Haptic Holography: A Primitive Computational Plastic

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Invited Paper

We describe our work on haptic holography, a combination of computational modeling and multimodal spatial display, which allows a person to see, feel, and interact with three-dimensional free-standing holographic images of material surfaces. In this paper, we combine various holographic displays with a force-feedback device to render multimodal images with programmatically prescribed material properties and behavior. After a brief overview of related work which situates visual display within the manual workspace, we describe our holo-haptic approach and survey three implementations, Touch, Lathe, and Poke, each named for the primitive functional affordance it offers. In Touch, static holographic images of simple geometric scenes are reconstructed in front of the hologram plane, and coregistered with a force model of the same geometry. These images can be visually inspected and haptically explored using a handheld interface. In Lathe, a holo-haptic image can be reshaped by haptic interaction in a dynamic but constrained manner. Finally in Poke, using a new technique for updating interference-modeled holographic fringe patterns, we render a holo-haptic image that permits more flexible interactive reshaping of its reconstructed surface. We situate this work within the context of related research and describe the strengths, shortcomings, and implications of our approach.

Keywords*—Augmented reality, computational holography, electroholography, haptic modeling, holographic video, multimodal, visual–haptic, visuo–haptic.*

I. Introduction

For those who grew up with Frisbees, Barbie dolls, and Tupperware, it is especially hard to imagine that before Bakelite in the early 1900s, we had only natural materials to fashion into the stuff of our everyday lives. The new synthetics changed our material life fundamentally—not only in a practical way, through the near ubiquity of their use; but also in an ideological way, with the revelation that we could actually *create new materials* with properties unlike any natural substance, which could change both the appearance and utility of substrates, surfaces, and objects.

Since Bakelite, countless new synthetic materials have been invented, but most remain popularly undistinguished. Polyethylenes, acrylics, silicones, and so many other appreciably different substances are often casually viewed as myriad variations of one—plastic. As such, plastic seems to be infinitely mutable. It can be silky-smooth, pliable or squishy, hard, durable, soft and fuzzy, shiny or matte, colored, patterned, textured or clear. But once it is fashioned into a particular shape, appearance, and material consistency, those qualities largely remain as prescribed, static, and fixed.

Now materials research is beginning to investigate miniature, embedded means of sensing, of switching a material's visual, tactual, and bulk material properties and of actuating its movement. With the eventual fusion of computational algorithms and this fabricated, malleable, programmable material, we would expect another huge practical and philosophical transformation in our lives.

We might think of this eventual "computational plastic" as a broad class of technologies, each a mixture of programmable behavior and both active and inert encapsulating matter. At the boundaries of its definition are two extremes: one is a completely autonomous computational substrate; the other is a nonmaterial composite of simulation and physically realistic multimodal display. In anticipation of the manufacture of the "matter" part (and the means of its address and instruction), many research efforts are implicitly experimenting at the more accessible extreme of this alloy's spectrum.

From an amalgam of computation and innovative display technologies, both visual and haptic, various instances of what we might call a primitive computational plastic

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are emerging, as we begin to contemplate the properties, usefulness, and broader implication of its eventual physical instantiation. Of these premonstrations which mediate the sensing, apprehension, and/or manipulation of purely computational objects within the physical environment, some are intended to suspend our disbelief or to evoke the impression of perceptual presence; and some simply provide a natural, interesting, and effective space for work or play. One important goal they all advance is the presentation of simulation in our own environment, where we might encounter and work with data objects as comfortably, skillfully, and imaginatively as—and maybe even better than—we do real ones.

Sharing this goal, our own work investigates the combination of haptics and holographic imaging for future use in industrial design applications. Holography's capacity for striking realism can render spatial images with a vivid material look, and that impression can become heightened in the presence of compatible information for touch. Since we think about these display and interface technologies as someday presenting simulated freestanding materials to be precisely shaped by handheld tools, interactively scaled, textured, colored, and so on, we find the notion of computational plastic to be a useful guide.

This materials metaphor may be useful in a broad array of research efforts loosely related to ours, which also investigate methods and means of delivering simulated things into the workspace. This work is collectively situated nearer the reality extreme of Milgram's well-known reality–virtuality continuum [1], which essentially describes how much of a person's environment is real or computer generated. It includes demonstrations that all display or indicate a responsive visual–haptic simulation in the same real space our bodies occupy rather than asking a viewer to be telepresent; all strive to display, within the augmented reality setting, *overlapped and coregistered* visual–haptic stimuli that are compatible with our phenomenal experience of physical environments; all offer their simulation for our hands (or handheld tools) to somehow directly apprehend or manipulate; and by their design, all take some steps to shrink our awareness of the technology mediating the experience.

In this paper, we first organize a selection of this related work, according to the basic technological approaches employed to create a visual–haptic workspace. Then, within this context, we summarize our work with haptics and holography, and discuss its many future challenges.

II. Putting Simulation at the Fingertips

A. TUIs: Instrumented or Sensed Physical Interfaces

Tangible User Interface (TUI) research offers an interesting approach to combining "bits and atoms." TUIs describe many flavors of physical handles for virtual objects, utilizing various sensing technologies and attaching tiny embedded displays and other electronics to real objects. Some examples are given in [2]–[8]. These tangible objects then act as *physical controllers* for virtual processes, providing intuitive whole-hand interaction and rich haptic feedback

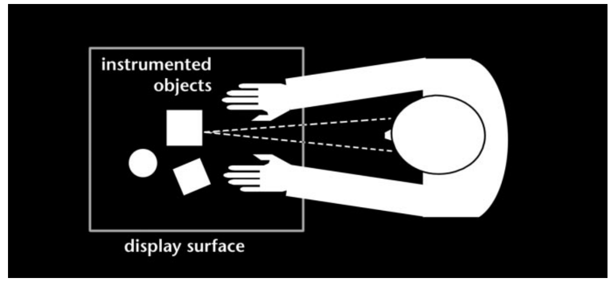

Fig. 1. Tangible real objects mediating interaction with simulation.

that seems both natural and obvious to a user (see Fig. 1). While physical interface objects are manipulated, either their visual properties may be updated in some way (for instance, by projecting images directly onto them), or else a spatially disparate visual display may change in response.

