Haptic Wrists: An Alternative Design Strategy Based on User Perception

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A new three degree-of-freedom (3DOF) torque feedback wrist is being developed to be added to an existing 3DOF force feedback haptic device. It is difficult to find a satisfactory solution to the mechanical design problem, mainly because of the required large rotational workspace and severe weight constraints. This work proposes an alternative design strategy based on user perception, which allows simplification of the mechanics. The proposed approach consists of substituting the last rotational DOF of the wrist with a pseudohaptic DOF. Thanks to specially designed visuotactile cues, the pseudohaptic DOF is integrated with the active DOF into the same device, being able to generate free motion and collision detection perception to the user. This approach provides for simpler kinematics, lightweight designs, lower inertias, and less friction, which are key advantages for the inclusion of torque feedback into force feedback devices. [DOI: 10.1115/1.3072899]

1 Introduction and Motivation

Haptic interfaces are both (i) input devices, which capture the movements of a user, and (ii) feedback devices, which allow the user to physically interact with a virtual or remote environment. Some haptic applications require a large-scale workspace. One example is the large haptic interface for aeronautics maintainability (LHIFAM) developed at CEIT [1,2]. LHIFAM measures 6DOF translation and orientation and provides 3DOF force feedback, allowing the user to interact with full-scale 3D virtual aircraft engines for maintainability analysis purposes.

Currently LHIFAM is being augmented to six active DOFs in order to provide both force and torque feedback. This demands a lightweight torque feedback wrist providing high output torques within a large rotational workspace. A state-of-the-art in mechanisms for haptic torque feedback was presented by the authors [3], concluding that none of the reviewed wrists suits our needs. An in-depth study of the challenges presented by torque feedback was also carried out by the authors [4] showing that, designwise, there is no way to simultaneously guarantee a large rotational workspace with high quality performance. In order to avoid the severe mechanical limitations, this work moves the scope of the design solutions closer to the user’s perception through pseudohaptic and sensory substitution techniques. This allows simplification of the mechanics.

The paper is organized as follows. Section 2 summarizes previous work on pseudohaptics and sensory substitution. The concept, implementation, applicability, and limitations of the proposed approach are explained in Sec. 3. Finally, conclusions and future work are presented in Sec. 4.

2 Related Work

The first choice for simplifying the 6DOF mechanics is to simulate torque with the pure force mechanism itself, without adding any wrists. In that respect, Lécuyer et al. [5] proposed an interaction paradigm called the “virtual haptic sphere,” which allows one to use the PHANTOM alternately as a 3DOF input/output device in translation and as a 2DOF input/output device in rotation. Another work [6] argues that even without true torque feedback exerted by the haptic device, the user can voluntarily supply the sense of torque, aided by visualization and previous experience with the task being performed. This was emphasized by Wang [7] with further experiments displaying haptic information with both torque and visual feedback. His work poses the following question: “Can the same level of haptic perception be maintained if the number of degrees-of-freedom of the haptic interface is reduced?”

The impact of visually presented spatial cues on the human perception of mechanical stiffness in virtual environments is studied in Ref. [8], demonstrating a clear visual dominance over the kinesthetic sense of hand position. Based on this idea and previous work [9] with isometric and elastic/isotonic input devices1 [10] for target acquisition tasks in virtual environments, Lécuyer et al. [11] proposed the “pseudohaptic” concept. This preliminary state consists of coupling a SpaceballTM input device with a visual feedback, displaying a visual stiffness different from the mechanical stiffness of the device. This results in the user being able to perceive different stiffness values by means of a misleading visual stiffness display, even if the mechanical stiffness is always the same. Thus, a passive input device like a SpaceballTM can, to a certain extent, simulate force feedback. Going even deeper into this concept with exhaustive experimentation, Lécuyer et al. [12] showed the unconscious participation of the user in this phenomenon. It is linked, on one hand, to the user’s cognitive strategy during the experimental task and, on the other hand, to the role of sensory motor commands in the user’s own perception loop. Later, the same authors extend the pseudohaptic definition to “the generation, augmentation or deformation of haptic sensations by information coming from other sensory modalities” [13], concluding that integration of pseudohaptic and haptic feedback in the design of virtual environments (VEs) is possible. All of these concepts come together on a virtual milling machine technical trainer.[14]. Regarding torque feedback, Palijc et al. [15] validated the applicability of the pseudohaptic concept to 1DOF torque feedback for torsional stiffness discrimination, stating that elastic devices provide a better resolution than isometric ones.

1 Isometric devices are designed to display displacement variables and read back forces, so they have ideally infinite stiffness and stay put while force is exerted on them. Elastic/isotonic devices are designed to display forces and read position variables, thus they offer no significant resistance and are used to track users as they move within the virtual world (from Refs. [10,11]).
Fig. 1 Proposed 2.5DOF approach

Closely related to these phenomena, "sensory substitution" was defined by Bach-y-Rita et al. [16], and later studied by Lenay et al. [17], as "the provision to the brain of information that is usually in one sensory domain (for example visual information via the eyes and visual system) by means of the receptors, pathways, and brain projection, integrative and interpretative areas of another sensory system (for example visual information through the skin and somatosensory system)." In virtual assembly tasks [18], 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. In the medical field [19], they analyzed the effects of substituting direct haptic feedback with visual and auditory cues to provide surgeons with a representation of force magnitude in teleoperated surgery manipulation procedures. They showed that sensory substitution is capable of providing sufficient feedback for the user to control these robotically applied forces. The potential of the sensory substitution for force feedback through tactile and auditory senses was studied by Massimino [20], 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, such as detecting the presence of contact forces.

