as using the scaling function
that depends on the force intensity [24]. We used the term function since we think that the scaling should occur in a way that it erases the JND% degradation. It seems quite obvious that it is not useful to scale high intensity forces, that are well discriminated by human, while it is important to amplify the differences at lower scale. However, it is crucial to maintain a one-to-one correspondence between measured forces and manipulated ones.

Our proposal is to manipulate the force signal considering the scale factor, fitted on experimental data, in order to reach a perceptual threshold constant across the stimulus domain. That is, according to Eq. (1), for each sensed force value $F_i$ the scaling function $\alpha(F_i)$ maps to an unique scaled force value according to:

$$S(F_i) = F_i \cdot (1 + \alpha(F_i)/100)$$  \hspace{1cm} (2)

In Fig. 3 we plot our idea of signal processing for the prototypical $x$ direction. Given the following parameters: $k_1 = 0.230$ and $c_1 = 14.250$, retrieved from Table 1, and the following sensed force values: $F_i = 1, 2, 3, 4, 5$, Given such values, Eq. (1) provides the following scaling manipulation values: $\alpha(F_i) = 22.927, 18.422, 14.843, 11.998, 9.739$, expressed as a percentage. According to Eq. (2) these scaling factors augment the dependent forces to $S(F_i) = 1.229, 2.368, 3.445, 4.480, 5.487$.

One possible shortcoming deriving from our variable force scaling approach is a “flattening” of the force intensity along the whole range. The
mapping from sensed to scaled force is reported in Fig. 3. For large intensities the scaled force coincides with the measured force because the scaling tends to 1.01. For low intensities the scaled force is significantly different from the measured force because of the application of the scaling. However, the scaling is an “order” preserving function, namely the signs of the derivatives of the scaled force and of the non scaled force are the same. In this way an increase/decrease of the measured force is always transformed in an increase/decrease of the scaled force rendered to the user. In other words, the signal perceived by the user is only scaled and not distorted.

In Minimally Invasive Robotic Surgery, for instance, and in general in all macro/micro manipulation tasks, it is more important to let the operator perceive or discriminate between stimuli than render a “perfect” force. In our perception-centric approach the signal at the master side is manipulated with respect to what is registered at the slave side, enhancing the environment perception.

This scaling can be used to improve performance in passivity based bilateral teleoperation. Nevertheless, a variable scaling is not a passivity preserving operation.

In the next two sections we will show how under suitable assumptions it is possible to guarantee a stable behavior while using the variable scaling for increasing performance. In Section 5, by arranging a new psychophysics experiment, we will evaluate the goodness of the scaling with respect of the user perception.

3. PASSIVITY BASED CONTROL OF BILATERAL TELEMANIPULATION SYSTEMS

The goal of this section is to provide a short introduction to port-Hamiltonian systems and bilateral telemanipulation based on port-Hamiltonian systems. The interested reader can find further details in [25, 26, 12].

The port-Hamiltonian modeling framework is the mathematical formalization of the bond-graph strategy for representing physical systems [27]. Loosely speaking a port-Hamiltonian system is made up of a set of energy processing elements (energy storing, energy dissipating and energy sources) that exchange energy along a power preserving interconnection that is a generalization of Kirchhoff laws and that represents the way into which energy processing elements exchange energy. Along the interconnection, energy is neither stored nor dissipated but simply transferred. More formally, we can
consider a port-Hamiltonian system $\mathcal{H}$ as composed of a state manifold $\mathcal{X}$, an energy function $H : \mathcal{X} \to \mathbb{R}$ corresponding to the internal energy, a Dirac structure, which represents the power preserving interconnection structure, and a power port represented by a pair of dual power variables $(e, f) \in V^* \times V$ called effort and flow respectively (corresponding to wrenches and twists in the mechanical domain). This port is used to interact energetically with the system: the power supplied through the port is equal to $e^T f$. One of the most used representations for port-Hamiltonian systems is the following

$$\mathcal{H} := \begin{cases} \dot{x}(t) = (J(x) - R(x))\frac{\partial H}{\partial x} + g(x)e(t) \\ f(t) = g^T(x)\frac{\partial H}{\partial x} \end{cases}$$

where $x \in \mathbb{R}^n$ is the vector of energy variables, $J(x)$ is a skew-symmetric matrix representing the power preserving interconnection, namely the Dirac structure, $R(x)$ is a positive semidefinite matrix representing the energy dissipated by the system, $H : \mathbb{R}^n \mapsto \mathbb{R}$ is the Hamiltonian function, that expresses the amount of energy stored in a given configuration, and $g(x)$ is the input matrix. The input-output pair $(e(t), f(t))$ is a pair of dual variables that forms the power port. Depending on the system causality, the effort can be the input and the flow the output or viceversa. It can be easily seen that

$$\dot{H} + \frac{\partial^T H}{\partial x} R(x) \frac{\partial H}{\partial x} = \dot{H}(t) + P_d(t) = e^T f$$

