Will Haptics Research Parallel Computer Graphics Research?

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Abstract

We compare and contrast Computer Graphics research and Haptics research. Haptics is a growing field, as sparse, wild, and woolly as Computer Graphics was 20 years ago. As a research field, it has its own interdisciplinary flavor incorporating mechanical engineering, robotics, and teleoperation along with computation. Nevertheless, it is fundamentally integrated with computer graphics, audio, and interactivity research as we create expressive, immersive environments. We develop the comparisons by introducing a Layered-Description model of haptics: World-based, Perceptually-based, and Representation-based description. Looking at techniques for haptic display at each Description Layer, we discuss 1. where haptics research parallels that in graphics, 2. ways in which its practitioners *could* benefit directly from current graphics techniques and 3. inherent differences between graphics and haptics technical challenges.

Key words: Haptics, Touch Interaction, Virtual Reality, Texture, Computer Graphics

1. Introduction

Haptics is the study of the sense of touch and human-computer interaction using it. Research in haptics is in a period of booming growth. The number of research groups is increasing as well as the amount and diversity of the research in those labs. This expansion is reminiscent of the early growth of Computer Graphics (CG) — and the issues are similar, too: how does one create an effective, psychologically sound, and esthetically pleasing simulation of an essential human sensory system, using computational tools and/or specialized hardware?

In this paper we introduce a three-part model for haptics simulations—we call it the Layered-Description model. We compare successful trends in Computer Graphics with those in Haptics, using the Layered-Description model to analyze similarities and differences.

There are many key similarities between the fields of CG and Haptics — which both began with Ivan Sutherland's first attempts to develop VR [1]. First, there is parallel development of geometric and physical models. Second, the challenge of specialized and standardized hardware faced by CG is even more challenging for haptics. Third, the driving domains are similar: entertainment, medicine, exploration, education. Fourth, both fields can benefit from representations in which the rendering system "knows" high level information about the objects and actions being represented, for example, in order to do effective "non-realistic" rendering of material properties of objects.

Haptics practitioners *may* benefit directly from current graphics techniques such as sharing of polygonal 3D models, physically-based modeling and particle systems for dynamics, volume data processing and rendering techniques, deformable object techniques, and standard graphics library packages.

One notable difference between the Haptic and CG display is the speed requirement for interactivity. Another difference is the need for more basic research on the human sense of touch.

2. Graphics and Haptics

Computer Graphics systems are static or animated; they support 1st-person or 3rd-person points of view. The history of the field has always involved all corners of this space; interactive systems such as Sketchpad [2] actually heralded the beginning of interest in Computer Graphics.

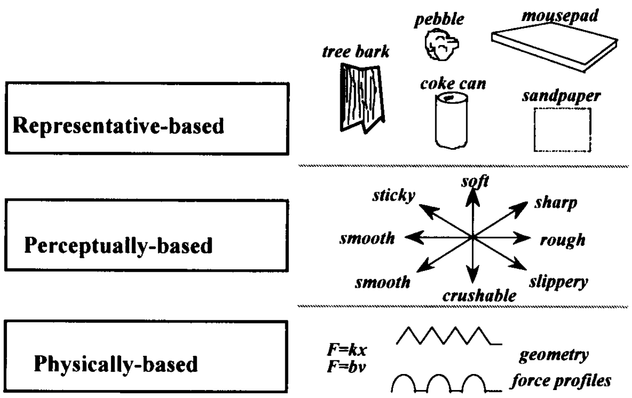
In contrast, haptic displays are inherently dynamic; they involve exchange of mechanical energy with parts of the human body. Haptic displays also always take on a 1st-person quality: The user actively scans the image with hands or body.

Haptic display technology poses great challenges. Haptic display is mechanical and interacts with the human haptic system Haptic displays require higher update rates than graphic displays: usually about 1000 Hz. rather than the 30 frames/sec most common for real-time graphics. In addition, the human haptic senses are an integrated system of many types of sensors in the skin, muscles, and joints.

