Haptic rendering for under-actuated 6/3-DOF haptic devices

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Abstract. Under-actuated 6/3-DOF haptic devices are mostly used for simple 3-DOF point-based haptic interaction because of missing torque feedback. In this work, we present a system involving sensory substitution and pseudo-haptic feedback that effectively simulate torque feedback using visuo-tactile cues. The proposed system was implemented into a 6-DOF haptic rendering algorithm and tested on an under-actuated haptic device in a user study. We found that by applying our torque simulation system, the torque perception increases significantly and that 6/3-DOF devices can be used in complex tasks involving 6-DOF interactions.

Keywords: Haptic Rendering, 6/3 Degrees of Freedom, Under-actuated

1 Introduction

Although there are many types of 6-DOF (degrees of freedom) haptic devices, inexpensive devices are still limited to 3-DOF force feedback. Including 6-DOF sensors to a 3-DOF device does not substantially increase the complexity of device design and thus many of todays devices that fall into the group of 6-DOF sensing devices are limited to force-only feedback and do not provide torque feedback. Such devices with more sensors than actuators, i.e. 6/3-DOF, are called asymmetric or under-actuated devices [1].

The most common way of using 6/3-DOF haptic device is to implement a 3-DOF haptic rendering algorithm for a sphere-shaped tip of a 6-DOF controlled haptic probe where the rest of the probe simply penetrates the scene without reflecting any force feedback. While this approach ensures stability of the system, the overall haptic feedback impression is not realistic [2].

The aim of this paper is to improve the haptic feedback plausibility for under-actuated 6/3-DOF haptic devices. We propose to adjust a 6-DOF haptic rendering algorithm to 6/3-DOF haptic devices so that it eliminates instability and unnatural behavior when the virtual probe is subjected to torque due to the interaction with the scene.

We introduce the use of a sensory substitution and pseudo-haptic system [3] to create an illusion and a cue of missing torque feedback by using a combination of perceptual information obtained from different modalities. An experimental study was carried out in order to determine the benefit of our system. The results show that the proposed torque simulation system significantly increases task performance in interaction scenarios when torque perception is important and that 6/3-DOF haptic devices are suitable even for complex 6-DOF manipulation tasks.

2 Related Work

Barbagli et al. [1] formally defined the problem of sensor/actuator asymmetry and provided a framework for under-actuated haptic device analysis. Two 2-DOF examples showed that it is possible to correctly perceive a missing degree of freedom to some extent. Several studies examined the benefit of 6-DOF over 3-DOF manipulation in various tasks [2][4][5]. Forsslund et al. [6] compare task performance in virtual surgical environments using 3-DOF haptic rendering and 6-DOF haptic rendering on under-actuated 6/3-DOF and fully-actuated 6-DOF haptic devices. Results showed that for a 6-DOF controlled haptic probe, utilization of a 6-DOF haptic rendering algorithm with discarded torque feedback on an under-actuated device significantly increases task performance over the 3-DOF feedback of a sphere-shaped tip of the probe. Nevertheless, completely discarding the torque feedback from a 6-DOF haptic rendering often creates instability of the system and some interactions utilizing the torque become non-intuitive and confusing for the user.

Pseudo-haptic systems can be defined as "systems providing haptic information generated, augmented or modified, by the influence of another sensory modality" [7]. Most of the current research in pseudo-haptic feedback is focused on simulating haptic properties on passive devices with no force feedback [8]. Lécuyer et al. [9] showed that a passive apparatus (such as a 6-DOF Space-Ball device) can simulate haptic information and that haptic sense is blurred by visual feedback. Pseudo-haptically simulated haptic properties are currently applied in graphical user interfaces, tactile images, video games and include friction, stiffness, mass or haptic textures [8]. However, no work has attempted to address the problem of 6/3-DOF haptic rendering using pseudo-haptic feedback and sensory substitution.

