Haptography: Capturing the Feel of Real Objects to Enable Authentic Haptic Rendering (Invited Paper)

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ABSTRACT

Haptic interfaces are designed to allow humans to touch virtual objects as though they were real. Unfortunately, virtual surface models currently require extensive hand tuning and do not feel authentic, which limits the usefulness and applicability of such systems. The proposed approach of haptography seeks to address this deficiency by basing models on haptic data recorded from real interactions between a human and a target object. The studio haptographer uses a fully instrumented stylus to tap, press, and stroke an item in a controlled environment while a computer system records positions, orientations, velocities, accelerations, and forces. The point-and-touch haptographer carries a simply instrumented stylus around during daily life, using it to capture interesting haptic properties of items in the real world. Recorded data is distilled into a haptograph, the haptic impression of the object or surface patch, including properties such as local shape, stiffness, friction, and texture. Finally, the feel of the probed object is recreated via a haptic interface by accounting for the device's natural dynamics and focusing on the feedback of high-frequency accelerations.

Categories and Subject Descriptors

H.5.1 [**Information Interfaces and Presentation**]: Multimedia Information Systems—*Artificial, augmented, and virtual realities*; H.5.2 [**Information Interfaces and Presentation**]: User Interfaces—*Haptic I/O*

1. INTRODUCTION

When you contact things in your surroundings through a tool, you can feel a rich array of haptic cues that reveal the shape, stiffness, friction, texture, and other characteristics of the object you are touching. For example, the vibrations and forces experienced by your hand as you stroke a piece of paper or travel over its edge with a pen are distinctly different from those generated by touching a curved rubber surface or tapping on a wooden table. Humans are amazingly adept at eliciting and interpreting haptic feedback during interactions with physical objects, naturally leveraging this wealth of information to guide both exploratory and dexterous manipulation.

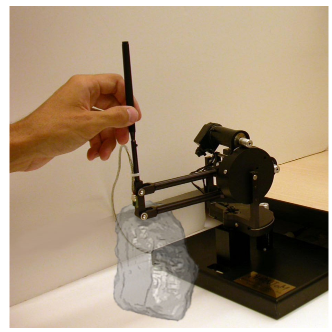

Figure 1: Haptic interfaces like the SensAble Phantom (pictured) allow a user to feel virtual objects through a pen-like tool.

Haptic interfaces seek to extend the normal reach of the human hand to enable interaction with virtual objects. Often taking the form of a lightweight, backdrivable robotic arm (Fig. 1), haptic interfaces measure the motion of the human hand and map it into the virtual environment. The control computer uses specialized algorithms to determine when and how the user is touching objects in the virtual environment; when contact occurs, the system employs the device's actuators (often DC motors) to provide the user with force and vibration feedback.

When accompanied by a graphical rendering of the virtual world, such haptic systems are well suited to training individuals to perform skilled tasks such as surgery and dentistry, presenting spatial data such as land topography or part geometry, creating and manipulating three-dimensional shapes for sculpture or design, and enhancing educational and entertainment media. Throughout this rich variety of endeavors, haptic feedback provides a powerful communication channel for the expanding field of human-computer interaction.

2. HAPTIC REALISM

In order to effectively meet the needs of these diverse applications and succeed in new areas, haptic interfaces must be able to compellingly imitate the feel of a vast variety of physical interactions. Currently, the geometry of objects

HAS '08, February 11–14, 2008, Quebec City, Canada

in a virtual environment may be based on real-world data, but haptic properties like stiffness, friction, and texture are almost always programmed by hand via simple parametric relationships that are only loosely based on the behavior of physical objects. The time-consuming, subjective nature of this tuning process does not extend well to the creation of haptic environments that contain a broad assortment of simulated objects, such as a virtual antique shop or a haptically augmented materials database.

