Evaluation of Sensory Substitution to Simplify the Mechanical Design of a Haptic Wrist

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Abstract — The design of a new 3 degrees-of-freedom (DOF) haptic wrist for our 3-DOF force feedback haptic device is presenting a great design challenge. Required mechanical specifications make it difficult to find a satisfactory design solution. This paper studies whether sensory substitution can lead to the possibility of simplifying the mechanics while preserving haptic performance. The proposed approach consists of substituting the haptic actuation of one of the 3 rotational DOF by specially designed visual or auditory cues. We have carried out a user study where participants had to perform an accessibility task with the aid of different sensorial stimuli. The results of these experiments show that the performance obtained by visual or auditory substitution can be satisfactory for accomplishing specific tasks, although it does not meet the performance obtained with a full haptic wrist.

Keywords — Haptic, sensory substitution, multisensory

I. INTRODUCTION

Providing users with the natural ability to use all their senses in a simulation environment is an important goal in the Virtual Reality research area. Within this context, haptic devices are used to provide us with force feedback in domains where it is needed. Over the past years haptic interfaces have been successfully integrated into a wide range of fields such as engineering [1] or surgery [2, 3]. These devices allow users to interact with a certain environment, either remote or virtual, by the sense of touch.

LHIIfAM (Large Haptic Interface for Aeronautics Maintainability) [4, 5] is a floor-grounded device developed at CEIT. It measures 6 DOF translation and orientation and provides 3 DOF force feedback, allowing the user to move within a human-size workspace. Currently it is being augmented to 6 active DOF in order to provide both force and torque feedback. However, required high output torques and wide rotational workspace make it difficult to find a satisfactory design solution [6, 7].

The research in this paper is intended to analyze whether sensory substitution for torque feedback can simplify the mechanics while preserving task performance. The idea is to substitute the torque feedback of one DOF by appropriate visual or auditory stimuli and evaluate its performance. If successful, the proposed approach enables simpler kinematics and lightweight designs.

A user study has been carried out to evaluate how far these sensorial modalities can be from an active haptic DOF to provide the users with valuable collision information. The virtual environment designed for the experiments is a real aeronautics accessibility tasks, where haptic feedback is essential for the operator to perform the task properly.

This paper is organized as follows: Section II summarizes previous work on sensory substitution in virtual haptic environments. Section III describes the sensory substitution strategy proposed for the haptic wrist, and Section IV presents the experiment carried out to support this research, along with yielded results. Finally, conclusions and future work are presented in Section V.

II. RELATED WORK

With the introduction of haptic interfaces in virtual reality systems, several studies have evaluated the benefits and backwards of multisensory integration. A good introduction to multisensory interaction is presented in [8].

In the sensory substitution field, [9] analyzed the effects of substituting direct haptic feedback with visual and auditory cues to provide surgeons with a representation of force magnitude in teleoperated suture-manipulation procedures. They showed that sensory substitution is capable of providing sufficient feedback for the user to control these robotically-applied forces.

In [10], the authors carried out a user-study to evaluate the influence of sensory augmentation and sensory substitution in telepresent tasks. Their results showed that the use of haptic feedback improved significantly operation effectiveness. In cases in which haptic feedback was not provided, the best results were achieved when auditory and visual force information was applied together.

In virtual assembly tasks, [11] investigated whether the substitution of force feedback with auditory cues improved manipulation performance and subjective perception of usability. They found that, depending on the specific goal (minimize number of collisions, increase user perception, etc.), this sensory substitution could be valuable. They also described a number of guidelines for designers to that effect.

The potential of the sensory substitution for force feedback through tactile and auditory senses was studied by [12], concluding that “sensory substitution can be considered as a proven method by which force information can be presented if traditional force feedback is too costly, impractical, inefficient, or unstable for the given task conditions”. In particular, his experiments showed that sensory substitution through tactile and auditory senses was well suited for tasks that were highly dependent on reaction time, like detecting the presence of contact forces.
III. DESCRIPTION OF THE SENSORY SUBSTITUTION STRATEGY PROPOSED FOR THE HAPTIC WRIST

The strategy proposed consists of the substitution of the torque actuation in one active DOF of the haptic wrist by appropriate visual or auditory cues. In this work, we pretend to replace the actuation about the tool’s axis. From now on this rotation will be referred to as “hand-roll” (Figure 3). We selected this DOF because dealing with hand-roll separately from the pitch/yaw movements is a common mechanical haptic design philosophy [6].

