Influence of User Grasping Position on Haptic Rendering

Mildred J. Puerto, Jorge Juan Gil, Hugo Álvarez and Emilio Sánchez

Abstract—This paper investigates the effect of user grasping position on the performance of haptic rendering. Two dynamic models, with seven and eleven parameters respectively, have been used to characterise the PHANToM haptic interface and the user. The parameter variability analysis shows that user grasping position significantly affects system dynamics. This variation also influences the phase margin of the system, leading to different damping factors in response to contacts with rigid virtual objects. To compensate this effect, an adaptive haptic rendering has been developed and successfully implemented, imposing a similar damping factor in the transient responses for all grip positions.

Index Terms—Haptics and haptic interfaces, human factors, physical human-robot interaction.

I. INTRODUCTION

Mechanical design of haptic interfaces is an important research field to ensure the usability of this kind of system [1], [2], [3], [4]. The end-effector of the interface is one of the key elements to achieve a natural immersion in the virtual task. Stylus-like end-effectors are commonly used in haptic interfaces [5]. Depending on the application, final users can hold the stylus in many different ways—probably, as he or she feels most confident. From the control point of view, this results in variable and unknown dynamic properties present in the system’s loop [6], which leads to variable stability margins. Thus, a good model of the human hand behaviour is fundamental to correctly design and tune haptic controllers.

Many researchers have proposed dynamic models for the user manipulating a mechanical device [7], [8], [9]. A second-order time-invariant system consisting of a mass-spring-damper body has been widely used to model the operator [10], [11], [12] and a five-parameter model has also been proposed for human impedance [13], [14]. Despite the increasing complexity of previous models, some human characteristics remain unmodelled when using these approximations. Moreover, the proposed models are usually taken as time-invariant, but the user can voluntarily change his/her own dynamics. For example, different frequency responses—and consequently human wrist models—can be obtained depending on the user’s grasping force [15]. The influence of the user depends on many factors, such as the user’s physical characteristics, grasping distance, applied force and even the task instructions [16]. Recently, some authors have included uncertainties in the human model, e.g., by means of introducing a fixed boundary in the frequency response [17], or introducing a factor that may take different values within a certain range [18].

It is possible to analyse the stability of the haptic interaction without a concrete model for the user, assuming that he/she is passive [19], [20], [21]. Only the model of the haptic interface is required in this kind of study. Nevertheless, without modelling either the user or the mechanical device, it is possible to experimentally analyse the influence of some factors on the haptic interaction or perception. For example, the effect of force saturation [22] or the virtual stiffness [23] on the haptic perception of detail.

The purpose of this work is to analyse system dynamics, depending on user grasping position, to establish a quantitative relation between the frequency response of the system and the transient properties of the response to a haptic rigid contact. First, some physical models for the system (device and user) with concentrated parameters are derived in Section II. Experiments with multiple participants show that system dynamics strongly vary with user grasping position. A statistical study (Section III) reveals that variability depends more significantly on the grip position than on the identity of the subject. Later on, in Section IV, the phase margin of the frequency response is related to the damping factor of the transient response to a rigid contact. This response is more stable (higher damping factor) when the user is grasping the stylus closer to its tip. Finally, in Section V, an adaptive control strategy is proposed to impose a nearly constant damping factor, that is, independent of the grasping position.

II. EXPERIMENTAL SYSTEM MODELS

To analyse the influence of grasping position on haptic rendering, some dynamic models for the overall system, the user and the haptic device, are estimated in this section. A system identification method based on frequency response has been applied to characterise the system’s transfer function. The protocol and details of the experimental process are explained in the following subsections.

A. Apparatus and participants

The first degree of freedom of the PHANToM Premium 1.0 was used as a testbed (φ-axis in Fig. 1). This device is a desktop haptic interface with low inertia and high back-drivability. To perform the experiments in the same kinematic configuration, the links of the parallelogram were mechanically locked. Thus, the centre of the gimbal (point A) was placed at 17 cm from the axis of rotation φ and at a height of 15 cm from the surface of the table.