Furthermore, virtual objects rendered via the standard haptic contact algorithm ($F = -kx$) generally struggle to provide convincing feedback to the user. This claim is difficult to substantiate because few researchers are willing to compare the realism of their virtual environment with that of the real objects being simulated. In one of the few studies that does address this issue, subjects blindly tapped on a variety of real and virtual wood samples, rating their realism on a scale from one to seven; the piece of soft foam and the virtual surface rendered via standard penetration-based feedback both received about a two out of seven, indicating that neither is an adequate stand-in for real wood [6]. In general, hard contacts, textured surfaces, and vibratory or stick-slip interactions are particularly difficult to capture and reproduce, as the common proportional force feedback algorithm is restricted to low stiffnesses and smoothly changing forces [1]. It is only by incorporating measurements of real-world interactions that virtual environment designers have begun to approach the realism of natural physical interactions, e.g. [10, 3, 6]; existing measurement-based modeling techniques for haptic rendering are summarized in [8].

3. HAPTOGRAPHY

The proposed approach of *haptography* aims to improve the authenticity of virtual touch by basing haptic models on multi-sensory recordings of the real experiences being emulated[1]. Despite their ubiquitous importance in human life, we currently lack a formal method for describing and analyzing haptic experiences with everyday objects. In contrast, consider the human mastery of visual stimuli; to create a lifelike image of an observed scene, we no longer need to start with a blank canvas, painting each element by hand. Instead, we use a sophisticated measuring system (a camera lens) to control the desired light pattern and project it onto a sensitive medium (either film or a digital image sensor). The latent image is then converted to a storable, portable record (a negative or an image file) using chemical or signal processing. Finally, we create realistic copies of the original stimulus (paper-based prints or screen-based images) for others to see. Haptography research seeks to understand and control haptic interactions to this same level of excellence, combining three distinct yet interwoven threads of inquiry: What sensations do humans experience when touching real objects? What dynamic relationships optimally characterize the feel of real touch-based interactions? and How can such objects be simulated authentically via a haptic interface?

3.1 Haptic Sensation

Haptography begins by creating a sensor system that can detect the perceptually relevant attributes of a haptic interaction. Unlike vision, the human sense of touch is distributed throughout the body. It interacts heavily with the motor system and merges the output of at least seven different biological sensory mechanisms. Most previous efforts to record haptic interactions have relied entirely on position and force, e.g., [7, 9], but these two variables cannot fully characterize dynamic haptic interactions, especially considering the human hand's sensitivity to high-frequency vibrations. Furthermore, these prior modeling efforts probed real objects with a specialized mechatronic system or an industrial robot, which has dynamic properties (mass, stiffness, damping) that are different from those of the human hand. Accurately capturing the acceleration transients that result from tapping on a hard object or stroking a textured surface requires the probe to be held in the same way that a human holds it.

Haptography entails thoroughly sensorizing real tools and environments to capture haptic interactions in their entirety, mimicking a human's afferent nervous system. Haptography sensor suites measure mechanical quantities such as position, orientation, velocity, acceleration, strain, contact force, and contact torque, as well as user characteristics such as grip force, hand position, and muscle activation. These local signal streams can be augmented by an audio and video recording of the interaction to facilitate further analysis. Instrumenting a stylus, a handheld surgical needle driver, or a vehicle's steering wheel in this manner will improve one's understanding of the haptic interaction and allow for sensorized comparison between simulation and reality.

3.2 Haptic Distillation

The second main thrust of haptography is to distill selected sensor readings into a meaningful representation of the haptic interaction that created them. While the human eye and a camera can acquire information about all parts of a scene simultaneously, the human hand can interact with only a small subset of its environment at each point in time. Thus, time-varying sensation data will be mapped to the appropriate environmental location and state during processing to determine the underlying principles governing the interaction. This step elucidates an additional benefit to recording haptic data from an interaction driven by a human rather than a robot; the human haptographer will naturally explore the areas of the object that are most haptically interesting, providing rich data streams for analysis.