Despite the conclusion of several studies that asymmetric devices have limited usability for certain situations demanding a realistic haptic feedback, propositions of future work in haptic rendering that would alleviate limitations of asymmetric devices were mentioned mainly due to the broad use of such devices.

3 6/3-DOF Haptic Rendering

The key concept of 6/3-DOF haptic rendering is to extend existing 6-DOF haptic rendering algorithms by applying methods that restrain instability and provide alternative means of torque simulation. The problem with instability lies within the full controllability and partial observability [1] of the haptic probe. The discarded torque feedback enables a haptic stylus to rotate freely in situations where the haptic probe movement is restricted, such as wrenching or prying. The user has no information about the magnitude of the exerted torque and the virtual energy that is unintentionally generated in the virtual environment. This can lead to unwanted haptic probe penetration or even pop-through effects when using penalty-based (repulsive force field) methods without proper constraints for collision response, such as the popular voxel sampling method [10].

3.1 Simulation of torque

To overcome the problem with the observability of the haptic probe, we propose to use sensory substitution and pseudo-haptic systems to simulate and create an illusion of the torque. We apply the following methods and criteria:

1. *Prevent scene penetration* by the haptic probe when exerting excessive torque.
2. Simulate a *torque feedback via a vibration effect* proportional to a measure of magnitude of the exerted torque to effectively stimulate the user.
3. Show a visually distinctive model of the haptic probe (e.g. wireframe model) having the actual position and *orientation of the haptic stylus* so the user can perceive and correct the discrepancies between the two.

Penetration prevention. Precise and robust collision detection that prevents penetration provides an effective way of modifying the user's perception of the haptic stylus orientation. A sensory conflict is presented to the user when the visual information of the orientation of the haptic probe differs from kinesthetic (proprioceptive) information of the haptic stylus. Dominance of the visual modality over the haptic modality [7][8] provides the illusion of torque feedback when the haptic probe rotation is restricted.

Torque feedback via a vibration effect. The sensory conflict as such does not provide enough information about the magnitude of the exerted torque in all situations. During experiments, we made one important observation that the torque exertion can be categorized into two general scenarios:

a) Force F applied at a point distant from the center of mass of the rotating haptic probe, causing the probe to both translate and rotate. We call this the *"good torque"* scenario (see Fig. 1-a).
b) Forces F_A, F_B applied at two different points causing only rotation and no translation (i.e. $F_A + F_B = 0$) of the rotating probe, such as wrenching or prying. We call this the *"bad torque"* scenario (see Fig. 1-b).

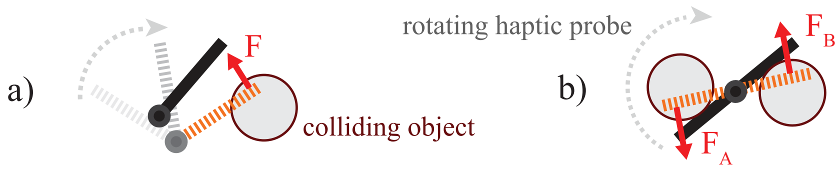


Fig. 1. a) The *"good torque"* scenario. b) The *"bad torque"* scenario.

In spite of the fact that the classification based on the "good torque"/"bad torque" is not exhaustive, we found that it is sufficient for typical haptic probes.

In the *"good torque"* scenario, a translational force restricts the probe from penetrating the scene and provides instant contact resolution just using force feedback. The level of realism of this contact resolution depends on the distance of the applied force from the center of mass and on the shape of the haptic probe. In most typical cases, people do not even notice the omitted torque and we do not apply any cue informing the user about the exerted torque as it can be rather distracting.

In the *"bad torque"* scenario, however, there is no natural contact resolution for under-actuated devices and hence it is necessary to provide the required information using a different modality. We propose to provide users with a non-visual stimulus that alerts them in a tactile manner using a *vibration* generated by the haptic device.