The system was controlled by a dSPACE DS1104 acquisition board running at a sampling frequency of 1 kHz. The input signal was a torque τ in the motor that moves the horizontal pulley of the device, while the measured output was the rotation of the encoder coupled to the motor. Both signals were mapped to φ-axis in SI units. Therefore, the transfer function,

\[ G(s) = \frac{\phi(s)}{\tau(s)}, \]

that will be obtained, only applies to the described kinematic configuration and contains rotational parameters. However, the equivalent linear parameters (in x-axis) for the user and the device at the tip of
the end-effector (point A) can be derived by dividing the rotational variables by 0.17² m².

Thirteen subjects took part in the experiments, five women and eight men, from 25 to 43 years old. All were right-handed and reported normal tactile function. All subjects had prior experience with haptic applications using the PHANToM, but they were not trained to perform the experiments.

B. Procedure

The participants were asked to hold the stylus of the device like a pencil (tripod grasp using thumb, index and middle fingers) with their right hand at six different positions along the stylus. Thus, six experiments were performed by each subject: one per grasping position. The stylus was divided into six segments: position 1 corresponded to placing the fingers at the tip of the stylus, while position 6 corresponded to the opposite extreme. Each segment was approximately 2 cm long. Fig. 2 shows the six different positions where the user could grasp the stylus. The user’s elbow rested on the table where the device was placed.

The only instruction given to the participants was to maintain a constant, moderate grip force and keep the hand still while the torque signal was being rendered, but not to resist the motion of the device.

C. Data processing and experimental frequency response

A good knowledge of the system helps define the input signal. The user’s dynamics mainly influences a robotic system at relatively low frequencies (typically < 30 Hz) [14]. On the contrary, rigid mechanical devices exhibit vibration modes at relatively high frequencies. In the case of the PHANToM 1.0, the first vibration mode takes place at approximately 60 Hz [14]. Therefore, to model both the user and the first vibration mode of the device, the frequency range under analysis in this study is from 0.5 to 70 Hz.

To correctly excite all the frequencies under study, the torque input was a white-noise signal lasting 20 s within a frequency range from 0.1 to 150 Hz, that is, slightly more than an octave under and above the selected limits. MATLAB’s empirical transfer function estimation algorithm (tfestimate) was used to plot the resulting Bode diagrams. A hanning window 4096 points in length with a 50% overlap was selected for data processing.

The length of the experiment, 20 s, allows the tfestimate algorithm to average the resulting Bode plot, leading to a smooth and reliable frequency response. Fig. 3 shows the frequency responses of the system for grasps by user 1 at the six different positions. As expected, the first vibration mode arose at approximately 60 Hz. Although the same user was grasping the stylus, the system response strongly varied with the grip position. Quite similar responses were obtained for the other users. The statistical analysis on the system’s variability as a function of the users and the grasping position will be performed in Section III.

D. System models and parameter fitting

To estimate a transfer function for the system described by (1), an appropriate model has to be selected. The shape of the frequency responses (Fig. 3) can be used to help determine the number of poles and zeros the models should have [24]. For user 1 and grasping positions 1, 2 and 3, the shape of the experimental response is quite complex, but a sixth-order transfer function with 6 poles and 4 zeros could adequately fit the system dynamics (Fig. 4 top). However, for grasping positions 4, 5 and 6, a fourth-order transfer function with only 4 poles and 2 zeros was enough to model the system (Fig. 4 bottom).

In both cases, the gain diagram is constant at low frequencies and the phase diagram tends to 0º. Thus, the models have to be type-0 transfer functions with position error constants of 20 log Kp (dB).

1) Eleven-parameter model: For positions 1, 2 and 3, an eleven-parameter model inspired by [14], [25] was used to characterise system response (Fig. 5 top). In [14] it was successfully used for this purpose. The device dynamics is decoupled into two masses, while the user introduces additional mass to the system. The use of these concentrated parameters is only a practical assumption that allows for a physical interpretation of the parameters, but the real device and user have distributed masses. Using this physical model, the relationship between the measured output position X1 and the input force of the motor F is

\[
G(s) = \frac{X_1(s)}{F(s)} = \frac{p_h(s)p_2(s) - p_1^2(s)}{[p_h(s)p_2(s) - p_1^2(s)]p_1(s) - p_2^2(s)p_h(s)}
\]
where

\[ p_c(s) = b_c s + k_c, \]  
\[ p_s(s) = b_s s + k_s, \]  
\[ p_1(s) = m_1 s^2 + b_1 s + p_c(s), \]  
\[ p_2(s) = m_2 s^2 + b_2 s + p_c(s) + p_s(s), \]  
\[ p_3(s) = m_h s^2 + b_h s + k_h + p_s(s), \]  

leading to a type-0 sixth-order transfer function (with 6 poles and 4 zeros), whose position error constant is

\[ K_p = \lim_{s \to 0} G(s) = \frac{1}{k_c} + \frac{1}{k_s} + \frac{1}{k_h}. \]  