Haptics displays include the entire family of force-feedback devices, spatial arrays of moving pins or other touch-able elements, and experimental full-body pneumatic and fluid displays, wind-based displays, shape-changing devices, and others. Most of the work described in this paper uses force-feedback displays.

3. Layered-Description Model

Observations of human descriptions of haptic materials has suggested a layered set of models used in implementing haptic systems: World-based models, Perceptually-based models, and Representative-based models [3].



World-based models specify the geometric and physical properties of materials, surfaces, or objects.

Perceptually-based models specify parameters of perceptual primitives, for example, roughness, stickiness, or softness.

Representative-based models specify object type and purpose. The display system translates these high-level descriptions into perceptually-based or world-based descriptions, and chooses the best representation for the purpose and hardware at the time.

4. World-based Models

4.1 Definition

World-based models specify the geometric and physical properties of materials, surfaces, or objects. For example, a block might be described by the positions of 6 rectangular polygons, perhaps with surface normals, and color and luminance values; a centroid and a mass might be added for a physical model.

4.2 World-based models in CG and Haptics

In computer graphics, geometric models are sufficient for many purposes, because many computer graphics tasks produce static pictures. Static models and kinematic models have been of immense value to image-making, with physically correct dynamics adding to their capabilities but not being necessary for all purposes. Historically, physically-based modeling has been a relative newcomer.

In haptics research, physically-based models came first, because the nature of haptic display is fundamentally dynamic. The first models for force-feedback haptic simulations had simple, often implicit descriptions of geometry, along with dynamics equations implementing the simulation. For array devices, geometry descriptions were often derived directly from array data (e.g. Braille), or digitized at low-resolution from imagery. The array element response speed has usually limited the dynamics of changing data.

4.3 Haptizing surface models

There are many kinds of 3D models in computer graphics: polygonal surfaces, implicit surfaces, volumes, and many exotic representations.

The development of 3D models in computer graphics has been driven by appearance (the way that the eye "contacts" an object), and interactivity. Recently, there has been resurgence of effort to model physical behavior as well, since it is hard to find effective visual approximations to complex situations involving many moving objects, or materials such as cloth and living tissue. As equations of motion for such situations are difficult to solve (and sometimes to derive), approximations are found which retain qualitatively correct properties.

The notion of incremental constraint solution as a method of settling situations is one that has seen use from time to time in graphical interactive systems and in modeling complex motion.

Combining constraint solutions with shading concepts has recently led to a highly successful line of research to quickly "haptize" scenes with multiple, fairly complex polygonal models: giving an effective fairly stiff surface contact with the objects, and allowing surface friction effects, certain texture and other surface effects.

Standard polygonal models are now being directly imported into haptic display environments, with surfaces automatically available to haptic display. Techniques analogous to shading have permitted a fairly straightforward pipeline allowing polygonal 3D models to gain haptic presence. This approach, initiated by the work of Zilles [4], has been elaborated into a complete solution by Ruspini, Kolarov, and Khatib [5]. They describe a standardized technique and modeling library (called HL) for "haptization" of polygonal models which uses a constraint technique and a shading technique.

4.4 Dynamics

Classical physical models have sometimes been fast enough for haptic simulation of very interesting, complex dynamics. For example, Gillespie [6] models a piano key action in detail. The very successful arcade game Hard Drivin' [7] contains a full, 4-wheel model of automobile dynamics. These simulations were able to run at haptic speeds through dimension reduction and in the second case, dedicated processors.

Physically-based modeling work of Barr, Fleisher, and others provides calculation techniques for moving and deforming objects in 3D. This work was not done in a real-time context, however, computational speed increases may make some of the techniques applicable.

A particle system approach has been successful in graphics for modeling a variety of natural phenomena qualitatively Particles with attraction and repulsion forces are a promising approach for modeling qualitative and quantitative properties of materials. For example, Cadoz and Luciani have shown several dozen particles interacting in real-time surrounding a two finger, 2 dof interface, in the Cordis-Anima system [8].