(3)

where $P_d(t) = \frac{\partial^T H}{\partial x} R(x) \frac{\partial H}{\partial x} \geq 0$ is the amount of power dissipated by the system. Eq.(3) clearly says that the supplied power $e^T f$ equals the increase of internal plus dissipated energy. This implies that, if the function $H$ is lower bounded, the port-Hamiltonian is passive.

The port-Hamiltonian based bilateral telemanipulation scheme is represented in Fig. 4 in a bond-graph notation: half arrows, $\mathbf{C}$ and $\mathbf{R}$ represent power flow, energy storing elements and energy dissipating elements respectively. The power ports $(e_H, f_H)$ and $(e_E, f_E)$ represent the means through which the human operator interacts with the master robot and the remote environment interacts with the slave robot respectively.

The robots are coupled in a power preserving way with impedance controllers for regulating their interactive behaviors. Both the robots and the controllers can be modeled as port-Hamiltonian systems [12] and, since the power preserving interconnection of two port-Hamiltonian systems is again a port-Hamiltonian system [25], master and slave sides can be modeled as
two port-Hamiltonian systems, $\mathcal{H}_m$ and $\mathcal{H}_s$, characterized by energy functions and states $H_m, x_m$ and $H_s, x_s$ respectively. The impedance controllers compensate the gravity effect and impose a desired compliance to the robots and, therefore, $H_m$ and $H_s$ are lower bounded functions. The power ports through which master and slave sides are interconnected to the communication channel, will be denoted by $(e_m, f_m)$ and $(e_s, f_s)$ respectively.

Master and slave sides exchange power through a transmission line. In case of negligible delay it is possible to implement the interconnection between master and slave sides by means of a power preserving interconnection using directly effort and flow variables.

There are infinite possible power preserving interconnections but one of the most used in port-Hamiltonian based bilateral telemanipulation is the common effort interconnection which is described by

$$
\begin{align*}
&\begin{cases}
  e_m(t) = e_s(t) \\
  f_s(t) = -f_m(t)
\end{cases}
\end{align*}
$$

Using this interconnection strategy, the power supplied to the slave side by means of $(e_s(t), f_s(t))$ is exactly that extracted from the master side through $(e_m(t), f_m(t))$ since:

$$
P_s(t) = e_s^T(t)f_s(t) = -e_m^T(t)f_m(t) = -P_m(t)
$$

Figure 4: The overall bilateral telemanipulation scheme
where $P_s(t)$ and $P_m(t)$ indicate the incoming power flow at the master and slave sides respectively.

Thus, the overall teleoperation system is a port-Hamiltonian system being the power preserving interconnection of two port-Hamiltonian system (master and slave sides). Because of Eq.(3) and because of the lower boundedness of $H_m$ and $H_s$, the overall system is passive and, therefore, characterized by a stable behavior both in free motion and in case of interaction with passive environments.

**4. FORCE DEPENDENT SCALING IN CASE OF NEGLIGIBLE COMMUNICATION DELAY**

In this section we consider port-Hamiltonian based bilateral telemanipulators where the communication channel is characterized by a negligible delay. We will show how to implement a variable scaling of the effort fed back to the master side, and in particular the scaling reported in Eq.(1), while preserving a dissipative, and therefore stable, behavior of the overall scheme. As reported in Section 2, in order to improve the feeling of remote interaction perceived by the user it is necessary to scale the effort fed back from the slave side. Thus, we consider the following interconnection between master and slave sides:

\[
\begin{align*}
  e_m(t) &= \alpha(e_s(t)) e_s(t) - \beta f_m(t) \\
  f_s(t) &= -f_m(t)
\end{align*}
\]  

The effort transmitted to the user is scaled and the scaling factor, $\alpha(e_s(t))$, is not constant. Furthermore, a variable damping action, characterized by a scalar $\beta > 0$ is added in the interconnection to guarantee the dissipativity of the overall telemanipulation system.