Therefore, the resulting \( K_p \) is the inverse of the overall stiffness of the system: \( k_c, k_s \) and \( k_h \) in series. This value is easily identified in the experimental responses (Fig. 3) and changes significantly with user grasping position.

2) Seven-parameter model: For grasping positions 4, 5 and 6, an alternative model with only two masses and 7 parameters was used (Fig. 5 bottom). With this new model, the transfer function for the system is

\[ H(s) = \frac{X_1(s)}{F(s)} = \frac{q_2(s) q_1(s) - q_3(s)}{q_2(s) q_1(s) - q_3(s)}, \]  

resulting in a type-0 fourth-order transfer function (with 4 poles and 2 zeros), whose position error constant is

\[ K_p = \lim_{s \to 0} H(s) = \frac{1}{k_c} + \frac{1}{k_s}. \]  

3) Parameter fitting: Model parameters have been identified by fitting the experimental responses to the proposed transfer functions with 11 and 7 variables, equations (2) and (9) respectively. A least-squares iterative method developed in Matlab has been used. Table I shows the estimation for all the participants, while Fig. 6 shows the frequency response of the models for user 1. Null values in Table I are, in fact, very small non-null values (<0.001) that are not shown to avoid overstating the precision with which they are known.

Most of the participants had the model transition (eleven-parameter model) from grasping position 3 to 4, but this was not a general behaviour.

E. Discussion on the models

Analysing the resulting parameters in Table I, and for farther grasping positions, variable \( K_p \) can be approximated by

\[ K_p = \lim_{s \to 0} H(s) \approx \frac{1}{k_s}, \]  

because the stylus/skin stiffness \( k_s \) is much smaller than the stiffness associated with the first vibration mode \( k_c \ll k_s \), therefore stiffness \( k_s \) prevails at low frequencies.
TABLE I
Physical parameters of the PHANToM and thirteen users grasping at six different positions (m: g m⁻², b: Nms/rad, k: Nm/rad)

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A possible physical cause of the model simplification (from 11 to 7 variables) is precisely the fact that $k_b$ becomes smaller as the grasping position changes. Beyond a certain point and although the user has not an infinite impedance, such a weak link cannot “move” the user and therefore the human operator is seen as a perfect connection to ground from the motor’s point of view. Aside from this link to ground, the user stops intervening in the dynamics of the system. However, we stress that without the presented ground connection, the previous ground condition would not exist. This is consistent with (26), where the user was modelled as a linearised endpoint stiffness.

It is interesting to note that the gain diagram of Fig. 3 starts at a lower level as the user grasps the stylus closer to the tip. Thus, the equivalent stiffness of the system —the inverse of (8) and (13)— increases as the user grasps the device closer to the tip of the stylus. Not all the parameters contribute in the same way —and weight—to the transfer function. For example, only the three stiffness coefficients impose $K_p$ (8). The combination of stiffness coefficients and masses fix the location of poles and zeros (Fig. 4), that is, their natural frequencies. Finally, the damping coefficients result in each double pole (or double zero) being more or less damped. This brief description also indicates the order of “importance” of the parameters in the transfer function (a relatively small change in one stiffness modifies the Bode diagram more than a relatively large change in one of the damping coefficients). However, the sensitivity analysis of the parameters is beyond the scope of this study. Only the variability of those parameters depending on the grip position has been analysed.