In this latter case, separating the physical controller from the virtual controlled system requires vision to switch between guiding the hand and monitoring system feedback, rendering what Ishii describes as a kind of functional seam [9] between interaction and display spaces. Here, we instead focus on the case in which display and interaction spaces are designed to be coincident and, hence, "seamless" in this regard. An interesting example is Underkoffler's *Luminous Room* [6], [7], which shows a spatial and thematic coupling between the physical controllers and the displayed quantities they manipulate. Here, the tangible interface becomes a literal part or thematic extension of the displayed information, rather than just an obvious physical handle. For example, in an urban planning application [7], a person manipulates physical architectural models, which the system tracks and registers with computationally generated and projected shadows and reflections. More recently, Piper *et al.* demonstrated a system for landscape analysis [8] which provides a malleable surface onto which visual information, tailored to the changing surface geometry, is projected. In both of these demonstrations, it is quite natural for a user to think of the visual projections as arising from the model itself, rather than as "system output." These representative systems suggest a broad and imaginative palette of ideas for instrumenting interactive space, and appeal to the rich set of sensibilities and skills people develop from years of experience with real-world objects, tools, and their physics. The richness of visual and haptic cues resident in these systems does indeed compare with those available when operating entirely in an unwired physical space, and natural strategies for manipulating the instrumented controllers can often be used. However, while the visual appearance of a physical interface object's surface may be dynamic and programmable, in most cases its shape and haptic properties remain largely static and unchangeable.

B. Magic Windows: Video See-Through

In a "magic window" configuration (see Fig. 2), the visual display behaves like a movable transparent screen interposed between the viewer's eyes and hand, and through

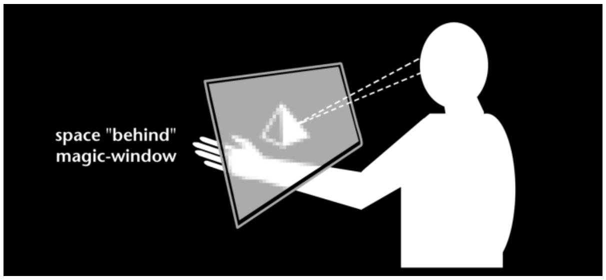

Fig. 2. Reaching behind a magic window to find an augmented reality scene.

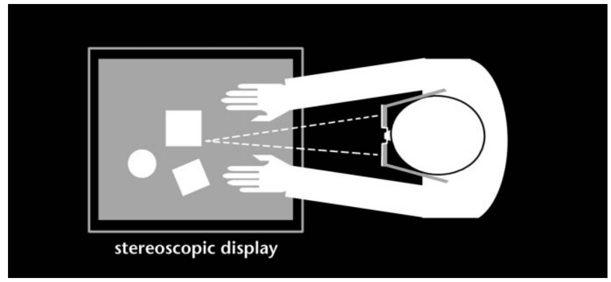

Fig. 3. Seeing the augmented reality scene and your body, or your body implied.

which the hand can be seen interacting with an augmented reality, tangible scene. Some systems have been reported which provide visual display in this fashion without the ability to haptically interact with the scene, for instance, [10], [11], though the hand may physically enter and occupy the same space. An interesting system that does incorporate force has been demonstrated by researchers at Carnegie Mellon University, Pittsburgh, PA, called the *WYSIWYF* (What You See Is What You Feel) display [12]. This work employs a six degree-of-freedom haptic manipulator and monographic visual rendering to combine three pieces of information in this final coincident spatial display: a video image of the operator's hand/arm, the computer graphically rendered scene, and the accompanying force model. An interacting person looks "through" the display to monitor her hand, sees its video image manipulating a computer-generated model, and feels forces due to the interaction.

In this system, visual display and capture are provided by a color LCD panel with a charge-coupled device camera attached to its backplane. This display–camera unit can be moved with respect to the physical scene, while vision-based pose estimation is employed to determine its new orientation. The displayed image is assembled by compositing a computer graphic view of the synthetic scene, generated from the newly computed viewpoint, with a live Chroma Keyed image of the operator's hand/arm interacting with the haptic device. This display can produce incorrect occlusion relationships between the hand/arm and virtual objects, and it provides only monocular cues to scene depth and layout (no stereo viewing or head-tracked motion parallax is available). Yet, through its display window, the operator can see a video view of her hand presented where her real hand is spatially positioned, and can feel forces due to interaction with the real and virtual objects presented there.

C. Magic Glasses and Reach-In Spaces

A wide variety of augmented reality (AR) [13], [14] systems employ body-borne visual aides to present the visual simulation where the hand can encounter it (see Fig. 3). These implementations require a person to wear view-multiplexing glasses or a see-through head-worn display (HWD) and to work within some tracked/sensed area or at a workstation or workbench. A growing number of efforts to join eyes and hands in a coincident visual–haptic workspace (which may even include other people in a collaborative setting [15]) have been reported. One configuration, which uses a force-feedback device and head-tracked stereo graphics, multiplexed with LCD shutter glasses and displayed workbench-style, is the University of North Carolina at Chapel Hill's *nanoWorkbench* [16]. This system not only allows an operator to see, feel, and interact with computer-generated, coregistered visual and haptic molecular models, but permits her to interactively control an atomic force microscope and work at an entirely different physical scale as a teleoperator.

Feiner's *KARMA* [17], State's AR-assisted surgery [18], and Billinghurst's *Magic Book* [19] are just a few of many notable research efforts that employ a handheld or head-worn display combined with a stereo video camera assembly, body-borne user tracking, and techniques to extract real-world geometry and composite it with computer-generated elements (in some cases, displaying correct occlusion relationships, which is both important and challenging). Most of these efforts rely on haptic feedback from real objects populating the physical scenes they are visually augmenting. For instance, a reader of the *Magic Book* may hold a physical book on her desk and, by looking through a shareable handheld display, see an animated character displayed on the book's actual pages. This particular demonstration combines the familiar interaction style we use when reading a storybook, provides haptic feedback from the book's pages and content, and visually augments its pages with simulated characters and scene elements (which are not tangible).