Consider the sample interaction of probing a static three-dimensional environment, such as a book, mouse pad, and coffee cup sitting on a desktop. Haptic distillation requires the development of algorithms that can automatically reconstruct its haptic impression (including geometry, stiffness, transient response, texture, and friction) from several minutes of data from the haptography sensor suite. This goal can be framed as a problem in hybrid system identification, where we seek to identify the transitions between three dynamic modes (free-space motion, pressing into a surface, sliding along a surface), as well as the dynamics that govern each distinct contact mode. Analyzing real haptic interactions in this manner will provide a succinct representation of a haptic experience and a quantitative metric for evaluating simulated environment renderings. The models that result from haptographic distillation will follow a standard, portable format to facilitate the creation of a comprehensive haptic library, which can be shared worldwide via the Internet, including both entire objects and independent surface properties.

[1]Haptography was first described in Chapter 6 of [5].

3.3 Haptic Rendering

The final component of haptography is to reproduce stored interactions for a human user via a haptic interface. As with photography, this final step should accurately convey the stored stimuli without distortion or degradation. The main challenge to accurately controlling a touch-based interaction is that the important mechanical relationships are strongly affected by the dynamics of both the haptic device [4] and the user's hand [2]. Most existing systems neglect these influences, presuming that a haptic device can render any dynamic relationship for which it is programmed.

The goal of haptic re-creation can be approached from two complementary perspectives: algorithm development and electro-mechanical device design. The dynamic properties of a haptic interface can be obtained via specialized system identification techniques and then accounted for in subsequent renderings of virtual objects. For example, a haptic interface's ability to create high-frequency fingertip accelerations can be quantified by applying swept sine-wave current commands to the motors while the stylus is held by a user; conditioning desired acceleration transients by the inverse of the obtained model enables the creation of accurate virtual acceleration transients [6]. Though undesirable mechanical behaviors can be adjusted somewhat through software, the best strategy for improving haptic rendering is often to improve the device itself, for example by increasing the bandwidth of its current amplifiers and mechanical linkages.

4. SYSTEM VISION

There are two main paradigms for enabling individuals to capture the feel of objects from their daily life: studio haptography and portable haptography. In studio haptography, the user to walks up to a specialized station with a unique object, perhaps a beautifully manufactured mechanical component or an interesting bone specimen. The person picks up an instrumented stylus and uses it to explore the surfaces of the object by tapping, stroking, and pressing. The computer system collects multiple data streams throughout the interaction, including the movement of the stylus and the object, the high-frequency accelerations of the stylus tip, the tangential and normal forces applied to the object's surface, the sounds of contact, and the appearance of the object's surface. In real time, it constructs a geometric, visual, auditory, and haptic model of the object, projecting its progress onto an adjacent display. If a certain area of the model would benefit from the acquisition of more data, the studio system provides the user with appropriate guidance.

The second haptic sensing paradigm is portable (point-and-touch) haptography, which has obvious parallels to point-and-shoot photography. Here, the user carries a simple, self-contained probe with him or her during everyday life. This probe will have a reduced set of essential sensors, perhaps including three orthogonal accelerometers, strain gauges for tangential force, and a two-dimensional translation sensor like that used in optical mice. The haptographer notices interesting haptic properties of the objects around him or her, such as a crisp contact, anisotropic friction, or a distinctive texture, and quickly records an interaction with the target surface patch. The haptographic data is stored on the probe until it can be wirelessly downloaded to a computer, which distills out haptic models for each recording session.

Regardless of the method by which the data is captured, the primary properties of a haptograph are the object's transient tapping response, quasi-static stiffness, vibratory texture response, and coefficient of friction, each of which is mapped across the object's surface. Acquired haptographic models are rendered by attaching the instrumented stylus to a haptic interface. After donning 3D goggles, a user can immersively explore the simulated object, and the system can quantitatively assess rendering fidelity via analysis of its sensor readings.

In summary, the proposed technique of haptography has multiple applications, including medicine, dentistry, automotive engineering, hazardous material handling, education, and art; its ultimate goal is to generate virtual objects that are indistinguishable from their real counterparts, enabling authentic simulation and efficient training of an abundance of tasks involving hand-object interaction.

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