Orientation of the haptic stylus. In situations when the haptic probe rotation is limited and the task demands highly accurate motion, the vibration that informs the user about the magnitude of the exerted torque may not be sufficient. To prevent orientation difficulties, a wireframe model of the haptic probe with the stylus orientation (i.e. an orientation not constrained by surrounding objects in the virtual scene) can be optionally shown when the magnitude of the torque exceeds a certain threshold. To prevent distractive blinking, we apply hysteresis thresholding.

3.2 Algorithm Description

We extended a 6-DOF haptic rendering algorithm by McNeely et al. [10]. We chose the method for its simplicity and wide use, and implemented the algorithm using the CHAI 3D library set [11]. The original 6-DOF haptic rendering algorithm uses volumetric representation for collision detection (voxelized meshes) and a penalty-based method for collision response. Stabilization and force filtering is performed using a simulation-based method known as virtual coupling.

The haptic rendering pipeline including our torque simulation extension is shown in Figure 2. The haptic loop starts with a position and orientation (p_h, q_h) of the stylus sent to the virtual coupling unit. Collisions of the dynamic

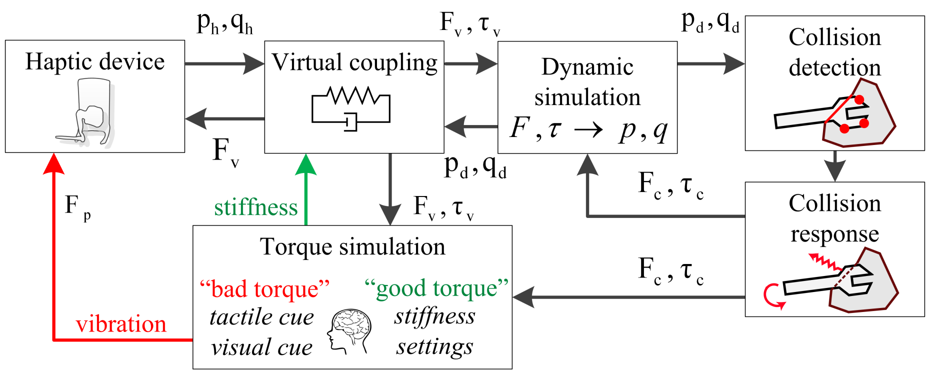
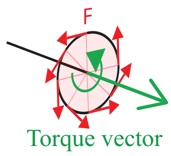


Fig. 2. 6/3-DOF Haptic Rendering Pipeline

haptic probe are detected and a contact force and torque ($\mathrm{F_c}$, τ_c) are computed and applied together with the coupling force and torque ($\mathrm{F_v}$, τ_v) on the dynamic probe. A new position and orientation ($\mathrm{p_d}$, $\mathrm{q_d}$) of the dynamic probe are computed using semi-implicit numerical integration. The new coupling force ($\mathrm{F_v}$) is then sent to the device.

Torque simulation extension. The first step of our torque simulation extension is a determination of the torque type. In the *"good torque"* case, we just need to ensure that the virtual coupling torque stiffness is high enough to achieve the best coupling transparency. However, the high torque stiffness of the coupling may result in scene penetrations of the haptic probe in the *"bad torque"* case. That is because users may unintentionally generate excessive torque by rotating the stylus in a situation when the physical torque feedback would not allow it. Therefore, in the *"bad torque"* case, we limit the virtual coupling torque stiffness to prevent penetration. Furthermore, we apply the vibration feedback and the optional visual cue.