Many systems employ a "reach-in" workspace, in order to accommodate overlapped and coregistered computer-generated haptic models and simulated or augmented reality visual display. Most commonly, as demonstrated in an early report by Schmandt [20], these spaces consist of one or several partially silvered mirrors to superimpose one or more displays' pixel planes onto the haptic workspace, and some view-multiplexing eyewear (in essence, this arrangement provides most of what the HWD encapsulates, but takes much of it off the viewer's head). One such example is the *Virtual Workbench*, [21] developed at the Research Lab for Electronics, Massachusetts Institute of Technology (MIT), Cambridge. This system, used to study human sensorimotor capabilities and to develop training applications, employs a haptic interface and a fully silvered mirror to visually substitute stereo computer graphics for the actual view of the haptic workspace. Additionally, audio cueing is presented in the system, which is designed to present all three modalities in spatial register. Using the Virtual Workbench, an operator

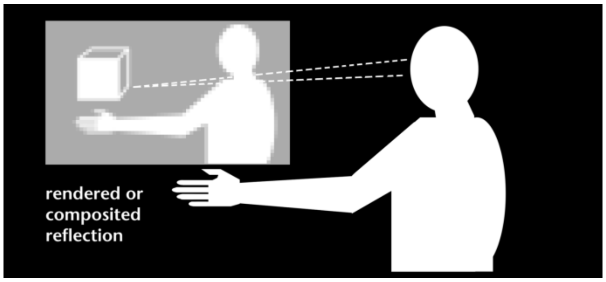

Fig. 4. Seeing a reflection of yourself interacting with an augmented reality scene.

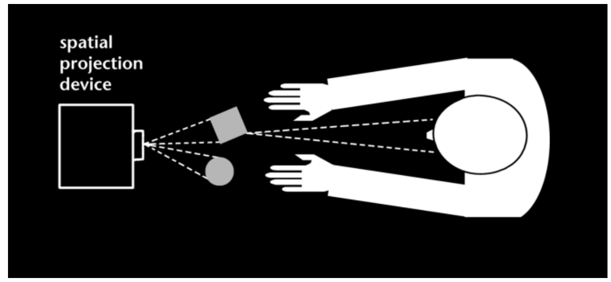

Fig. 5. Spatial projection into the workspace.

looks toward the space where her hand is operating the haptic device and, while feeling force cues, sees a stereoscopic view of the computer-generated model and tool. No real or rendered view of the hand is presented, though the hand's collocated position is kinesthetically sensed.

In systems which use semisilvered combiners, a person can see her hand and the actual haptic device interacting with the computer-generated scene. One troublesome drawback to this arrangement is the apparent occlusion violation that arises when the hand or a nontracked portion of the haptic apparatus is seen passing into or through a simulated object (this problem also arises with see-through HWDs). One approach taken by Inami *et al.* [22] to minimize this visual conflict was to coat the haptic device with a retro-reflecting material and then project the computer-generated scene onto the workspace. With appropriate projection, the scene is reflected back to the eye by the device, giving its otherwise opaque and occluding silhouette a semitransparent "camouflaged" appearance.

D. Magic Mirrors: Shadow or Reflection Projection

Some systems present a viewer with a projected display that shows them composited and interacting with augmented visual information (see Fig. 4). The use of video for interactive capture, compositing, and display has been demonstrated literally for decades by Krueger; his evolving *VideoPlace* installation [23] allows a viewer's "digital shadow" to interact with augmented information without haptic feedback. Human performance issues aside, our experience with shadows and mirrored reflections of ourselves allows such composited displays to be visually persuasive, if they are carefully rendered, projected, and updated.

The *ALIVE* system [24], developed at the MIT Media Laboratory, used a reflected display format and permitted people to interact with autonomous agents (a dog and a hamster) exhibiting convincing and lifelike behaviors. Especially since gestures were used to interact with the animals in ALIVE, and no high-precision manual skills were required, the "magic mirror" was strikingly effective; unless a viewer tried to pet the dog, her sense of occupying an ambulatory space with computational animals was quite strong. Of course, a viewer would receive visual–haptic feedback when interacting with physical things also placed in the environment with her.

Finally, one variation of Billinghurst's *Shared Space* [25] demonstration presented a graphics window in which the image of an interacting person holding a rectangular card is shown, along with simple synthetic objects rendered as sitting on the card. The visual responsiveness of the demonstration and using two hands to both *feel* and *manipulate* the card made this experiment especially powerful.

E. Spatial Projectors: Holograms, Autostereoscopic Display

Spatial projectors display a volume of data to a viewer's eyes without the need for head-worn gear (see Fig. 5). A variety of approaches have been investigated for three-dimensional (3-D) display [26] based upon a number of fundamental technologies; for instance, integral and lenticular arrays, raster barrier panels, projected polarizing masks, volume-sweeping devices, and diffractive optics including holograms. One system which optically projected a 3-D view and offered programmable haptic display was Dimensional Media's *High Definition Volumetric Display (HDVD)* [27]. This system incorporated force feedback and a reimaging display, which employed optical components to relay and composite images of physical 3-D objects and/or two-dimensional (2-D) displays. As a result, visual images were strikingly realistic, and a force-feedback device could be used to inspect the optical output. While changing the geometry of the displayed 3-D object was not possible with such a system, the information presented on the 2-D displays could be updated in response to haptic interaction, thus producing visual changes in the workspace.