From the experimental results reported in Section 2, it turns out that the amount of scaling along each component of $e_m(t)$ can be different and that the scaling factor of the $i^{th}$ component is independent of the other scaling factors. Thus, $\alpha(e_s(t))$ is a diagonal matrix whose entries in the diagonal are, in general, variable and different. Furthermore, in order to preserve the sign of the effort transmitted to the master side, all the diagonal entries of $\alpha(e_s(t))$ have to be positive (this is verified for the experimental scaling derived in Eq.(1)). Finally, all the scaling factors have to be lower bounded, with a lower bound greater than zero, in order to avoid that the scaling deletes the
force feedback, and upper bounded because of the intrinsic saturation of the force that can be fed back. In summary, the scaling matrix is given by

\[
\alpha(e_s(t)) = \begin{pmatrix}
a_1(e_{s1}(t)) & 0 & 0 & \ldots & 0 \\
0 & a_2(e_{s2}(t)) & 0 & \ldots & 0 \\
\vdots & \vdots & \ddots & \ddots & \vdots \\
0 & 0 & 0 & \ldots & a_n(e_{sn}(t))
\end{pmatrix}
\]  

(7)

where \( e_s(t) = (e_{s1}(t), \ldots, e_{sn}(t)) \), \( n \) is the dimension of the effort fed back to the master side and

\[
\bar{a}_{\min} < a_i(e_{si}(t)) < \bar{a}_{\max}, \quad i = 1, \ldots, n
\]

Setting \( \bar{a}_{\min} = \arg\min_i \bar{a}_{\min} \) and \( \bar{a}_{\max} = \arg\max_i \bar{a}_{\max} \), we obtain

\[
\bar{a}_{\min} < a_i(e_{si}(t)) < \bar{a}_{\max} \quad i = 1, \ldots, n
\]

(8)

In the following, to keep the notation light, we will drop the dependency of all the scaling variables from \( e_s(t) \) and its components.

Notice that, using Eq.(6), we have that

\[
P_s(t) = e_s^T(t)f_s(t) \neq -e_m^T(t)f_m(t) = -P_m(t)
\]  

(9)

Thus the interconnection between master and slave sides is no more power preserving. This prevents us from proving passivity of the overall teleoperation system. Nevertheless, we will prove the dissipativity of the system with respect to the supply rate \( e_s^T f_H + e_m^T \alpha f_E \). This will be sufficient for guaranteeing a stable behavior of the teleoperation system. In the following, we will use the following Lemma, proposed in [28] in the context of haptic interfaces. The proof is reported in Appendix A for completeness.

**Lemma 1.** Let \( f : \mathbb{R} \mapsto \mathbb{R} \) be a real function such that

\[
\int_0^t \dot{f}(\tau)d\tau \geq -\delta \quad \forall t \quad \delta \in \mathbb{R}^+, \delta < \infty
\]  

(10)

and let \( \gamma : \mathbb{R} \mapsto \mathbb{R}^+ \) be a scaling function such that

\[
\gamma \leq \gamma(t) \leq \overline{\gamma} \quad \forall t \quad \gamma, \overline{\gamma} \in \mathbb{R}^+
\]  

(11)
Suppose that the function \( f(\cdot) \) has a finite number of critical points, namely that its derivative changes sign a finite number of times. Then

\[
\int_0^t \gamma(\tau) \dot{f}(\tau) d\tau
\]  

(12)
is lower bounded.

The master side and the slave sides are port-Hamiltonian systems and the following power balances hold:

\[
e^T_H(t) f_H(t) + e^T_m(t) f(t) = \dot{H}_m(t) + P_{dm}(t)
\]

(13)

\[
e^T_E(t) f_E(t) + e^T_s(t) f_s(t) = \dot{H}_s(t) + P_s(t)
\]

It is possible to relate the the supply rate \( e^T_H(t) f_H(t) + e^T_E(t) \alpha(t) f_E(t) \) to the energy stored at the master side. In fact, using Eq.(6), it can be written:

\[
e^T_m(t) f_m(t) + e^T_s(t) \alpha(t) f_s(t) + \beta f^T_s(t) f_s(t) = 0
\]  

(14)

Thus, we can add the quantity at the left hand side of Eq.(14) to the supply rate without altering its value. In other words, we can write:

\[
e^T_H(t) f_H(t) + e^T_E(t) \alpha(t) f_E(t) =
\]

\[
e^T_H(t) f_H(t) + e^T_m(t) f_m(t) + e^T_s(t) \alpha(t) f_s(t) + \beta f^T_s(t) f_s(t) + e^T_E(t) \alpha(t) f_E(t)
\]  