### III. PARAMETER VARIABILITY ANALYSIS

The variability of system parameters has been statistically analysed by using the two-way balanced ANOVA test on the seven parameters with balanced data, and the General Linear Model with multivariate design on the four parameters with unbalanced data ($b_2, m_1, b_6,$ and $k_6$). In both tests, the two factors are the grip position (fixed factor) and the subject (random factor). It was found that the influence of the grasping position on ten of the eleven parameters is significant ($p<0.05$). Moreover, it is extremely significant ($p<0.001$) in eight of them. Only one damping coefficient is not significantly affected: $b_6$ ($p=0.313$).

The subject factor was found to significantly influence the parameters governing the user’s dynamics ($m_1, b_6$, and $k_6$) and also half of the other parameters: $m_1$ ($p=0.031$), $k_c$ ($p<0.001$), $m_2$ ($p=0.043$) and $b_6$ ($p=0.014$). Thus, these tests show that both the user and the grip position influence the dynamics of the system. However, the grasping position affects more parameters —and in a more significant way— than the user identity. Therefore, the variability due to grasping position is greater—or more significant—than the inter-subject variability.

Given the appreciable influence of the stiffness coefficients on the frequency response of the system, parameters $k_c$ and $k_b$ have been analysed more comprehensively. The box plot of parameter $k_c$ (Fig. 7 top) shows that this stiffness coefficient tends to increase with the grasping position. A positive correlation with this parameter (Fig. 7 bottom) indicates that four groups of grip positions were identified of those parameters depending on the grip position has been analysed.
Regarding the stylus/skin stiffness \( k_s \), it tends to decrease with user grasping position (Fig. 8 upper). In fact, this parameter exhibits an exponential increment as the user grasps the stylus closer to the tip. To corroborate this, the box plot of \( \log_k(k) \) has also been included (Fig. 8 middle) showing the linear tendency of this parameter with grip position. Thus, analysing \( \log_k(k) \) instead of \( k \), a negative correlation was found (Pearson’s \( p = -0.748, p < 0.001 \)). The 95% confidence intervals for the means of \( \log_k(k) \) (Fig. 8 lower) indicate that none of the grasping positions is significantly different from its adjacent ones (except for positions 3 and 4). However, grasping positions whose relative position is at two or more locations, are always significantly different.

The comparison of the confidence intervals for parameters \( k_c \) and \( \log_k(k) \) suggests that the stylus could have been divided into only four distinguishable grasping positions. In other words, independent of the user grasping the device, system dynamics begin to be significantly different if the subject holds the stylus in positions approximately 4 cm apart. Thus, and despite the large variability found in system parameters (Table I), given a model for the system response it is possible to identify the grasping position.

This conclusion does not mean that the grasping position is the only factor that can be statistically distinguished. Other elements can be studied (grasping force levels, fist vs. tripod grasp, etc.). The experiments performed in this study have been done for a particular device, and the users held the stylus in a very similar way. The small discrepancies in the grasping between users (performing a comfortable tripod grasp) do not compromise the findings of this study. On the contrary, it seems that this kind of grasping does not present a high variability, or maybe better, it is included within user variability.

Fig. 9 shows the box plots of \( m_h \), \( b_h \) and \( k_h \) parameters using linear units. Their median values for grasping position 1 (the most appropriate for the pen-like grasp) are \( m_h = 420 \text{ g} \), \( b_h = 7.92 \text{ Ns/m} \) and \( k_h = 174 \text{ N/m} \). Some authors [27] have reported comparable values for these physical parameters, but suggesting a human model or validating an existing one is not the aim of this study.

### IV. Influence on Rigid Contacts

The frequency response of the system can be used to derive some properties of the time response to rigid contacts. Haptic controllers consist of discrete-time loops running at high frequency. The discrete-time transfer function of \( G(s) \) is defined as follows:

\[
G(z) = Z[H_0(s)G(s)],
\]

where \( H_0(s) \) is the zero-order hold. Assuming that the haptic rendering function consist of a discrete-time closed loop without delay and stiffness \( K \) to simulate a rigid wall collision, the critical stiffness for a virtual contact [14] is the gain margin (Gm) of \( G(z) \):

\[
K_{CR} = \text{Gm}\{G(z)\}.
\]

Stiffness coefficients under this limit (\( K < K_{CR} \)) exhibit stable responses. The transient properties of those responses depend on the resulting phase margin (Pm) of the system. In particular, the damping factor \( \zeta \) of the transient response is approximately the phase margin (in degrees) divided by 100° [28]:

\[
\zeta \approx \frac{\text{Pm}\{KG(z)\}}{100°}.
\]