Basdogan *et al.* [28] have demonstrated an elegant tabletop workspace containing coincident visual–haptic simulation generated by a system they intend for use in a variety of applications. Here, both visual and haptic images are computer generated, and can be manipulated by a user interacting very naturally. The system currently delivers a stereo view which does not track the viewer; however, future versions of their system will display more parallax as a viewer moves through its viewzone. As in the case with see-through HWDs and reach-in displays, similar conflicting occlusion cues can be present here, when the haptic device penetrates the spatial visual image.

The combination of haptics and holography was first reported by researchers at De Montfort University, Leicester, U.K., for an object inspection task [29]. In this work, a reflection transfer hologram displayed an aerial image of a control valve and a computer-controlled tactile glove (CCTG) provided coincident haptic display of the same

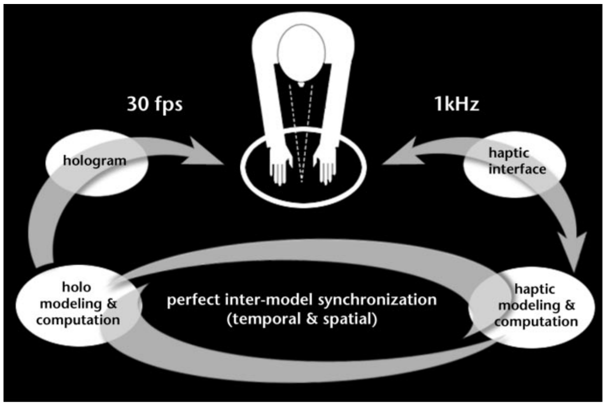

Fig. 6. Idealized design goals for a holo-haptic system.

data. Similar combinations of reflection transfer holograms and force feedback were also informally later investigated early in our laboratory. In all attempts at using reflection holograms, the interacting hand could be oriented to inadvertently block the reflection hologram's illumination, preventing image reconstruction and generating confusing occlusion cues in the scene. That problem aside, the immediacy of seeing and feeling the interaction among image, hand, and tool, and the freedom to visually inspect a highly realistic image both from a distance and up very close (the way a designer or craftsperson might iteratively work materials and contemplate the result) was compelling enough for us to investigate some of the technical challenges. We began with a simple set of design goals for an idealized holo-haptic system, as shown in Fig. 6.

The figure shows an interacting person seeing and feeling cues being displayed within the multimodal workspace. At the right, a haptic device is indicated which displays bulk force and tactile cues to the interacting person, tracks their manual interaction, and reports it back to the haptic simulation. Here, simulation dynamics are computed, and appropriate haptic cues are updated in the workspace at minimum required rate of 1 kHz. Changes in the haptic model are also considered in hologram computation; that computation is performed rapidly and the holographic display is updated at a rate within 20–30 Hz. The visual and haptic models in this system should be perceived by an interacting person as being in precise spatial and temporal register.

III. Touch: Static Visual Haptic Simulation

A. Goals and Tools

The goal of our first experiment, *Touch* [30], was to render a simple visual–haptic workspace that displayed scene geometry within a user's tabletop workspace in good spatial and temporal registration, and allowed the user to haptically inspect the scene without blocking its reconstruction. We chose to create a freestanding image within the viewer's manipulatory space by projecting a static, high-resolution, holographic real image that provided both horizontal and vertical scene parallax. To prevent the interacting hand and device from blocking the reconstructing light source, we chose to experiment with edge-illuminated holographic stereograms.

In addition to providing a workspace which admits the hand without interfering with illumination, edge-illuminated holograms have a compact design resistant to improper lighting [31] and the image distortions it causes. Providing full parallax in these holograms allows greater freedom of movement throughout the viewzone, and presents a stable and compelling impression of a scene's dimensionality without the astigmatic image distortions [32] associated with horizontal-parallax-only (HPO) holograms.

To generate any full-parallax holographic stereogram, many thousands of component computer graphic views of a scene may be required. Traditionally, these views were computer-graphically rendered and either put to film or saved to a computer disk for subsequent holographic exposure. Thus, the production of each holographic stereogram was characterized by three distinct processes: designing the image, rendering the component views, and exposing these stored images. This sequential process expanded the production timeline and multiplied the number of resources required for stereograms in the production pipeline concurrently.

To streamline this process, we built a suite of client-server based tools for design and preview, rendering, and printing: a rendering server (*HoloServe*) which provides hardware-assisted computer graphic rendering to client applications; a scene modeling and preview client (*HoloBuild*); and a hologram printing client (*HoloPrint*), which can request a specific component view of the design from *HoloServe* and send appropriate exposure and frame-advance control sequences to the hologram printer for optical recording [30]. Versions of both *HoloBuild* and *HoloServe* currently use OpenGL, and *HoloServe* provides single- or double-frustum rendering [33] to generate conventional and predistorted perspective views of computer graphic models in a few seconds.

To provide force display in all of our holo-haptic experiments, we use a Phantom Haptic Interface, a mechanical linkage with a three-degrees-of-freedom passive gimbal that supports a thimble or stylus used by the hand. Six encoders on the device provide positional information resolved to approximately 0.1 mm, and three servo motors provide force display up to roughly 8 N in a workspace of approximately $290 \times 400 \times 560\ \mathrm{mm}^3$. The stylus or thimble is used to probe the simulated scene while device encoders are polled to compute the position of the end effector (stylus or thimble tip). This information is checked against the geometry of the scene; if contact is detected, appropriate torque commands are delivered to the device's three servo motors, and a restoring force is felt by the hand holding the stylus. In all of our holo-haptic applications, we use the Phantom in a fairly small workspace measuring about 100 mm along each axis.