Determining the torque type. To distinguish between the *"good torque"* and *"bad torque"* scenarios, the algorithm analyzes correlation of force and torque magnitude. For the *"bad torque"* scenario, torque magnitude is significantly higher than the magnitude of forces that could have affected the torque. Such forces are directed perpendicularly to the torque vector (as shown in the figure on the right). To filter these forces, we project the coupling force ($\mathrm{F_v}$) to a plane perpendicular to the torque vector and determine the *"bad torque"* using the following equations:



$$\mathrm{F_{proj}} = \mathrm{F_v} - \frac{\tau_\mathrm{v}}{|\tau_\mathrm{v}|}\left(\mathrm{F_v} \cdot \tau_\mathrm{v}\right) \tag{1}$$

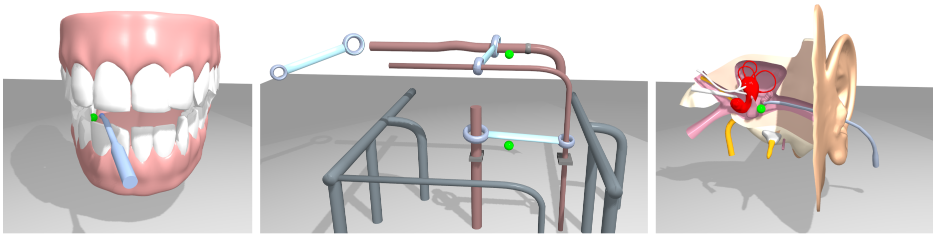
$$\textit{"bad torque"} = \begin{cases} \mathit{true} & \text{if } |\tau_\mathrm{c}| > 0 \quad \wedge \quad |\tau_\mathrm{v}| > \mathrm{T_{min}} \quad \wedge \quad |\tau_\mathrm{v}| > \mathrm{R_d}\,|\mathrm{F_{proj}}| \\ \mathit{false} & \text{otherwise} \end{cases} \tag{2}$$

where $\mathrm{T_{min}}$ is a minimal torque threshold and $\mathrm{R_d}$ is the radius of the probe.

Vibration pattern. The vibration pattern for the *"bad torque"* scenario was chosen to be non-distractive, yet stimulative, for users. Experiments showed that the pattern of a constant frequency of 200 Hz is suitable for this purpose. We set the magnitude of the vibration force to be logarithmically proportional to the magnitude of the coupling torque: $|\mathrm{F_p}| \propto \mathit{log}(|\tau_\mathrm{v}|)$ and the generated vibration force ($\mathrm{F_p}$) is sent directly to the haptic device so that it does not affect the virtual coupling (see Fig. 2).

4 User Study

An experimental study was designed to assess the influence of our torque simulation system on perceiving the missing physical torque feedback when using an under-actuated 6/3-DOF haptic device. We expand on the results from the study of Forsslund et al. [6] who showed that there is a significant improvement in a task performance when using a 6-DOF haptic rendering algorithm even with discarded torque feedback. In our study, we measured the effect of the tactile (vibration) and visuo-tactile (vibration and wireframe model) cues on the perception of torque feedback.



(a) Teeth scene (b) Piping scene (c) Ear scene

Fig. 3. Experimental scenes used in the study.

Experiment design. We designed three scenes presenting different interaction scenarios, as shown in Fig. 3: Teeth, Piping and Ear scene. In each scene, the participant's task was to use the haptic probe to touch a visible checkpoint for 3 seconds until it disappeared and a next checkpoint became visible.

In the Teeth scene, the haptic probe represented a dental instrument. Checkpoints were located on hard-to-access locations such as interdental spaces to force the participant to manipulate the haptic probe in a non-trivial manner so that both force and torque feedback are employed. The Piping scene represented a virtual assembly scenario using a wrench with the shape of a ring spanner as the haptic probe. The participant had to move the ring spanner through the piping while being constrained by two pipes at both sides of the spanner as shown in Fig. 3-b. In the Ear scene, a needle insertion procedure was simulated. Careful manipulation with rolling of the bent needle was needed to complete the task.