### A. Hypothesis

The shape of the frequency responses obtained in Section II shows that once a stiffness coefficient \( K \) is selected, the phase margin of the system substantially increases as the user holds the stylus closer to
its tip. Fig. 10 shows a scheme representing this idea, inspired by the frequency response of user 1. A stiffness coefficient of, for example, $K = 10 \text{ Nm/rad}$, moves the gain diagram up 20 dB, setting—in this particular example—the gain crossover frequency at $\omega_{cg} \approx 11 \text{ Hz}$ (Fig. 3). For grasping positions 3 and 5, the resulting phase margins are 40° and 15° respectively. This means that the expected damping factor $\zeta$ of the transient response varies from 0.4 to 0.15, comparing the responses of these grip positions.

The damping factor imposes the overshoot of the position signal. In the previous example, $\zeta = 0.4$ and 0.15 lead to overshoots of 25% and 62% respectively [28]. The damping factor is also related to the settling time $t_s$ of the transient response [28]. A rough approximation is

$$t_s \approx \frac{4}{\zeta \omega_{cg}},$$

which gives 0.14 and 0.38 s for the settling times of the transient oscillations (again for user 1 grasping positions 3 and 5 respectively).

Thus, the hypothesis is that as the user grasps the stylus farther from its tip, the system response to the subject colliding against a virtual wall of 10 Nm/rad will exhibit a less damped transient. And this change in the damping factor will manifest itself in a higher overshoot and a longer system response settling time.

**B. Experimental collision responses**

A set of experimental responses have been recorded to analyse the validity of the previous hypothesis. A unique participant (user 1, female, aged 28) took part in these experiments. To simulate rigid contacts, a scenario containing a virtual wall (Fig. 11) was implemented using the Virtual Reality toolbox for MATLAB. The virtual wall was set at $\phi = 0.7 \text{ rad}$, that exactly corresponds to the plane $x = 0$ (Fig. 1), with a stiffness coefficient of 10 Nm/rad. Since the device was not mechanically locked in this case, the participant was asked to collide the wall at the marked point of the scene on the screen. This point corresponds to the same kinematic configuration as in the experiments of Section II.

The participant held the stylus of the device like a pencil (tripod grasp using thumb, index and middle fingers) with her right hand (as in Section II). In these experiments, only grasping positions 1, 3 and 5 were recorded. Although it is difficult to reproduce the same conditions in the multiple contacts (user’s force, contact velocity, etc.) the user was asked to try to collide with the same velocity and force against the wall.

Fig. 12 shows some of the obtained responses to the rigid contact. The collisions shown are typical among all the recorded experiments and were chosen particularly because they have similar contact conditions. For example, the force exerted by the user was estimated with the final penetration in the wall (very similar in the three cases), and user’s velocity before the contact was estimated by differentiating the position signal (the slope in Fig. 12). The recorded oscillations confirm the hypothesis that the same virtual object exhibits a more or less damped transient response depending on grip position. Moreover,
the experimental responses in Fig. 12 fit well with the settling times estimated in the previous subsection. Considering all the recorded trials that have similar contact conditions for grip position 5, the mean settling time is 0.401 ± 0.03 s. For grasping position 3, this mean settling time is 0.248 ± 0.036 s. The overshoots present a larger magnitude with respect to the steady-state because the initial condition for velocity was not zero (as in the case of the theoretical step response). This is also the reason why the recorded oscillation leaves the virtual wall for the third test.

It is important to note that the virtual wall of 10 Nm/rad (346 N/m at collision point A) did not include any virtual damping. The resulting damping factors depend only on the phase margin of the system, and this phase margin is introduced and enlarged by the user, as she (or he) holds the stylus closer to its tip.

C. Discussion on the contact response

The extra phase margin provided by the user justifies a common conclusion for haptic interfaces: a firm grasp tends to stabilise the system [9], [29]. The beneficial effect of the presence of the user is greater as the user holds the stylus closer to its tip. Some non-expert users tend to hold the end-effector lightly, e.g., with only two fingers at position 5 or 6, probably afraid of being harmed by the device. However, our recommendation would be to grasp the stylus firmly, closer to the tip, in order to increase the phase margin of the system.