For convincing visual–haptic display within this volume, coregistered and calibrated workspaces proved to be essential, particularly when *contact* with simulated elements of the 3-D scene is simultaneously seen and felt. Our haptic simulation, not surprisingly dubbed *HoloFeel*, rendered a force image of the scene geometry in space, which we overlap and coregister with the projected holographic image. *HoloFeel* rendered the scene geometry and haptic modeling parameters that correspond to a given holographic image and the

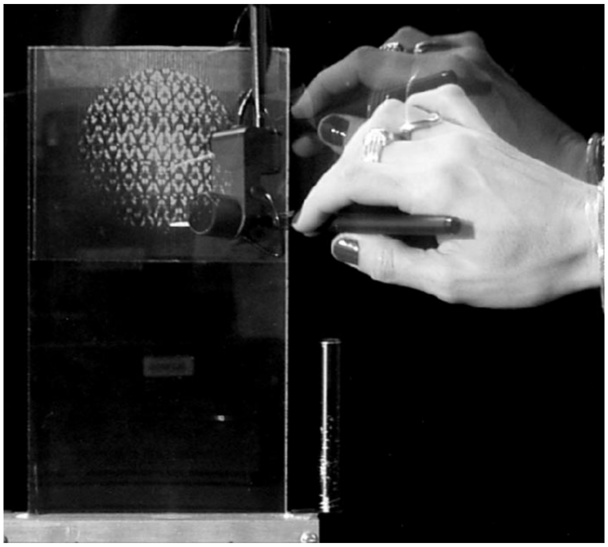

Fig. 7. Edge-illuminated hemisphere haptic hologram.

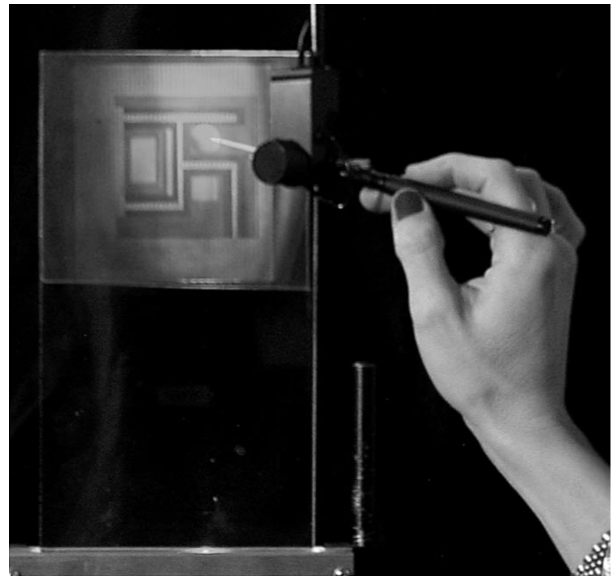

Fig. 8. Edge-illuminated block haptic hologram.

force simulation can be felt using the Phantom. *HoloFeel* currently runs on an SGI Octane, with a servo rate between 1 and 15 KHz. Its basic functionality includes the ability to render some implicit and parametric surfaces, object surface and bulk properties (static and sliding friction, compliance, damping, and texture), some ambient effects, and some physical dynamics.

B. Two Haptic Holograms

HoloBuild, *HoloServe*, and *HoloPrint* were used to produce two 2-optical-step edge-illuminated holographic stereograms used in conjunction with haptic simulations rendered by *HoloFeel*. The simpler of the two holograms displayed a hemisphere affixed to a vertically oriented plane. Both the full-parallax mastering and transferring steps used a recording wavelength of 528 nm, and reconstruction illumination was provided by an LED centered at 520 mm. The total depth of the final hologram (shown in Fig. 7) was approximately 40 mm—all in front of the image plane—and image plane width and height each measured 100 mm. The hologram permitted a broad angular range of head motion of approximately 50° horizontally and 30° vertically, and projected 15 000 rendered views to produce a bright 3-D image.

The multimodal scene presented was intended to have very few formal features; this tangible hologram provided a simple example with which to examine perceptual tolerances for spatial misregistration and mismatches in curvature of the visual and haptic models. The hemisphere, which was visually textured, could either be presented with a corresponding haptic texture or without, and friction was modeled between the stylus tip and all displayed surfaces. The bulk resistance of the entire haptic model was modeled as a stiff spring.

The second and slightly more complicated holo-haptic example used an arrangement of blocks forming a maze, which was oriented against a vertical back plane. The blocks varied in size and spacing, and the channels formed between them were narrow. The back plane was visually and haptically texture mapped with a fine, shallow vertical grating, and friction and bulk restoring force were present as in the hemisphere model. The full-parallax master hologram was comprised of 6700 exposures of pseudoscopically rendered frames [33] and the final hologram, produced in an additional optical transfer step, provided a 35° field of view (see Fig. 8). As in the hemisphere hologram, all recording steps used a wavelength of 528 nm, and reconstruction illumination was centered at 520 nm.

When the haptic model's geometry was well-aligned with the holographic image, the impression of inspecting a single, multimodal image was quite strong; yet our initial intermodal registration was not precise. Even slight spatial misregistration between the visual and haptic models noticeably diminished the impression that all multimodal cues about 3-D shape were arising from a single source. To achieve more reliable coregistration, the holograms were displayed in a mount which was fixed, along with the haptic device, to an optical breadboard. We developed software which allowed us to interactively transform the haptic workspace to match projected landmarks in the 3-D visual workspace. While this process could be tedious and would not correct for distortions within either modality, it gave us reliable coregistered visual and haptic workspaces within the small spatial volume we were addressing.

Perhaps the most serious challenge to these multimodal experiments (as was evident in systems using see-through HWDs and reach-in displays) is that physical volumes can readily penetrate holographic ones—all parts of the interacting hand and the haptic apparatus, but for the stylus tip, could freely pass through the holographic image. Thus, while the workspace does admit natural movement of the hand and handheld tool, it cannot report all the properties we would expect from one populated by physical things.

Despite this and other less troublesome cue conflicts [30], however, the full-parallax haptic holograms presented a com-

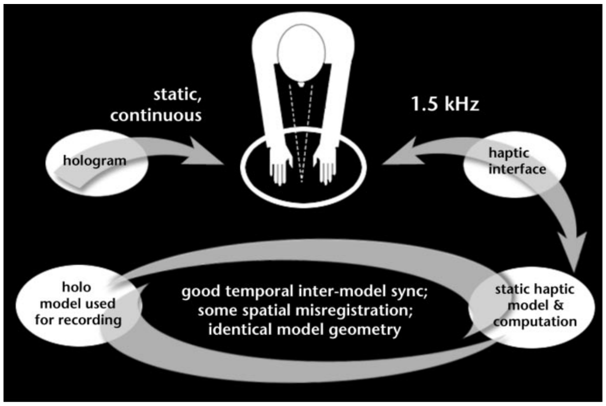

Fig. 9. *Touch* system in context.

