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Customization, control, and characterization of a commercial haptic device for high-fidelity rendering of weak forces

Netta Gurari*, Gabriel Baud-Bovy

Robotics, Brain and Cognitive Sciences, Istituto Italiano di Tecnologia, Via Morego, 30, Genoa 16163, Italy

HIGHLIGHTS

- Customization of a commercial haptic device for studying human force perception.
- Implementation of a closed-loop controller for enhancing the device's transparency.
- Identification of the parameters affecting the device's transparency.
- Evaluation of the system stability based on data collected from a human subject study.
- Description of a custom system that measures a user's grip force.

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ABSTRACT

Background: The emergence of commercial haptic devices offers new research opportunities to enhance our understanding of the human sensory-motor system. Yet, commercial device capabilities have limitations which need to be addressed. This paper describes the customization of a commercial force feedback device for displaying forces with a precision that exceeds the human force perception threshold.
New method: The device was outfitted with a multi-axis force sensor and closed-loop controlled to improve its transparency. Additionally, two force sensing resistors were attached to the device to measure grip force. Force errors were modeled in the frequency- and time-domain to identify contributions from the mass, viscous friction, and Coulomb friction during open- and closed-loop control. The effect of user interaction on system stability was assessed in the context of a user study which aimed to measure force perceptual thresholds.
Results: Findings based on 15 participants demonstrate that the system maintains stability when rendering forces ranging from 0–0.20 N, with an average maximum absolute force error of 0.041 ± 0.013 N. Modeling the force errors revealed that Coulomb friction and inertia were the main contributors to force distortions during respectively slow and fast motions.
Comparison with existing methods: Existing commercial force feedback devices cannot render forces with the required precision for certain testing scenarios. Building on existing robotics work, this paper shows how a device can be customized to make it reliable for studying the perception of weak forces.
Conclusions: The customized and closed-loop controlled device is suitable for measuring force perceptual thresholds.

1. Introduction

1.1. Haptic devices

Haptic devices enable the creation of virtual touch environments, making it is possible to touch and grasp and feel the shape and weight of virtual objects, just as head-mounted display devices enable the observation of virtual visual scenes. Benefits of haptic systems include that a single device can generate many different virtual touch environments; environments can be modified on the fly; and data related to one's interaction can be monitored and stored. Haptic devices include tactile systems, such as Braille displays and cellular phones that vibrate, which interact primarily with the skin, while the focus of this paper is on kinesthetic, or force feedback, devices, which interact primarily with the kinesthetic system (although the contribution of tactile afferents should not be neglected). By allowing real-time control of the physical interaction

* Corresponding author. Tel.: +39 010 71781 400; fax: +39 010 7170817.
E-mail addresses: netta.gurari@iit.it, gurari@gmail.com (N. Gurari), gabriel.baud-bovy@iit.it (G. Baud-Bovy).

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between the body and virtual touch environment, these devices are offering to a growing number of researchers a promising tool for investigating sensory-motor, cognitive, and neuronal mechanisms involved in areas including touch, proprioception, and object manipulation, e.g., (Shadmehr and Mussa-Ivaldi, 1994; Flanagan and Wing, 1997b; Burdet et al., 2001; Baud-Bovy and Gentaz, 2006; Drewing and Ernst, 2006). Reviews of the history of haptic devices, as well as methods for controlling them, can be found in Adams (1999) and Kern (2009).

Haptic devices are relevant for psychophysical testing, which quantifies the capacity of the human sensory system to sense physical properties, e.g., (Beauregard et al., 1995; Gurari et al., 2013; Dominjon et al., 2005; Kawai et al., 2012). They allow the experimenter to control and adjust the touch sensation using a single apparatus, making it relatively easy to conduct such studies. Further, they enable the experimenter to control the interaction force in a manner which would be impossible to achieve with real objects. For example, geometric and force cues can be dissociated to study haptic shape perception (Robles-De-La-Torre and Hayward, 2001) and visual and haptic cues can be isolated to identify how such information integrates (Ernst and Banks, 2002).