(15)

Using Eq.(13) in Eq.(15), we can write

\[
e^T_H(t) f_H(t) + e^T_E(t) \alpha(t) f_E(t) =
\]

\[
= \dot{H}_m(t) + P_{dm}(t) + e^T_s(t) \alpha(t) f_s(t) + e^T_E(t) \alpha(t) f_E(t) + \beta f^T_s(t) f_s(t)
\]  

(16)

Considering that the scaling matrix \( \alpha(t) \) has the structure reported in Eq.(7) we can write:

\[
e^T_m(t) \alpha(t) f_m(t) + e^T_s(t) \alpha(t) f_s(t) + \beta f^T_s(t) f_s(t) =
\]

\[
= \sum_{i=1}^n a_i(t)(e_{s_i}(t)f_{s_i}(t) + e_{E_i}(t)f_{E_i}(t)) + \beta \sum_{i=1}^n f_{s_i}^2(t)
\]  

(17)
In order to make the notation compact, we set
\[ e_{s_i}(t)f_{s_i}(t) + e_{E_i}(t)f_{E_i}(t) = e_i(t)f_i(t) \quad i = 1, \ldots, n \]  
(18)

Notice that
\[ \sum_{i=1}^{n} e_i(t)f_i(t) = e_s^T(t)f_s(t) + e_E^T(t)f_E(t) \]  
(19)

Now, using Eq.(18) in Eq.(17) we have that
\[ e_s^T(t)\alpha(t)f_s(t) + e_E^T(t)\alpha(t)f_E(t) + \beta f_s^T(t)f_s(t) = \sum_{i=1}^{n} a_i(t)e_i(t)f_i(t) + \beta \sum_{i=1}^{n} f_{s_i}^2 \]  
(20)

Denote by \( I = \{1, \ldots, n\} \) a set of indexes and let
\[ J_1(t) = \{i \in I \text{ s.t. } e_i(t)f_i(t) > 0\} \quad J_2(t) = \{i \in I \text{ s.t. } e_i(t)f_i(t) \leq 0\} \]  
(21)

be two time dependent subsets of \( I \). Using Eq.(21), we can rewrite Eq.(20) as
\[ P_1(t) = \sum_{i=1}^{n} a_i(t)e_i(t)f_i(t) = \sum_{i \in J_1(t)} a_i(t)e_i(t)f_i(t) + \sum_{i \in J_2(t)} a_i(t)e_i(t)f_i(t) \]  
(22)

Now set
\[ a_m(t) = \min\{a_i(t) \text{ s.t. } i \in J_1(t)\} \quad a_M(t) = \max\{a_i(t) \text{ s.t. } i \in J_2(t)\} \]  
(23)

then, using Eq.(22) we can write
\[ P_1(t) \geq a_m(t) \sum_{i \in J_1(t)} e_i(t)f_i(t) + a_M(t) \sum_{i \in J_2(t)} e_i(t)f_i(t) \geq a_m(t) \sum_{i=1}^{n} e_i(t)f_i(t) - \bar{d}(t) \]  
(24)

where \( d(t) > 0 \) represent a possible power production due to the fact that Eq.(6) is not a power preserving interconnection. If \( a_m(t) > a_M(t) \), it can be easily seen that Eq.(24) holds with \( d(t) = 0 \). If \( a_m \leq a_M \) it may happen that \( d(t) \) has to be strictly positive for the inequality to hold. Let \( \bar{d}(t) = \min d(t) \) such that
\[ P_1(t) \geq a_m(t) \sum_{i=1}^{n} e_i(t)f_i(t) - \bar{d}(t) \]  
(25)
and set

$$
\beta = \begin{cases} 
0 & \text{if } \bar{d} = 0 \\
\frac{d}{\sum_{i=1}^{n} f_i} & \text{else}
\end{cases}
$$

(26)

**Remark 1.** Notice that \( f_s(t) = f_E(t) \), namely the velocity of the slave at the interconnection is the same as the velocity the slave interacts with the environment by. Thus, if \( f_s(t) = 0 \), we will never have \( \bar{d}(t) > 0 \) and \( \beta \) is always well defined.