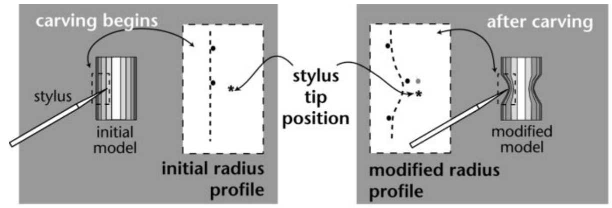

Fig. 10. Haptic model of stock.

pelling way to haptically inspect simulated spatial objects using a compact tabletop display. For instance, when a person tapped a block, felt along its edge, or located a texture trough with the stylus tip and traced it through the image while observing, the impression of seeing and feeling a unified representation was very strong.

A generalized diagram of the entire *Touch* system, as it relates to our idealized target, is shown in Fig. 9. As shown, the haptic and holographic images were eventually displayed in good spatial register—and good temporal synchrony, too, since the visual and haptic models were both static. The haptic update rate was adequate enough to maintain simulation stability, and the images were realistically rendered, visually rich in pictorial cues to depth and layout, and vividly 3-D. The principal disadvantage to these displays was their static nature; they had utility for inspecting 3-D shapes, but did not permit interaction with or modification of computer-generated content. Our next experiment was to add limited malleability to a haptic hologram, rendering it more like the programmable material we envisioned.

IV. Lathe: A Dynamic Haptic Hologram With Limited Malleability

A. Overview

To produce "rewritable" holograms, we used the MIT second-generation holographic video display (*holovideo*) [34], and registered its display volume with that of the Phantom. The 3-D image produced by holovideo supports the most important depth cues: stereopsis, motion parallax, occlusion, and many pictorial and physiological cues to depth. However, choosing an electroholographic display does currently require trading off image quality (as compared with the holograms produced for *Touch*, or even conventional displays) for limited dynamism. Currently, the system is capable of displaying monochromatic, HPO images in a volume of $150 \times 57.5 \times 150$ mm^3, with a viewing angle of 30°. For the present purpose, we may consider holovideo to be a black box which accepts two inputs: a computer-generated hologram and light. The output of the black box is a 3-D holographic image which can be updated as quickly as a new hologram can be computed and relayed to and through the system.

The *Lathe* demonstration presented electroholographic and force images of a vertically oriented, spinning cylindrical stock, which could be carved along its length into an arbitrary surface of revolution. The holographic and force images of the stock were overlapped and coregistered to provide a freestanding 3-D image that could be shaped by the phantom stylus, and which responded to a user's interaction both visually and haptically. *Lathe* achieved a reasonable update rate by taking two shortcuts: first, by employing a set of precomputed holograms from which a hologram of the rotationally symmetric shape being carved was assembled; and second, by updating the hologram only in regions where interaction had changed it, rather than reassembling the whole thing.

B. Haptic and Hologram Modeling

The haptic stock, initially and in subsequent stages of carving, was modeled as a parametric surface of revolution with maximum and minimum radii of 25 mm and 15 mm, respectively, and two algorithmically defined caps (see Fig. 10). It was given a mass of 1 gm, an algorithmically defined vertical grating as surface texture, static and dynamic frictional properties, stiff spring bulk resistance, and rotated about its axis at 1 r/s (see [35] for more detail). The stock's model straddled a static haptic plane, which spatially corresponded with the physical output plane of the holovideo optical system, and was assigned the same bulk and frictional properties as the stock. The haptics simulation was implemented on an SGI Octane with an average servo rate of 5 KHz.

To create the "building blocks" for visual display, a set of five precomputed holograms (each of a cylinder with a different radius) from which the carved stock could be assembled was computed using interference modeling [36]. To generate each hologram, the surface of a given cylinder was first populated by a collection of isotropic spherical-emitting sources. The interference of a plane wave and the analytic fields radiated by that collection of point-sources was then simulated on a 250-MHz SGI Onyx, generating a hologram that would reconstruct that given cylinder's 3-D image. Each resulting HPO hologram displays video-like resolution vertically but projects horizontal parallax; thus, each hologram "line" (or hololine) encodes and displays only the "slice" of a cylinder at its height in the image. So, in effect, a new hologram of a rotationally symmetric shape can be created by using lines from *different* holograms in the original precomputed set—quite like slicing up several photographs and borrowing pieces from each to assemble a new image. The

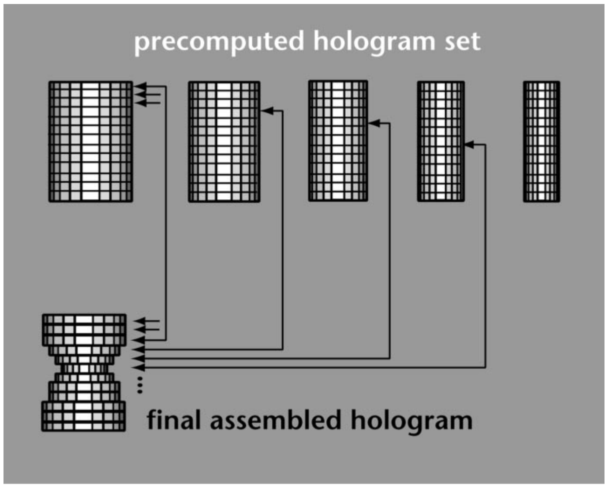

Fig. 11. Assembling *Lathe*'s hologram.