4.5 Volume Data and Rendering

Volume data and techniques for rendering images directly from it should feed directly into display of haptic objects that are "haptic all the way through" their 3D volume, for example, medical simulations

Many objects and materials are most naturally represented as volume data.. The computer graphics community is occupied with such models for several reasons: they show promise as representations of material properties, they may be good for representing elastic and deformable objects, and medical scans come in this form. It may be that haptic display of volume data is easier than graphic display, since the human does the scanning! Rendering of volume data as forces has been demonstrated by Iwata [9], and is now a focus of haptics activity.

4.6 Deformable Objects

Deformable objects are a very important class of objects for haptic display, as they encompass material properties that are perhaps best perceived haptically. These haptically important objects are some of the most intractable kinds of objects for graphics systems - deformable materials are often composite materials made of many tiny interacting pieces with emergent bulk properties such as liquids and textiles.

The human visual system sometimes cannot fully interpret the behavior of such objects and a person reaches out to touch messy things, drapey things, and living things. One could go as far as to say that these "natural materials" all lie in an intermediate zone between rigid, predictable objects and animate beings.

Many techniques for the representation of deformable objects are being tried. Geometric and physical techniques have been used in graphics; including spring-lattice and finite-element methods [10]. For example, Pieper [11] demonstrates a facial plastic surgery simulation using a finite-element representation for skin layers. Most techniques for deformable objects are difficult to compute in graphics real-time (not to mention haptic rates).

4.7 Standard Libraries

Another important idea from computer graphics is standardized libraries. In graphics these have almost never accomplished the aim of universality, but are often useful by a substantial group of researchers and allow people outside the field to make faster use of the techniques. Haptics libraries such as GHOST [12], HL [5], and others are just starting to appear.

4.8 Photo-realism and the goal of Hapti-realism

The computer graphics world benefited since its inception from properties of the human visual system that allowed display technology to display effective images. These are 1. persistence of vision, which allows animation with a relatively low frame rate 2. visual filling, which allows line diagrams, low resolution, black-and-white images to be perceived as defining coherent, even realistic, shapes in 2D and in 3D, and 3. tristimulus effect, wherein display of 3 colors allows the perception of a good simulation of real-world colors.

The haptics world has not yet discovered the properties of the haptic-motor systems that will allow such simplification of display. Thus it has been necessary to drive higher-performance machines and model physics more accurately than required by graphics.

It has also meant that we have not spent that pleasant stage that CG passed through, where photo-realism was unimaginable but intellectually stimulating work on interactive animation, visual programming, scientific visualization, and effective art, were all possible even with single-color vector displays.

Photo-realism is a laudable goal indeed, but CG researchers are constantly rediscovering how to use artistic and perceptual "puns" to create means of visual interaction and communication that can be even more expressive.

In fact, one can see vision/perception research re-coupling to CG particularly in areas of simulation of complex natural materials and textures.

In haptics, there are some discoveries which point along these directions. We will discuss them in the next two sections.

5. Perceptually-based Models

5.1 Definition

Perceptually-based models include information that is represented in terms of human perceptual systems. The faces of a block might be "shiny" or "dull", leaving it up to the rendering system to interpret these in terms of reflectance values.

5.2 CG and Haptics Perceptually-Based Models

Haptics simulation work is running right alongside psychologists exploring the fundamentals of human haptics, and the fields are interacting directly. Computer Graphics, in contrast, does not depend much on active research in vision. The basic research grounding for CG is both historically further back (3-part color models are 19th century) and indirect, these models were processed through art and technology such as photography and television before CG was invented. Haptic simulation was preceded only by the more recent engineering field of teleoperation technology.

In the following sections we review some examples of how current perception research directly influences haptic simulation research.