**Remark 2.** The damping action in Eq.(6) perturbs a little the ideal interconnection between master and slave but it is necessary for compensating the active behavior of the interconnection. Nevertheless, we activate the damping action only when necessary, namely only when some extra power is produced in the interconnection, minimizing its effect on the transparency of the teleoperation system. When the damping term is active a viscous force is added to the scaled force that is fed back to the user.

Using Eq.(24) with Eq.(26) and Eq.(20) it can be seen that

$$
e_s(t)\alpha(t)f_s(t) + e_E^T(t)\alpha(t)f_E(t) \geq a_m(t) \sum_{i=1}^{n} e_i(t) f_i(t) 
$$

(27)

Recalling Eq.(19) and using Eq.(13), we can write

$$
e_s^T(t)\alpha(t)f_s(t) + e_E^T(t)\alpha(t)f_E(t) \geq a_m(t)(e_s^T(t)f_s(t) + e_E^T(t)f_E(t)) = a_m(t)(\dot{H}_s(t) + P_{d_s}(t))
$$

(28)

By construction, \( a_m(t) > 0 \) and, because of the passivity of the slave side, we have that \( P_{d_s}(t) \geq 0 \). Thus, we can write that

$$
e_s^T(t)\alpha(t)f_s(t) + e_E^T(t)\alpha(t)f_E(t) \geq a_m(t)\dot{H}_s(t)
$$

(29)

Using Eq.(29) with Eq.(16) and reminding that, because of the passivity of the master side, \( P_{d_m}(t) \geq 0 \), we can write

$$
e_s^T(t)\alpha(t)f_H(t) + e_E^T(t)\alpha(t)f_E(t) \geq \dot{H}_m(t) + a_m(t)\dot{H}_s(t)
$$

(30)

the overall telemanipulation system is dissipative if and only if the right-hand side is the derivative of a lower bounded storage function. \( \dot{H}_m(t) \) is the
derivative of $H_m(t)$ which is lower bounded because of the passivity of the master side. The term $a_m(t)\dot{H}_s(t)$ is the derivative of

$$\int_0^t a_m(\tau)\dot{H}_s(\tau)d\tau$$

which is lower bounded since both $H_s(t)$ (in all the realistic cases) and $a_m(t)$ satisfy the hypotheses of Lemma 1. Thus we have that

$$\int_0^t [e_H^T(\tau)f_H(\tau) + e_E^T(\tau)\alpha(\tau)f_E(\tau)]d\tau \geq H(t) - H(0) \quad (31)$$

namely the integral of a function of the power variables through which the system interacts with the rest of the universe is greater or equal than the amount of generalized energy stored in the system. This means that the system is dissipative [25]. This result can be summarized in the following:

**Proposition 1.** Consider the port-Hamiltonian based telemanipulation system represented in Fig. 4. If master and slave sides are interconnected by means of the effort dependent scaling reported in Eq.(6), where the scaling matrix satisfies the conditions reported in Eq.(7) and Eq.(8) and the damping coefficient is chosen accordingly to Eq.(26), then the overall telemanipulation system is dissipative.

As stated in [18] for constantly scaled interconnections, the scaling between master and slave prevents from proving passivity of the overall system and allows only proving dissipativity. Dissipativity comes from the fact that it is necessary to scale the energetic behavior of the slave side in order to give to the operator a realistic feeling and thus, the power balance of the overall system has to contain a scaled version of the power exchanged with the environment instead of the “real” power. Nevertheless the fact that the telemanipulation system is dissipative with respect to the supply rate $e_H^T(t)f_H(t) + e_E^T(t)\alpha(t)f_E(t)$ is still sufficient for guaranteeing that the overall system is characterized by a stable behavior when interacting with any passive environment. In fact, as it happens in non scaled telemanipulation, in case of interaction with any passive environment $-e_E^T(t)f_E(t) \geq H_e(t)$, where $H_e(t)$ is the lower bounded storage function characterizing the passive environment. Using the same techniques exploited in Proposition 1 and assuming that $H_e(t)$ has only a finite number of critical points (as it happens for the big majority of physical environments), it is possible to see that
\[-e_E^T(t)\alpha(t)f_E(t) \geq \dot{\tilde{H}}_e(t),\] where $\tilde{H}_e(t)$ is a lower bounded energy function.

Thus, replacing this power balance in Eq.(31) it is possible to see that the overall system is passive with respect to the power port $(e_H(t), f_H(t))$ and that, therefore, it is characterized by a stable behavior. In case of free motion, $e_E(t) = 0$ and, therefore, it follows directly from Eq.(31) that the overall system is passive with respect the port $(e_H(t), f_H(t))$.