A possible application of this knowledge for a better performance of haptic interfaces is to design the end-effector in such a way that

the user is obliged to grasp the handle in a specific manner (e.g., by means of dead-man buttons or ergonomic designs) that leads to the best dynamic properties. In the case of devices with handles that allow different types of grasps, the grip position could be sensed in order to automatically modify the properties of the virtual objects. This last application is investigated in the following section.

V. ADAPTIVE HAPTIC RENDERING

The results of the previous sections have inspired the development of an adaptive haptic rendering strategy to obtain collisions with similar damping factors. Although other possible algorithms could be designed for the same purpose, the proposed controller is relatively simple: it uses a number of predefined impedances (one per grasping position), but requires knowledge of the user’s grip position (to change from one impedance to another). Fig. 13 shows the scheme of the proposed technique.

A. Impedances definition

A viscoelastic impedance law, including a stiffness coefficient $K$ and a damping $B$, was used for the adaptive haptic rendering. The stiffness was fixed to $K = 10$ Nm/rad for all the grasping positions. The motivation for this was to ensure a nearly constant steady-state response (that is, the final penetration in the wall) if the user was exerting the same force. Thus, the damping coefficient is the only element ensuring that the damping factor is similar for all grasping positions. The required specification was to obtain a damping factor of at least 0.5 ($\zeta \geq 0.5$), that is, a phase margin of at least $50^\circ$ in the phase Bode diagram.

The models proposed for user 1 (Table I) were used to tune the damping coefficients. For grasping positions 1 and 2, and a stiffness of 10 Nm/rad (an increment of 20 dB in the gain Bode diagram), the system already has a phase margin larger than $50^\circ$. Therefore, for those grip positions, the proposed impedance (Table II) does not include any additional damping. In the other cases, the damping coefficient was tuned by using Matlab's margin function. As could be expected, the required damping coefficient $B$ increases as the user holds the stylus farther from its tip. However, quite small damping values are enough to compensate the influence of the grasping position.

B. Grasping position detection

The online transition between impedances requires the grip position to be sensed. This was done by means of computer vision

![Fig. 13. Adaptive impedance rendering depending on the grip position.](image)}

<table>
<thead>
<tr>
<th>Grasping position</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stiffness $K$ (Nm/rad)</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Damping $B$ (Nm/rad)</td>
<td>-</td>
<td>-</td>
<td>0.03</td>
<td>0.07</td>
<td>0.11</td>
<td>0.14</td>
</tr>
</tbody>
</table>
the OpenCV library. Since the colour appearances were built using
from now on.

was coloured in green. This piece will be called simply “gimbal”
to distinguish the stylus and the skin from the background during
any treatment to get a good skin detection. To help the algorithm
enveloped with a blue cover (Fig. 14). The user’s hand did not require
the online process. Since colour is used to detect the stylus, it was
selected for the plot. The expected specification for the
had the most similar conditions (velocity before the contact and force
of the users for grasping positions 1, 3 and 5. The experiments that
was 0.183 ± 0.04 s, and for grasping position 3 the mean settling time
was 0.183 ± 0.038 s. Fig. 15 shows the collision responses of one
the participants reported quite similar transition responses. The
mean value of the settling times for grasping position 5 was
0.185 ± 0.037 s and for grasping position 3 the mean settling time
0.183 ± 0.038 s. Fig. 15 shows the collision responses of one
the six possible grasping positions.

C. Experimental responses

A number of experimental collision responses to the adaptive wall
have been recorded to analyse the behaviour of this strategy. The
same 13 participants of the experiments of Section II were recruited
for these experiments and the same virtual scenario as in Section IV-B
(Fig. 11) was used. Again, the virtual wall was placed at ϕ = 0.7 rad
(as in the previous experiments) to achieve the exact correspondence
to the plane x = 0.

The instructions given to the users were to collide at the marked
point of the wall in a similar way (in terms of velocity and force)
holding the device with the tripod grasp. They could collide as many
times as they wanted (at least three times for each position). After
several contacts in a specific grasping position, they were allowed
to change the grip position to a farther position (outside the virtual
wall) and perform more collisions (without stopping the application).
An external supervisor was checking that the participants covered the
six possible grasping positions.