While many of the early studies involving haptic devices have been conducted with custom designed systems, a growing number of commercial apparatuses are coming to the market. As a result, the use of these systems has expanded from the realm of mechanical engineering and haptic research groups towards use by researchers in other disciplines. As the interest in haptic devices grows, some inherent limitations, or challenges, related to the underlying technology may occur, especially when the systems are used beyond the confines of haptic research labs. In particular, researchers may not always be aware, or might sometimes over-look the fact that haptic interfaces are real objects exhibiting real world properties, such as mass and friction, which impact the rendering fidelity of virtual touch environments (Salisbury et al., 2009). In robotics, this problem is known as a transparency issue (Hannaford, 1989; Lawrence, 1993; McJunkin et al., 2005). While perfectly transparent haptic devices do not and cannot exist, it is possible to design their hardware and control laws to minimize the undesired artifacts (e.g., Panarese and Edin, 2011). Unfortunately, commercially available haptic devices, as sold off-the-shelf, are not fit for creating precisely controlled stimuli, and thus, are not appropriate for use in many studies. This issue is particularly relevant for psychophysical and neurophysiological studies, where precise control of the stimulus is needed.

1.2. High-fidelity weak force rendering

The objective of this work was to create a setup which can display weak forces accurately and precisely enough to allow for the identification of force detection thresholds. Although force perception has been studied for many years, starting from the seminal work of Weber (1978) in 1834, nearly all studies have measured discrimination thresholds and not detection thresholds (see Jones, 1986 for a review of this literature). To identify force thresholds, weak forces need to be displayed which are unaffected by possible movements of the object that is in contact with the human. This is not feasible in the real world, especially when the object is in motion, since an object has a mass and, in turn, when moved creates an inertial force. A previous study on weight perception showed that the ability to sense an object's weight improves when it is moved, and it is hypothesized that this enhancement may be due to the availability of inertial cues (Brodie and Ross, 1985). Thus, the inertial contributions need to be removed in order to compare force detection thresholds at rest or when moving the arm with the same stimuli.

Understanding the mechanism governing the perception and detection of weak forces can assist in better interpreting how humans dexterously manipulate objects. Given that the fingertips are very compliant at low interaction forces (Srinivasan and LaMotte, 1995), the application of weak forces induces a relatively large finger pad deformation which stimulates mechanoreceptors in the skin (Birznieks et al., 2001). When these cues are muffled or absent, such as when the fingertips are anesthetized or are very cold, it can become quite challenging to interact with the world (e.g., fastening a coat button while wearing gloves).

It should be noted that the ability to display weak forces with a high level of fidelity is relevant to areas beyond our aims indicated here. These include the desire to conduct neurophysiological research to investigate the sensitivity of the nervous system to a mechanical stimulation (e.g., stretching of one's skin (Panarese and Edin, 2011)) and the creation of training simulators to teach one how to perform highly dexterous tasks (e.g. palpating very soft tissue, assembling fragile piece).

In prior work, a custom-designed one-degree-of-freedom haptic device was developed to accurately render weak forces (inertial cues were negligible). One of the main features of this device was the inclusion of a deformable end-effector, which decoupled the actuator inertia from the end-effector inertia. Preliminary research in this area demonstrated that humans can typically sense forces in the range of 0.05–0.10 N, where the force threshold is defined as the minimum amount of force which is needed for the user to correctly identify the direction of the applied force in 75% of the trials (Baud-Bovy and Gatti, 2010). A limitation to these earlier studies is that the user's grasp was not monitored. Thus, the contribution of the tactile cues is not known.

Here, we describe the customization and control of a commercially available force feedback device, which enables the display of weak forces in the range of a few mN with the desired accuracy and precision. To achieve this aim, the device was outfitted with a force sensor, which allows for the control of accurately rendered forces (by implementing a force feedback controller). Additionally, two more sensors were affixed to the haptic device to monitor the user's impedance by measuring the user's applied grip force. A large part of this paper is devoted to the analysis of the force feedback controller, and its impact on system transparency and stability.

The manuscript proceeds as follows. In Section 2, a description is provided for how the device was customized with sensors to improve its transparency and monitor the human's interaction. In Section 3, the haptic device is characterized under both open- and closed-loop control, and the system response is analyzed in the frequency- and time-domain. Additionally, we model the response of the sensors monitoring the grip force and describe the calibration procedure. In Section 4, the system response is characterized based on data collected from 15 participants who interacted with the setup during an experiment. Findings demonstrate that the customized haptic device was reliable for rendering weak forces with various users and interaction methods. In Section 5, the results are summarized and research directions using the experimental apparatus are proposed.

2. Materials and methods

The experimental setup described in this paper has two subsystems: (i) a force feedback device customized to render the force more transparently (while maintaining stability) and (ii) a system to measure the user's applied grip force. The whole system is controlled by a program running on a PC with an AMD Sempron processor and Windows XP operating system. A 16-bit PCI DAQ card (PCI 6034E, National Instruments Corporation, Austin, TX, USA) is also used. All software was developed in C/C++ with Visual Studio