

Principles of haptic perception in virtual environments

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Introduction

During haptic interaction with *everyday environments*, haptic perception relies on sensory signals arising from mechanical signals such as contact forces, torques, movement of objects and limbs, mass or weight of objects, stiffness of materials, geometry of objects, etc. (Fig. 1a). In contrast, haptic perception in Virtual Environments (VEs) relies on sensory signals arising from computer-controlled mechanical signals produced by haptic interfaces (see Fig. 1b, the online animation [1] under Selected Readings and Websites, and [1, 2]). Haptic interfaces are programmable systems, which can reproduce mechanical signals that are normally experienced when haptically exploring real, everyday environments. Perhaps more importantly, haptic interfaces can create combinations of mechanical signals that *do not have* counterparts in real environments. This allows creating haptic VEs in which entirely new haptic sensory experiences are possible. As a result, it becomes feasible to investigate haptic perception and related phenomena, such as motor control, in entirely new ways. In this regard, interfaces do for haptic perception research what computer graphics does for human vision research. The importance of haptic technology extends beyond scientific research. This technology opens the door to new applications in a variety of fields.

The main objective of this chapter is to discuss the essentials for effective use of haptic VEs in perception research and applications involving user testing. To illustrate this, the chapter also discusses some recent haptic perception discoveries in which haptic VEs played a key

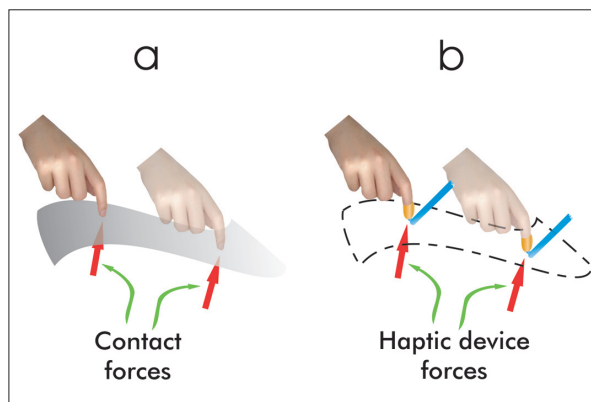


FIGURE 1.

(a) Haptic perception in everyday environments, as when a perceiver explores a surface (the dark object here), involves mechanical variables such as contact forces, which arise from the physics of the haptic interaction scenario. (b) In contrast, haptic perception in virtual environments involves mechanical variables generated through haptic interfaces (here in blue, only part of the interface is pictured). Perceivers use haptic manipulandums (the golden, thimble-like part attached to the interface) to interact with interfaces. Under computer control, haptic interfaces produce mechanical variables (device forces) defining haptic virtual objects (the dashed surface). Note that during interaction with the virtual object, the perceiver's hand moves in an empty area of space.

role. This chapter does not review the growing perception literature that uses haptic VEs. A full treatment of this literature would require an entire book of its own. Also, an important part of this literature can be consulted in several other chapters of this book. In this chapter, practitioners from fields such as neuroscience will

find information to understand the similarities and differences between real and virtual haptic environments. Such practitioners will also find important information about designing and conducting perception experiments involving haptic VEs. This information would also benefit practitioners from areas such as engineering who are interested in haptic perception assessment in specific applications. The close interplay of basic research and engineering in haptic VEs has important implications for perception research and for haptic interface design. This is illustrated with examples of how haptic technology research contributes to our basic understanding of perception, and also of how perception research contributes to practical applications of haptic technology.

Haptic interaction, mechanical variables and haptic signals

Haptic perception relies on sensory signals arising from haptic interaction with a real or virtual environment. Haptic interaction involves mechanical (or haptic) variables such as forces, torques, masses, motions, stiffness of materials, etc. Note that mechanical variables arise from the environment, but also from the body of the person (i.e., the *perceiver*) that haptically interacts with the environment. For example, haptic interaction involves motion of limbs, as when actively moving a hand/arm when exploring a surface (Fig. 1a). When touching objects, contact forces between limbs and objects coexist with limb movement, as when lightly pressing down on a rigid surface while exploring it (Fig. 1a). In this example, mechanical variables involving the perceiver's body (hand/limb motion) are related to mechanical variables (contact forces) arising in part from mechanical characteristics of the environment (the surface's rigid material). This interplay between mechanical variables arising from environment and perceiver is an essential characteristic of haptic interaction, and has important roles in haptic perception. More gen-

erally, this interplay relates a perceiver's *actions* (such as precisely-controlled hand movements) to the *environment's reactions* (such as the motion of an object when pushed by a perceiver). Note that the interplay is bi-directional, as the environment's reactions may have an effect on subsequent actions by the perceiver. For example, when haptically exploring an object, the object may deform when squeezed or move when pushed. As a result, subsequent haptic exploration actions would need to be adjusted accordingly.

During haptic interaction, a given mechanical variable may or may not supply information that contributes to haptic perception. Throughout this chapter, a mechanical or haptic variable that supplies important information for haptic perception will be interchangeably called a *mechanical* or *haptic signal*. One or more mechanical variables or haptic signals define a *haptic stimulus*. A haptic environment consists of one or more haptic stimuli, which define the haptic properties of entities such as objects. A haptic object or environment is *virtual* if it is created through haptic technology. A haptic environment is *real* if it is not created through haptic technology. To further clarify important terminology, 'mechanical variable' and 'haptic variable' will be used interchangeably throughout.

The physics of haptic interaction and its importance in haptic perception

Haptic interaction is a process subject to the applicable laws of physics, such as those of dynamics [3]. This is because the laws of physics quantitatively describe the behaviour and characteristics of mechanical signals and variables present during haptic interaction. Physics describes haptic variables and signals in terms of mathematics. As haptic perception relies on haptic interaction, a thorough understanding of the relevant physics is essential to investigate how different mechanical signals contribute to haptic perception.