5. APPROACH VALIDATION

In this section we report the experimental results that validate the role of the force dependent scaling matrix in improving the capabilities of the user in the detection of force variations.

5.0.1. Hypothesis

Since in a teleoperated kinesthetic interaction, the subject lacks direct tactile information, the probe of the slave robot has to firmly penetrate the object before she/he, via force feedback, is able to make use of kinesthetic cues and deduce the features of the environment [9]. The deeper the probe pushes into the deformable body, the higher the contact forces are, and the better the user perceives the object. But, in several tasks, it is necessary to achieve a compromise between accuracy in object discrimination, governed by the magnitude of force feedback, and the temporal and displacement extent of surface penetration, which is tightly related to the probability of damaging the object [29].

In the current work, we evaluate the goodness of the proposed scaling method by arranging perceptual experiments in a teleoperation setup. We hypothesized that, by involving the just mentioned signal processing, subjects can feel the presence of a deformable object with a reduced penetration inside the object itself, that is, a reduced probability of object damage.

5.0.2. Apparatus

The experimental setup involves the use of a Force Reflecting Hand Controller (FRHC), designed and developed at NASA’s Jet Propulsion Laboratory [30], on the master side, and a Staubli Puma 260 on the slave side. Force sensing is performed by an Ati Mini 45 Force/Torque sensor, mounted on the tip of the slave. Communication between master, slave and sensor is handled by the Penelope architecture developed at the Altair Laboratory [31].
FRHC is a fully backdrivable mechanical system and it behaves as a passive system. The Staubli Puma 260 has been made passive by compensating the gravitational effects. Master and slave sides exchange information using the interconnection structure proposed in Eq. (6) where the scaling matrix is deduced from the experimental psychophysical data reported in Sec. 2.

Master positions are mapped on the slave workspace, while force/torque information is mapped and sent to the master at a rate of 1 KHz.

Stimuli are 60×40×20 mm gel wax objects (Hobbyland srl, Legnano, Italy), with different paraffin inclusions (none, 8%, and 16%). The stiffness value of these objects was measured, and it was found to be, respectively, 111, 308, and 1517 N/m.

5.0.3. Methods

Two experiments measure the penetration depth threshold for a task of pliable surface detection. This threshold corresponds to the smallest penetration depth that can be used to reliably perceive the contact with the surface of a pliable object, and to retract the probe upon touching it.

Subjects are asked to move the haptic device along the designed direction until they feel contact with the surface of the object; once contact is perceived, subjects are instructed to instantly stop their motion and move backwards, as soon as possible.

In the first experiment we account for a movement along one direction (i.e. along the horizontal plane, movement close-far, direction $x$, and along the vertical plane, movement up-down, direction $z$, see Fig. 1). Three factors are manipulated in a full factorial design: 3 stimuli × 2 movement directions × 2 signal manipulation activation (on, or off).

In the second experiment we involve a movement along two directions (i.e. along the x-z space) to feel a surface not aligned with the FRHC axes. Two factors are here manipulated: 3 stimuli × 2 signal manipulation activation.

Penetration depth ($D_p$), exerted force ($F$), and reaction time ($RT$) are recorded as dependent variables. Combinations of the experimental parameters are tested in random order for 15 repetitions each. Each experiment takes about 30 minutes. The subjects take a break every 3 minutes and whenever fatigue occurs. All the participants are given practice trials before experimental data is recorded.
5.0.4. Participants

A total of 7 males have been examined (age range from 22 to 33). The participants have been recruited from within the staff of the ALTAIR laboratory of the University of Verona (Italy). All the participants have a normal sense of touch and have used their dominant hand to perform the task. All the participants took part to the first experiment; three ones were involved in the second one.

5.0.5. Statistical Analysis

Statistical analysis was conducted separately for each subject and for aggregate data. Every analysis of variance (ANOVA) included a factor for individual subjects so that differences between subjects were not counted as random variation; this made each analysis more sensitive to the stimulus parameter being varied.

5.0.6. Results

For each trial, penetration depth and penetration force are logged for data analysis. Fig. 5 shows a prototypical motion path. It is possible to observe how measured force is constant until the object is reached; when the object is reached, the force/torque sensor measure the force rendered by the pliable object; the maximum penetration is reached when the maximum force is exerted. From this point, a clear movement in the opposite direction is begun. Moreover, it can be seen that the damping term is rarely needed, and that the perturbation of the scaling term is limited. The exerted force measured with the factorial design is plotted in Fig. 6(a) for one prototypical direction, and in Fig. 6(b) for the motion along the $x$-$z$ space. For all subjects, data clearly show that the applied force increases as surface stiffness increases. A decreasing trend is observed in applied force in the presence of scaling.