The user can rotate this DOF freely, but there will not be any haptic actuation. In case of collision in this rotating axis, appropriate sensorial feedback will substitute the motor actuation for this DOF. If sound feedback is used, a continuous sound is displayed to the user while there is collision with the environment, stopping the sound when the user exits collision. Similarly, if visual feedback is used, the virtual tool managed by the user changes its color while there is a collision with the environment, returning to its initial color when the user exits collision.

We want to evaluate whether sensory substitution can give the impression of 3 active DOF with only 2 actuated DOF, providing the user with a comprehensive perception of collisions and helping him to correct trajectory in a natural way.

IV. EXPERIMENT

A user-study has been carried out to validate the performance of sensory substitution to convey user perception of collision. For this purpose, four torque feedback modalities are compared for the hand-roll DOF actuation:

i) Without feedback, which can be considered as the worst case.
ii) Visual cues (color feedback).
iii) Auditory cues (sound feedback).
iv) Haptic feedback, which is the standard intended to be met.

The first modality has been taken as a worst-case term of comparison. With this modality, the collisions must be noticed by the user by pure visual feedback of the clamp-environment interpenetration, without any sound, color or haptic feedback.

A. Experimental Design and Apparatus

The experiment is conceived to meet the following requirements: i) the task must involve torque feedback, ii) the experiment must provide a measure of the effectiveness of the system in warning the user that a collision has happened and providing them for a comprehensive and effective criterion to escape collision, iii) both the task and the environment must be simple enough to test the working principle in its essence without misleading the user, a priori not familiarized with haptics.

To fulfill these requirements, the task designed for the experiment is similar to the extraction of a clamp from a pipe (Figure 1), which frequently appears in engine assembly/disassembly tasks in aeronautics maintenance. Once the clamp is unfastened, the exit path is established by following the spatial trajectory laid out by the pipe itself.

Figure 1. Experimental task illustrated in a virtual scene related to aeronautics.

Figure 2 shows the virtual clamp movement associated with the hand-roll.

The haptic device used for the experiments provides 3 rotational DOF for clamp orientation and 1 translational DOF for clamp displacement along the pipe. The orienting mechanism (Figure 3) was designed and built at CEIT and inspired by previous work [13]. It is a parallel 2-DOF pitch/yaw device with a serially coupled hand-roll DOF along the handle axis. Parallel DOF are driven by commercial Maxon motors and specially designed and built cable transmissions. The hand-roll is driven by a Maxon planetary gearhead. Rotation of each DOF is measured by an encoder coupled to its motor.
For the translational DOF, a linear actuator designed and built at CEIT [14] was used (Figure 4). The linear transmission provides a 1018 mm linear stroke and a resolution of 18.84 μm with a HP HEDS-5500 encoder. The displacement along this linear DOF is mapped into a displacement of the clamp along the axial direction of the pipe.

The haptic device is controlled by a dSPACE DS1104 board that reads encoders’ information, processes the haptic control loop and outputs torque commands to the motors, at a haptic sampling rate of 1 kHz. Graphic rendering and collision detection are run on a Pentium IV 2.5 GHz PC with 1 GB RAM, NVIDIA GeForce 4 Ti 4200 graphics card and Windows XP operating system. The complete setup is shown in Figure 5.

B. Procedure

Eleven subjects took part in the experiments, eight men and three women. They were between the ages of 25 and 32. All of them had normal or corrected vision and reported normal tactile function. Most of the subjects had no prior experience with haptic interfaces. All participants were naïve to the details and hypothesis of the experiments.

Participants were asked to move the clamp from a starting position to a goal position (from one extreme of the pipe to the other), once per trial. They were asked to avoid collisions with the environment and, in case of colliding, to exit collision as soon as possible using the feedback provided by the device. In case of collision pitch and yaw DOF were haptically actuated, and for hand-roll actuation the previously explained feedback modalities were displayed: without feedback, visual feedback, sound feedback and haptic feedback.

Each subject performed four trials, each one with a different feedback modality, which was displayed in a randomized order. In addition, a minimum of 12-hours was set between trials. Each subject was also allowed to participate in a short training period before the trials, in order to familiarize themselves with the haptic device, the virtual environment and the different feedback modalities. In addition, a complete clamp extraction demo was shown to each participant before the first trial.

As previously explained, the experiment was designed to measure the effectiveness of the sensory substitution strategies in warning the user of the presence of object contact forces and providing a comprehensive and effective criterion to escape collision. Hence, the parameter used to compare the four approaches was the mean reaction time measured for each feedback modality. Reaction time is measured as the length of the period that begins when the user starts colliding with the virtual environment and ends when the user exits the state of collision. Thus, mean reaction time is measured for each trial as the ratio between total collision time and number of collisions. As the only
difference between the four feedback modalities is the feedback provided by the hand-roll, only collisions due to hand-roll rotation are taken into account for the reaction time measurement. The task completion time was not considered relevant for the purpose of the experiment, so it has not been taken into account for the results. At the end of each experiment the participants were asked about comments or questions, which were recorded by the experimenter.