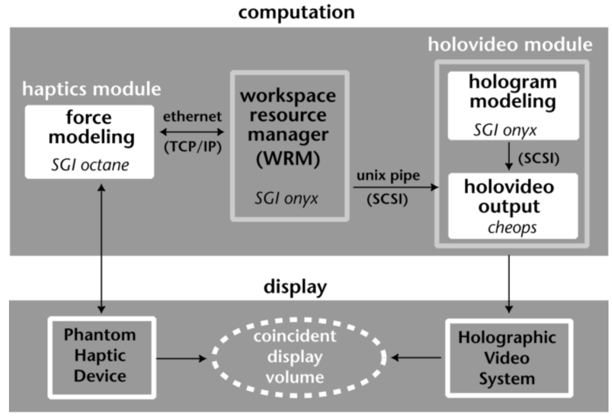

Fig. 12. *Lathe* system overview.

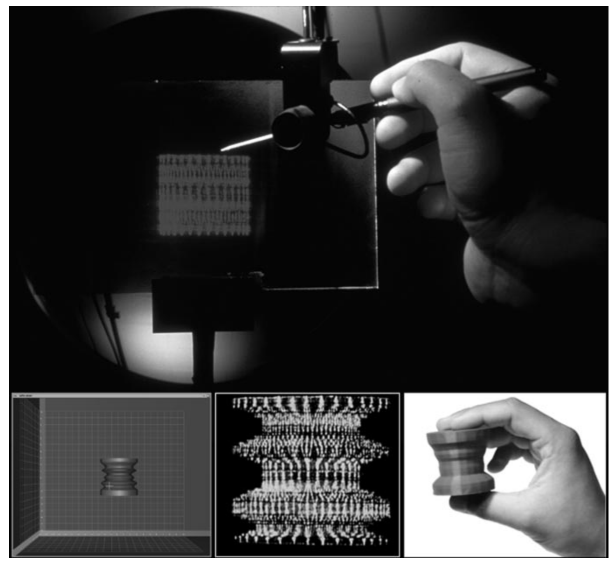

Fig. 13. Interaction with *Lathe*'s haptic hologram.

five precomputed holograms were used in this manner to assemble the display hologram according to a description of haptic model changes. Hologram assembly was performed on our Cheops Imaging System [37], developed at the MIT Media Laboratory for video processing, and used by our holovideo system for the computation, storing, and display of holograms. The assembled holographic image showed a wireframe stock throughout various stages of carving, with its smooth curves approximated by the quantized radius values represented in the precomputed hologram set (see Fig. 11).

C. The Lathe System

Three distinct systems comprised the computation for this multimodal experiment; the *haptics module* (a modified version of *HoloFeel*), which performed force modeling, and the *holovideo module* which initially precomputed holograms and subsequently drove rapid local holographic display updates based on changes to the haptic model. An intermediate process, the *Workspace Resource Manager (WRM)*, performed two functions: first, it translated haptic model changes into appropriate hololine changes and communicated the instructions to the *holovideo module*; second, for debugging, it provided an intermediate computer graphic rendering of the stock and stylus position as carving went along. A diagram of the *Lathe* system is shown below in Fig. 12.

D. Interacting With the Haptic Hologram

When a person carved the holographic surface of revolution with the Phantom, the holographic image changed due to force apparently applied at the tip of the stylus. The resulting shape could be explored by moving the stylus tip around the surface without exerting sufficient force for carving. Of course, physical objects in the workspace could also be seen and apprehended, so that physical and simulated forces were displayed within the same augmented reality workspace. When the viewer maintained the correct viewing distance for holovideo [34], the perception of a single multimodal stimulus is quite strong. Images of a user interacting with the image are shown in Fig. 13, along with the *WRM*'s intermediate computer graphic rendering, and a detail of the carved holographic stock. Additionally, once the model was carved into "finished" form, it could be dispatched to a 3-D printer which constructed a same-scale physical prototype of the digital design, as is shown at the figure's bottom right.

Unlike many head-tracked parallax displays, an HPO holographic display provides the full range of horizontal parallax in the viewzone regardless of viewer position; thus, no lag was encountered as a person moved within the viewzone. Additionally, no jitter from tracker noise was present, and no special eyewear was necessary to perceive the stereo information. However, the system was vulnerable to sources of spatial misregistration. In order to approach a visual update rate of about 10 Hz, we could only update a maximum of 32 (of 144 total) hololines during simulation timestep; as long as haptic model changes within an update interval did not extend beyond the region represented by these 32 hololines, no visible discrepancies would result between the visual and haptic models. Additionally, since the display does not offer vertical parallax, a viewer had

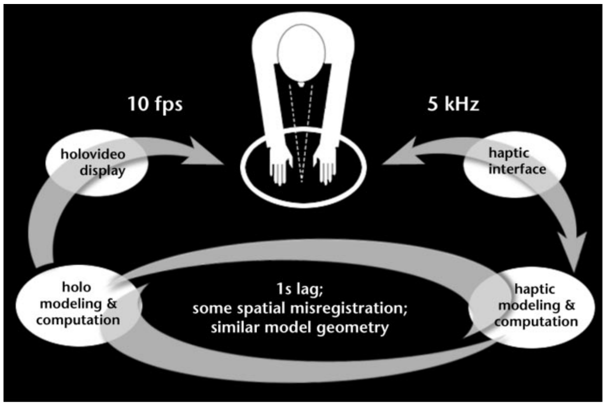

Fig. 14. *Lathe* system in context.

to be positioned at a correct viewing distance (600 mm) and height in the viewzone in order to see an image free of distortion. Shifting slightly from this location does not change the visual image noticeably during passive viewing, but it could cause an obvious intermodal disparity.

A compelling multimodal representation also requires imperceptible time lag between when model changes are felt and when they are seen. Our system lag, principally due to the speed at which we were able to transfer a new set of hololines to the display's framebuffer, ranged between 0.5 and 1 s, and resulted in a person seeing the stylus tip penetrate into the holographic surface before the surface was visually subtracted away. This effect was somewhat mitigated by rendering a wireframe visual image; were the model rendered as a smooth-shaded solid, seeing the stylus' visible surface penetration before the effects of carving would be more egregious. However, intermodal disparity was evident from *Lathe*'s lag and low frame rate, and also from using a holographic model that only approximated the continuous, analytic haptic model.