Taking all these concepts into account, we believe (i) design advantages can be achieved by integrating haptics and pseudohaptics into a single feedback device, and (ii) design guidelines derived from studies on sensory substitution can be helpful in making such integration more effective.

3 "2.5DOF" Haptic Torque Feedback Approach

Ergonomically, tool manipulation can be divided into a pointing movement (pitch/yaw) and a rotation along the tool axis (tool roll). Pointing movement of the tool involves certain arm-wrist movements, which are different from those needed for tool-roll rotation. As a matter of fact, it can be observed that, in haptics, dealing with tool roll separately from the pitch/yaw movements is a common mechanical design philosophy [3]. The alternative wrist design proposed in this paper consists of the substitution of the tool-roll haptic DOF with a tool-roll pseudohaptic DOF (Fig. 1).

This mixture of 2 haptic DOFs plus 1 pseudohaptic DOF is what the authors refer to as the 2.5DOF haptic torque feedback approach: a wrist with 2 active DOFs (pitch/yaw) plus an additional sensor, which measures the torque exerted by the user along the handle axis, which coincides with the tool-roll axis. By design, there is no physical rotation of the handle along the tool-roll axis, and measured torque is instead used for interaction with the virtual environment (isometric DOF).

In order to give the impression of three active DOFs with only two actuated DOFs, "it is necessary to facilitate the repositioning of the user perception to an implicit solution. It means that this implicit sensory alternative must be explicit enough to be found quickly by the user" [12]. Following this idea and inspired by the concepts reviewed in Sec. 2, a combination of visual and tactile cues (henceforth "visuoactuate cues") has been designed to convey user perception of tool-roll DOF. The designed visuoactuate cues follow the criteria stated by Massie et al. [22] for a haptic device to be an effective interface: (i) free space must feel free and (ii) solid virtual objects must feel stiff.

First, as rotation along the tool-roll axis is physically impossible, torque (T) is involuntarily exerted along the handle axis when the user tries to make such movement. This is measured by the torque sensor and then translated into a visual rotation of the virtual tool (with rotation speed ω̇), displayed to the user through visual feedback (Fig. 2).

As seen in Eq. (1), virtual tool-roll rotation speed (ω̇) is set proportional (a) to a power (b) of the measured tool-roll torque (T), with sign(ω̇) equal to sign(T). As b increases, precision manipulation produces slower rotations and power grip produces faster rotations. In addition, rotation speed is limited to a maximum realistic value (ωmax). The parameters of the function need to be tuned to achieve a free space perception as well as possible between the real DOF and the pseudohaptic DOF. This tuning is particular for each mechanical device and application

\[ \omega = a|T|^b \text{sign}(T), |\omega| \leq \omega_{\text{max}} \]  

(1)

When collision with a solid virtual object occurs, a tactile cue is sent to the user. In addition, as a visual cue, interpenetration between virtual tool and environment is avoided in the visual feedback. The visual cue suitably drives the tactile cue to convey collision perception to the user. The tactile cue consists of a single pulse of short duration (Δ) and small magnitude (M), given off at the moment of collision (t), and it is exerted by the pitch/yaw actuators (Fig. 3). Thus, collisions due to pitch/yaw rotation produce kinesthetic torque feedback and collisions due to tool-roll rotation produce tactile feedback. Collisions involving all rotational DOFs produce both kinds of feedback superimposed. Due to the short duration and small magnitude of the pulse, tactile feedback does not affect pitch/yaw kinesthetic feedback when both are superimposed. Moreover, since all feedback is carried out by the pitch/yaw actuators, no additional actuator is needed to produce the pulse. The magnitude of the pulse is set proportional to the virtual tool-roll rotation speed (ω̇) at the collision instant, and it can be invariably directed to the same actuator. Again, the parameters of the pulse need to be tuned depending on the mechanical device and the application.
The 2.5DOF haptic wrist provides for simpler kinematics, lightweight designs, lower inertias, and less friction, which are key advantages for the design of torque feedback wrists to be added to force feedback devices. On the other hand, the proposed approach has two main limitations. (i) It works best with longitudinal virtual tools and it requires the tool roll, the device handle and the longitudinal axis of the virtual tool to be aligned, and (ii) since the tool roll is an isotropic DOF, it provides collision detection ability but not stiffness discrimination. However, even if tool-roll rotation is not mechanically permitted by the device, we observed that the deformation of the skin at the contact points allows the rest of the hand to undertake a certain tool-roll rotation, which helps create a realistic sensation of physically turning the handle.

4 Conclusions and Future Work

A new approach has been proposed for the mechanical design of haptic wrist mechanisms, consisting of the substitution of the wrist tool-roll active DOF with a pseudohaptic DOF. Especially designed visuotactile cues integrate haptic and pseudohaptic torque feedback into the same device, providing the impression of three active DOFs with only two actuated DOFs. This gives rise to a 2.5DOF wrist. Such strategies have been exploited, and advantages and disadvantages of the new approach have been pointed out. The 2.5DOF haptic wrist does not intend to replace a full torque feedback wrist, but its mechanical simplification helps the inclusion of torque feedback into force feedback devices.

Experiments are being carried out to validate the applicability of the new approach in VE interactions. So far, we believe this approach introduces an alternative design strategy, spans new research lines and may help increase knowledge in the field of the haptic torque perception problem.

References