Procedure. Three variants of torque simulation were tested on each subject. The first variant (A) did not use any tactile or visuo-tactile cue. It was included to provide comparison with a stable (i.e. meets criterion 1 in Section 3.1) 6-DOF haptic rendering algorithm when its torque output is simply discarded. The second variant (B) employed the vibration effect proportional to the exerted torque magnitude. The third variant (C) used both the vibration effect and visual help (the wireframe model). In total, participants performed all three tasks six times. In order to minimize the learning effect, we presented torque simulation variants (i.e. A, B, C) in random order and participants performed the task for all variants two times with no time limit. Before the measurement, we let participants familiarize themselves with the vibration effect as long as they needed to adopt the perception.

The study was conducted with the 6/3-DOF Sensable Phantom Desktop haptic device and Dell U2713HM 27" non-stereo monitor placed 80 cm in front of the participants. Fifteen subjects (8 male, 7 female) volunteered to participate in the experiment. Most of them had no or little experience with haptic devices.

They ranged in age between 21 and 63 years, one of the subjects was left-handed. The procedure took 30 to 60 minutes for each participant.

Measurements. During each trial, we recorded information about the haptic probe interaction and analyzed the following factors: torque error E_τ, force error E_F and task completion time t_c:

$$\mathrm{E}_\tau = \int_0^{t_c} \tau_\mathrm{V}\,\mathrm{d}t \qquad \mathrm{E}_\mathrm{F} = \int_0^{t_c} \mathrm{F}_\mathrm{V}\,\mathrm{d}t \tag{3}$$

Torque error and force error factors were derived to estimate a possible structural damage of the virtual scene by incautious manipulation of the haptic probe.

Analysis. Every subject had different manipulation skills and spatial orientation abilities. Therefore, we used within-subjects repeated measures analysis of variance (ANOVA) using three torque simulations variants (A, B, C) as independent variables. To determine which variants significantly differed from each other, Bonferroni pairwise comparisons were performed with significance level 0.05.

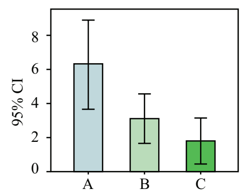


Fig. 4. Torque error mean estimates.

For the torque error factor E_τ, a significant difference was observed between the three variants [$\mathrm{F}(2, 14) = 13.589$; $\mathrm{p} < 0.001$]. Measured means and 95% confidence interval limits of three variants (A, B, C) are shown in Figure 4. The results showed that the tactile feedback (i.e. variant B) and visuo-tactile feedback (variant C) significantly decreased the torque error factor. According to Bonferroni pairwise comparisons, a significant difference was observed between the variant A and B ($p = 0.012 < 0.05$), and between A and C ($p < 0.001$), while no significant difference was observed between variants B and C ($p = 0.098 > 0.05$).

The ANOVA for force error E_F and task completion time t_c factors revealed statistically non-significant difference between measured torque simulation variants. Despite the completion time between subjects being considerably different, the within subject completion time was approximately the same for all three variants. This was mainly due to the fact that subjects were less aware of the produced torque error in the variant A.

One of the surprising results is that all participants were able to naturally discriminate between a vibration effect and forces generated by the virtual simulation. All participants agreed that they did not perceive the vibration effect as distractive, but they rather linked the effect with the torque feedback. They also agreed that the tactile cue as such provided an instant stimulation which can be used even for situations where the haptic probe is obscured by other objects and is not visible.

5 Conclusion

In this paper, we presented a new method to address the problem of haptic rendering for the widely used 6/3-DOF under-actuated haptic devices. To overcome the problem of limited observability of the haptic probe, we proposed and implemented torque simulation system involving visuo-tactile feedback. The user study showed that the proposed sensory substitution and pseudo-haptic system significantly increases torque perception and it is therefore possible to apply presented 6/3-DOF haptic rendering algorithm even for more complex tasks requiring a 6-DOF haptic probe interaction using under-actuated device.

In future work, we will examine the performance of torque simulation systems for advanced haptic rendering algorithms including surface materials, dynamic models or deformable models. We will also experiment with other pseudo-haptic systems and sensory substitution approaches, such as sound rendering.

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