For the movement along the horizontal plane, when no dedicated scaling is involved, we measure a median applied force equal to 1.26 N (Interquantile Range, IR, from 1.09 to 1.61 N) for the low stiffness object, a force of 1.60 N (IR from 1.27 to 2.09 N) for the medium stiffness object, and a force of 2.62 N (IR from 2.19 to 3.17 N) for the harder one. When the scaling function is applied, we observe a reduced force equal to 1.00 N (IR from 0.84 to 1.35 N), 1.49 (IR from 1.24 to 1.82 N), and 2.30 N (IR from 2.01 to 2.60 N) for the softer, medium, and harder objects respectively. That is, the scaling function reflects a 13.0 percent decrease in the force to the objects. Very similar results are obtained for the movement along the vertical plane and for the movement
Figure 5: Prototypical data for the contact of a high stiffness object when scaling is applied: a) the damping term $\beta f_m(t)$ plotted against time, b) in black scaled force and in blue measured force (timeframe is underlined by vertical dashed lines at values $T_0$, $T_1$, $T_2$), c) observed position, plotted against time. The dotted gray lines refer, from left to right respectively, to the contact time, the maximum penetration, and the total time inside the surface respectively.
along the $x$-$z$ space: a similar trend can be observed for both the stiffness factor and the scaling one.

For each subject, we test the significance of the observed differences due to the factorial design. We employ a Repeated-Measure ANOVA (penetration predicted by scaling, direction, and stimuli; error terms: subjects and repetitions) to determine if there are significant differences in penetration depth values.

For the first experiment, we obtain that the interaction between scaling, stiffness and direction ($F_{2,929} = 8.45$, $p$-value < 0.001), and between scaling and direction ($F_{1,929} = 6.46$, $p$-value < 0.01) are significant. Moreover, the applied force changes according to the factorial conditions movement direction ($F_{1,929} = 37.29$, $p$-value < 0.001), and stimuli are always recognized as different ($F_{2,929} = 275.28$, $p$-value < 0.001). For the second experiment, we observe comparable results. As expected, the factor scaling is highly significant ($F_{1,230} = 10.07$, $p$-value < 0.001), as well as the factor stiffness ($F_{2,230} = 4.27$, $p$-value < 0.01).

We can conclude that the scaling function has a significant role in decreasing the applied force for all the stimuli and along the different directions. As expected, due to the non linear definition of the scaling function, we expect a not equal improvement in stimuli perception along the different directions and the different stimuli.

With respect to [32], in which this experiment is conducted only in a
virtual environment, in the current study we observe a lower applied force, which can indicate that the perception of real objects is not degraded by a real teleoperation system.

6. CONCLUSIONS AND FUTURE WORKS

In this paper we presented an innovative force scaling for bilateral teleoperated system. We focused our attention on human perception capabilities and, on the base of previous psychophysical experiments, we exploited the human ability to perceive forces and torques differently along different directions. We used acquired information in order to obtain the right modifications needed to enhance the information contained in the force signal by defining a function that maps the JND% behavior and that can be customized for each subject and for each cartesian direction.

We described one way to enhance sensitivity by extending the human perception beyond differential thresholds. Then we proved the stability of the scaled teleoperation system in the case of negligible communication delay using Port-Hamiltonian systems and the theory of dissipativity.

A discrimination experiment aimed at testing whether previously undifferentiable forces are now differentiable is presented. Experiments with one- and two- dimension environments indicate that the operator is able to perceive the contact with pliable objects using a teleoperated system with signal manipulation by applying lower contact force than through direct manipulation.

Without signal manipulation the JND is high for low force signal value, so that it is degraded the perception of small differences in force, i.e. the ones that let the perception of the contact. While any linear force amplification, such as the one proposed in [10], can let a user to better perceive differences around small intensities, a non uniform scaling let the user both to identify such differences and simultaneously to not exceed in amplifying high intensities which could outbound the device capability. According with [33], we stress that a variable scaling can bring to a uniform JND, which can enhance discrimination of pliable objects. Anyway, in the current work we do not investigate the whole range of force perception, focusing only on the forces generating while touching a pliable object, and we do not compare the efficiency of different signal manipulation functions.