All the participants reported quite similar transition responses. The
mean value of the settling times for grasping position 5 was
0.185 ± 0.04 s, and for grasping position 3 the mean settling time
was 0.183 ± 0.038 s. Fig. 15 shows the collision responses of one
of the users for grasping positions 1, 3 and 5. The experiments that
had the most similar conditions (velocity before the contact and force
exerted) were selected for the plot. The expected specification for the
damping factor (ζ ≥ 0.5) was fulfilled for all users in all grasping
positions. Therefore, the adaptive haptic rendering can be successfully

techniques, using a common web camera. Image processing has been
recently used to estimate haptic properties of a remote environment
without force sensors [30]. In this case, only the grasping position
is estimated. This strategy does not require the implementation of a
sensing device in the stylus and therefore, it does not modify system
dynamics.

In an offline process, the vision algorithms learnt the colour
appearance of the stylus and skin textures. These patterns were used
to distinguish the stylus and the skin from the background during
the online process. Since colour is used to detect the stylus, it was
enveloped with a blue cover (Fig. 14). The user’s hand did not require
any treatment to get a good skin detection. To help the algorithm
identify the tip of the stylus, the gimbal link connected to the stylus
was coloured in green. This piece will be called simply “gimbal”

from now on.

The online detecting application was implemented in C++ using
the OpenCV library. Since the colour appearances were built using
hue histograms [31], the first step of the online procedure algorithm
was to convert the input image from RGB to HSV colour space.
After this, three different likelihood maps were built thresholding the
probability that the given pixel belongs to the stylus, gimbal and skin
textures (Fig. 14). Then, a contour detection was applied to the stylus
blue map, obtaining some stylus candidates. The extremes of each
candidate were extended while stylus or skin textures were detected
along its longitudinal direction. This refinement was necessary, as
the user’s hand creates small gaps in the stylus colour (Fig. 14).
To select the correct candidate, the stylus colour region having a
skin texture along it and a gimbal colour in one of its extremes was
chosen. If more than one candidate satisfied these restrictions, the
candidate with the largest area was retained. The gimbal in green
solved the ambiguity of stylus orientation. Once the stylus position
and orientation were set, the stylus was covered starting from its tip
until a skin texture was detected, which after subtracting the distance
from point A (Fig. 14) coincided with the position of the user’s grasp.
Finally, a smoothing filter [32] was applied to the estimated position
to prevent possible abrupt changes due to possible partial occlusions
or image blur.

1http://sourceforge.net/projects/opencvlibrary/
used to compensate the influence of user grip position.

It is important to note that, although the impedances were tuned using the models for user 1, the adaptive rendering worked properly for all the subjects. This result also confirms the findings reported in Section III: system dynamics varied more significantly with the grasping position than with different users.

VI. CONCLUSIONS AND FUTURE WORK

The influence of user grasping position on haptic system dynamics and its effect on the haptic rendering of rigid contacts has been thoroughly studied. It is evident that the presence of the user in the control loop is a persistent challenge for modelling system dynamics. In this study, two different mechanical models have been used to characterise the system’s transfer function. As the user holds the stylus farther from its tip, system dynamics become simpler, in terms of the number of poles and zeros needed to fit it. This phenomenon indicates that user grasping position strongly modifies the system’s behaviour. Moreover, the analysis of the model parameters demonstrate that, despite user variability, the system is affected by the grasping position more significantly than by the different end users.

Studying the phase margin of the system proved to be an adequate tool for determining the damping factor of the transient response to rigid contacts. This characteristic of the frequency response is also highly affected by the user grasping position, resulting in very different transient properties to virtual collisions. This knowledge has been applied in the design of an adaptive haptic rendering strategy that was able to impose a predefined value for the damping factor, compensating for the influence of the grasping position.

Furthermore, this work clearly illustrates how control engineering tools are a powerful way to analyse the performance of haptic interfaces, leaving room for further studies and applications. The conclusions of this study could be extended to other devices or kinematic configurations, and also to different ways of grasping or grip force levels.

REFERENCES