C. Results

Mean reaction times (seconds) measured for each trial are summarized in Table 1, and based on these data mean value and standard deviation are calculated for each feedback modality.

Table 1. Mean reaction time measured for each trial and mean and standard deviation calculated for each torque feedback modality.

<table>
<thead>
<tr>
<th>Subject</th>
<th>2 DOF</th>
<th>Colour</th>
<th>Sound</th>
<th>3 DOF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject 1</td>
<td>2.9490</td>
<td>0.9697</td>
<td>0.6891</td>
<td>0.514</td>
</tr>
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<td>2.8480</td>
<td>0.9023</td>
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<td>0.251</td>
</tr>
<tr>
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<td>0.8067</td>
<td>0.4233</td>
<td>0.648</td>
</tr>
<tr>
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<td>2.7545</td>
<td>0.7239</td>
<td>0.3968</td>
<td>0.286</td>
</tr>
<tr>
<td>Subject 5</td>
<td>1.0170</td>
<td>0.4205</td>
<td>0.6410</td>
<td>0.165</td>
</tr>
<tr>
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<td>0.6032</td>
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<td>0.544</td>
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<tr>
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</tr>
<tr>
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<tr>
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<td>0.327</td>
</tr>
<tr>
<td>Subject 10</td>
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<td>2.0181</td>
<td>0.5303</td>
<td>0.393</td>
</tr>
<tr>
<td>Subject 11</td>
<td>1.8300</td>
<td>0.6763</td>
<td>0.8769</td>
<td>0.759</td>
</tr>
<tr>
<td>Mean</td>
<td>1.9522</td>
<td>0.8404</td>
<td>0.6986</td>
<td>0.387</td>
</tr>
<tr>
<td>St. Dev.</td>
<td>0.7227</td>
<td>0.4255</td>
<td>0.3315</td>
<td>0.202</td>
</tr>
</tbody>
</table>

These results are graphically displayed in the box and whisker diagram of Figure 6.

![Figure 6. Spread of the mean reaction time. Line inside the box represents median values, star-dotted line represents mean values, and cross-points represent outliers.](Image)

Comparing mean reaction times, the diagram shows that both sound and color substitution modalities improve system performance with respect to the 2 DOF approach, but they still do not meet the effectiveness of the 3 DOF system. It also shows that the range of reaction times for the 2 DOF modality is significantly wide compared to the others. This is most likely due to the fact that collision avoidance with this feedback modality is less intuitive for the user.

In order to find statistically significant differences, a one way ANOVA (analysis of variance) procedure has been carried out to analyze the influence of the feedback modality on the reaction time. Prior to the test, a Box-Cox transformation was applied to meet the requirements of normality and homogeneity of distribution variance. Results of ANOVA test show that feedback modality displayed to participants has a statistically significant effect on reaction time for the experiment (p<0.001). A post-hoc Tukey test has been carried out on the results, which shows that there is only evidence of interaction between colour and sound feedback modalities. A paired sampled t-test between these modalities shows that it can not be concluded statistically that participants performed the task better with one or the other (p = 0.405). However, it is clear that in both cases performance is greatly improved compared to the 2 DOF modality.

Regarding average performance in mean reaction time, the experiments carried out with the 3 DOF approach were performed 80%, 54% and 44% better than without feedback, color feedback and sound feedback respectively. Apart from the analysis of the statistical data, user comments while performing the experiments were also taken into account. In general users reported that sensory substitution, both color and sound feedback, provided them with a significantly realistic impression and were really helpful to fulfill the task.

V. CONCLUSIONS AND FUTURE WORK

Sensory substitution techniques have been evaluated to simplify the mechanical design of a haptic wrist. The haptic actuation of one of the wrist’s DOF has been substituted by visual and auditory feedback to give the impression of 3 active DOF when only 2 of them are actuated. This solution enables simpler kinematics and lightweight design.

A user-study has been carried out to validate the performance of this sensory substitution approach to convey user perception of collision. The results show that, in terms of the capability of the system to display the presence of collisions with the environment, the performance obtained by visual or auditory substitution is clearly higher than with a system without feedback. However, it still does not meet the performance of a full active haptic wrist. A main conclusion is that, depending on the designer’s criterion and the specific application, a decrease in performance with respect to a full active wrist can be assumed in the interests of the benefits.

For future work, we still pretend to evaluate other sensory substitution techniques, as well as to prove their suitability in very different virtual tasks, before integrating these approaches to the LHfAM.