We think that the task proposed here can also be interpreted as evidence that the exploratory force is clearly reduced by the proposed signal manipu-
lation. That is, the users reliably feel the scaled contact force, against the not manipulated condition where they did not recognize the force contribution due to the contact experience. The exploitation of the variable scaling can enhance advance teleoperation applications, such as surgery.

In the future, we would like to extent the results obtained with the dissipativity based demonstration in case of non negligible communication delay, in order to make our scaling strategy robust for any type of transmission, including Internet.

A. PROOF OF LEMMA 1

Let \( \text{sign}(\cdot) \) indicate the sign function. Consider an interval \([t_0, t_1]\) such that \( \text{sign}(\dot{f}(t)) = \text{const.} \ \forall t \in [t_0, t_1] \). We can distinguish three cases. If \( \text{sign}(\dot{f}(t)) = 1 \) then

\[
\int_{t_0}^{t_1} \gamma(\tau) \dot{f}(\tau) d\tau \geq \gamma(f(t_1) - f(t_0)) = \gamma(f(t_1) - f(0)) + \gamma(f(0) - f(t_0)) \geq -\gamma \delta + \gamma(f(0) - f(t_0)) \quad (32)
\]

If \( \text{sign}(\dot{f}(t)) = 0 \) then

\[
\int_{t_0}^{t_1} \gamma(\tau) \dot{f}(\tau) d\tau = 0 \quad (33)
\]

If \( \text{sign}(\dot{f}(t)) = -1 \) then

\[
\int_{t_0}^{t_1} \gamma(\tau) \dot{f}(\tau) d\tau \geq \gamma(f(t_1) - f(0)) + \gamma(f(0) - f(t_0)) \geq -\gamma \delta + \gamma(f(0) - f(t_0)) \quad (34)
\]

Every interval \([0, t]\) can be split up in the following way

\[
[0, t] = [0, t_1] \bigcup \bigcup_{i=1}^{p} I_{p_i} \bigcup \bigcup_{j=1}^{n} I_{n_j} \bigcup \bigcup_{k=1}^{z} I_{z_k} \quad (35)
\]

where

\[
I_{p_i} = [t_1, \bar{t}_i] \quad \bar{t}_i > t_i \quad \text{sign}(\dot{f}(t)) = 1 \forall t \in I_{p_i}
\]

\[
I_{n_j} = [t_j, \bar{t}_j] \quad \bar{t}_j > t_j \quad \text{sign}(\dot{f}(t)) = -1 \forall t \in I_{n_j} \quad (36)
\]

\[
I_{z_k} = [t_k, \bar{t}_k] \quad \bar{t}_k > t_k \quad \text{sign}(\dot{f}(t)) = 0 \forall t \in I_{z_k}
\]
and where \( \text{sign}(\dot{f}(t)) = \text{const.} \) \( \forall t \in [0, t_1] \). Let \( \Gamma \) be defined as:

\[
\Gamma = \begin{cases} 
\gamma & \text{if } \text{sign}(\dot{f}(t)) = -1 \forall t \in [0, t_1] \\
0 & \text{if } \text{sign}(\dot{f}(t)) = 1 \forall t \in [0, t_1] \\
\gamma & \text{if } \text{sign}(\dot{f}(t)) = 1 \forall t \in [0, t_1] 
\end{cases}
\] (37)

Thus we can write

\[
\int_0^t \gamma(\tau) \dot{f}(\tau) d\tau \geq \Gamma \int_0^{t_1} \dot{f}(\tau) d\tau + \sum_{i=0}^p \int_{t_i}^{t_1} \gamma(\tau) \dot{f}(\tau) d\tau + \sum_{j=1}^n \int_{t_j}^{t_1} \gamma(\tau) \dot{f}(\tau) d\tau \\
\geq -\Gamma \delta + \sum_{i=0}^p (-\gamma \delta + \gamma(f(0) - f(t_i))) + \sum_{j=1}^n (-\gamma \delta + \gamma(f(0) - f(t_j))) \\
= -\Gamma \delta - p\gamma \delta - n\gamma \delta + \gamma \sum_{i=0}^p (f(0) - f(t_i)) + \gamma \sum_{j=1}^n (f(0) - f(t_j))
\] (38)

\( f(t_i) \) and \( f(t_j) \) are finite since they are critical points. Furthermore, because of the hypothesis, \( p < \infty \) and \( n < \infty \) and therefore the sums are finite and consequently the integral is lower bounded.

References