5.3 Texture

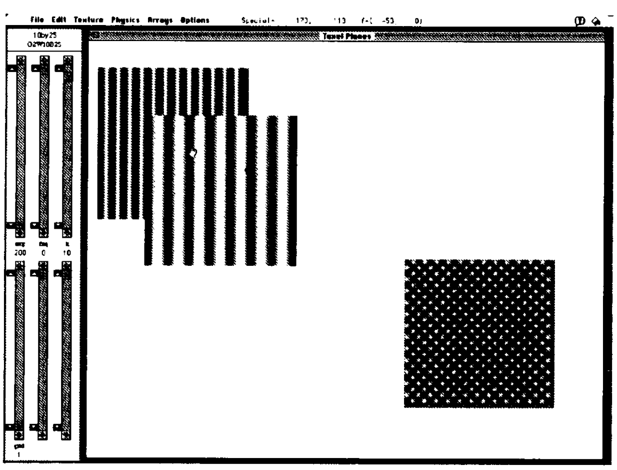
This author [3] introduced a technique for creating haptic textured surfaces. The key observations that prompted work on texture simulation were work by Lederman and Klatzky [15] on the nature of haptic exploration by the human hand, and earlier work by Lederman [14] identifying physical correlates of roughness sensation.

These haptic exploration studies indicate that people use particular hand motions when they identify texture and surface compliance, and that these material properties of objects are highly salient. The haptic identification of shape usually calls upon different exploratory hand motions and appears to be less salient for haptic classification of objects. This suggests that in integrated haptic and graphics simulation systems the work can be split, with computer graphics doing the best job of shape fidelity and haptic display used to emphasize and enhance the presence of material properties.

These perceptual studies were the direct justification for taking on the challenge of implementing rough surfaces and other material parameters.

In the specific case of creating rough textured surfaces, this author found that a perceptually-based model could be successful. World-based parameters chosen for adjustment were modeled by analogy with the physical parameters associated with roughness discovered in Lederman's psychophysical studies of rough gratings. By tuning one of these parameters (force amplitude) in the texture simulation of a grating, one can control perceived roughness [16].

This figure illustrates the grating textures as well as others that can be simulated with the Sandpaper system.



In the preceding texture simulations, a 2 dof joystick was used to give the perceptual impression of 3d textures.

Simulation of material surfaces has continued to be an important theme in haptics research. Some examples are simulations of discriminable bumpy textures in a 1D simulation [17], use of textured patches in a 2D system [Rosenberg], new techniques for roughness [Greenberg, MIT], slip and friction characteristics, integrated surface characteristics [5].

5.4 Hard Surfaces

In another example, Rosenberg and Adelstein [22] found a *perceptual* classification of simulated hard surfaces in terms of hardness, crispness and release characteristics. They found that these percepts were modeled in their simulation by adjustable world-based parameters of spring-stiffness, damping constant, and damping directionality. This observation led to a perceptually improved implementation of hard walls..

5.5 Perceptual Dimensions

A suggestion for haptic systems' implementation of material properties comes from a study by Hollins et. al. [23], who verified that the textures on 17 common objects plausibly define a three-dimensional texture space. The three dimensions appear to correspond to rough-smooth, hard-soft, and springiness. Despite limitations in this study, it suggests that by finding world-based parameters corresponding to these texture properties, one could design a system in which a wide variety of real-feeling textures could be compactly represented and created on the fly for haptic displays in VR environments.

5.6 Haptic Saltation

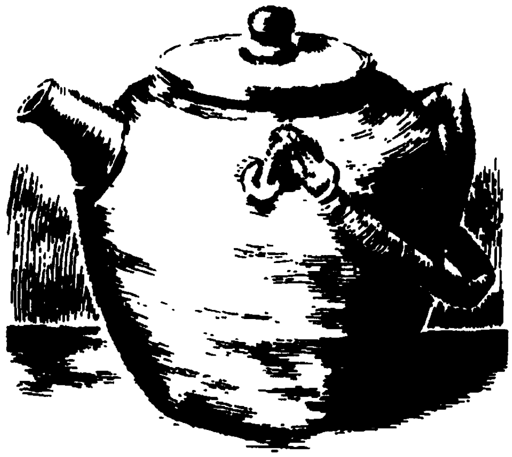
In the work of Tan [24], a haptic display is constructed based on the haptic perceptual effect of *saltation.* Successive taps or touches can be perceived as continuous motion of an object along parts of the body. Tan has recently made a haptic "smart" chair which has a low-resolution array of actuators concealed in its back, The illusion of smooth directional motion of an object along the sitter's back is has been effectively demonstrated.

6. Representative-based Models

Representative-based models carry explicit representations of situated properties such as high-level categories, purposes, and goals. For example, a child's toy might be represented simply as "block", leaving it up to the rendering system to know that this means a rectangular piece of wood, and to create the appropriate appearance.

Haptics researchers and Computer Graphics researchers both realize the value of adding high-level descriptive layers to their systems. Some of the advantages are increased display-independence, more compact representation, and most important, ultimately, increased possibilities for expressive display by the interaction system.

A particular challenge to haptics is to find a method of expressive display analogous to non-photo-realistic rendering. In CG, a recent trend has been to render diagrammatically, or artistically, rather than photo-realistically. This provides greatly increased expressive power both for providing information in illustrations and for expressing mood. Some key examples of progress in this area are [18], [19], [20]. These systems are classified as Representative-based because knowledge about the purpose and style of the objects being rendered is available within these systems. Imagine a haptic analogy to this kind of rendering:



3D teapot model rendered in the style of a pen-and-ink drawing, from Salisbury, Wong, Hughes, and Salesin [20].

Another analogy can be drawn from Perlin's "Responsive Animation" [21] in which animated characters look more real by virtue of small, lifelike motions such as gaze re-direction and breathing added automatically. In Perlin's system the animator can adjust a compact representation of these motions in terms of simple parameters to dial in a wide range of apparent emotional or purposive state in the character. In haptic rendering, we hope to find intelligent representations that will make the simulations expressive. For example, if a textile simulator explicitly represents "comfort" as an aspect of garments, then haptic simulations of clothing can be chosen to give a "comfortable" feeling to the user with the system making intelligent choices about how to create the feeling of comfort depending on the capabilities of the display.

These kinds of expressive renderings are no frill. In haptics and teleoperation, we wish to give impressions of the feel of remote planetary surfaces, underwater gardens, and tiny molecules, as well as fantasy environments. We will need to use haptic sensations to transmit such things as mood and salience in order to allow training and operation in these environments. In this case the literal feel of a rock, plant, or ambient fluid may be much less important than impressionistic representations of them to the user. Thus we need to represent the purpose and relative importance of elements of a scene that are being haptically rendered. This is an area that is just beginning to be explored.

7. Application areas

The enterprise of Computer Graphics has been driven by a variety of what Brooks [UNC] calls “driving problems” from science, arts, entertainment, and education. University, government, and commercial projects all shared in making progress from the beginning of the enterprise.

Some of the areas in which haptic interaction is particularly valued, often as part of an integrated VR system, are: games and rides, music, medicine, space exploration, prosthetics, and textiles.

Computer Graphics research at first combined hardware device research with image-making techniques. In certain areas, fast computer speeds and standardized displays made it possible to do research using standard, though expensive, platforms. This progress inspired inexpensive systems which put production of imagery and animation in the hands of almost anyone.

Haptics, coming further along the technology curve, is already spawning high-fidelity commercial research platforms which will create the opportunity for standardized platform research (without in any way reducing the need for device research).

An intriguing twist is that the computer games industry is driving a commercial thrust to make inexpensive, mass-produced force-feedback devices (mostly 2 dof joysticks). This unusual situation provides an opportunity to allow an enormous number of people to become “haptics researchers” if we create the appropriate educational tools that can be used on home computers.

8. Display Challenges

Because haptic systems must transfer energy with the human body, and usually must have high bandwidth response, the hardware is very challenging to design. This is another reason that the field naturally encompasses researchers trained in mechanical engineering, robotics, and teleoperation.

A world-based strategy tends to favor designs that implement as many physical properties of the real-world as one can. Designers of haptic systems have found it easier to pursue an evolutionary design strategy revolving around force-feedback and array interfaces. Considering the success of a perceptually-based approach in haptic software design, we can also adopt a perceptually-based strategy for display design. Haptic perceptual research underscores the importance of certain material properties not covered by these devices. For example, thermal properties of objects are highly salient. This is a call to action in the haptics research community to develop thermal display as a component of our haptic display systems. An example is the work of Ottensmeyer [25].

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