Finally, it should be stated that the method used to assemble holograms obviously applies only to models whose geometry can be described as a stack of "prefabbed" parts. (And it should also be noted that this method of hologram assembly is valid only for HPO holograms; for full-parallax holograms, locally updating the fringe pattern would be more complicated.) However, a more broadly applicable method for locally updating a hologram with a *more generalized* collection of precomputed elements grew out of this work, and supported our third holo-haptic experiment.

E. In Context

The dynamic and static systems described thus far offered interaction with holographic images on the tabletop, and this marked long-held goal in the field of holography. Putting this experiment into the broader context, Fig. 14 indicates the path now opened between hologram modeling and computation and provides a channel for updating the visual display. But the figure also underscores the challenges of reducing lag and improving the visual update rate; these are challenges which will likely be met only by making changes to our existing display and its computational subsystems. Not indicated in the figure are the additional sacrifices of vertical parallax, image complexity, and pictorial realism, in service of making the hologram move.

Even while we may not richly engage our skills for sculpting or materials-working using the holo-haptic *Lathe*, the system serves as a basic proof of concept, and hints at how a truly useful holo-haptic design tool might work. From our point of view, the freestanding multimodal simulation displayed by *Lathe* resembles a primitive computational material, available for both eyes and tools on the tabletop, whose visual and haptic texture were nominally programmable. We thought a more powerful demonstration would provide a way to make flexible modeling changes to the holo-haptic material being presented. In our next experiment, we investigated the use of a different set of precomputed elements to effect more general changes in the holographic image, within the computation and communication bandwidth limits of our holovideo system.

V. Poke: A Haptic Hologram With More Flexible Update

A. Overview and Modeling

In the *Poke* system, we presented coincident holographic and force images of a sheet of pliable material, which could be felt, poked, and deformed by a user holding the Phantom stylus. The holographic and force images were, as in our previous experiments, spatially overlapped and coregistered to provide a freestanding image that could be both seen and felt in the same spatial location.

The pliable sheet was represented as a Catmull–Rom spline surface, which smoothly interpolated a grid of control points, which also defined the nodes of a network of springs. The control points initially described a vertically oriented flat surface located in front of holovideo's image plane, which fit well within a 100×100-mm area, as did *Lathe*'s model (see [36] for more detail). Continuing beyond the parametric surface's extent was a haptic plane which prevented the stylus from exploring behind the deformable surface and, from a more practical standpoint, protected holovideo's optical components from contact with the haptic apparatus.

All around the surface's perimeter, the outermost three control points had their positions locked so that all edges of the deformable surface remained attached to the surrounding plane when the interior control points were haptically manipulated. As the Phantom stylus tip was pushed into the surface, interior control points were displaced, the surface deformed, and a springy resistance was displayed to the interacting user (see Fig. 15). Once displaced, the springs were "locked" to hold the surface's new shape.

We refer to the model from which the hologram was computed as the *holo-object*, and it was composed of primitives we call *holo-points.* These holo-points were distributed on the surface of the pliable sheet, and represented the image points to be holographically displayed in the workspace. In the initial holo-object, the holo-points corresponded exactly to the haptic module's initial set of control points and, thus,

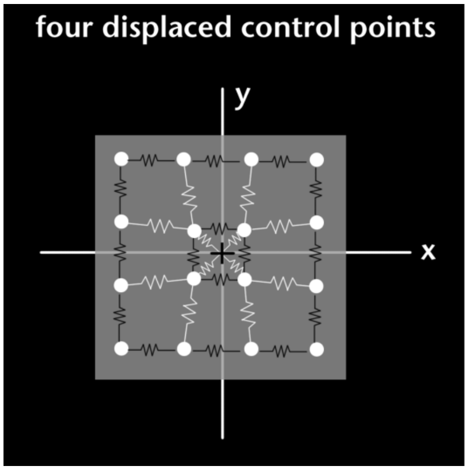

Fig. 15. *Poke*'s haptic deformable surface.

described the same vertically oriented flat surface. Serving as a "bridge" between haptic and holographic representations, each holo-point was matched with its twin control point in the haptic model, and was also matched with one of a set of *precomputed elemental fringes*, which were used to assemble the display hologram.

These precomputed elemental fringes are a more general set of hologram elements than the ones *Lathe* used, from which a hologram can also be quickly generated or updated. They are used by the incremental computing method [38], developed for *Poke* to make small but flexible changes to its reconstructed image. In *Poke*'s implementation of the incremental computing approach, each of these precomputed fringes was a one-dimensional holographic pattern capable of imaging a point into the holovideo display volume at some particular z depth, in front of or behind holovideo's image plane. Each elemental fringe's x–y position within the hologram specifies the x–y position of the imaged point, and the order of its samples determines whether it reconstructs a point at $+z$ or $-z$. Using these precomputed elements, a hologram can be initially assembled by simply summing x–y translated instances of elemental fringes, one for every point that should appear in the image, as was shown in earlier work by Lucente [39].

Incremental computing further maintains a *state* hologram, and a link between each control-point/holo-point pair and the elemental fringe being used to represent its image. So, for instance, if an image point needs to change as a result of haptic interaction, its associated elemental fringe can simply be subtracted from the state hologram and a new fringe may be added to represent the updated image point. Thus, it is necessary to apply only simple arithmetic operations to initially compute and subsequently update the state hologram. An example of the relationship among holo-points (here, only arrayed in the x–y plane), a set of precomputed elemental fringes, and the hologram assembled from them is shown in Fig. 16. The simulation indicated in the figure used a wavelength of 2 mm, for the sake of illustration only.

Poke used a precomputed table of 100 fringes, representing uniformly spaced holo-points at depths between

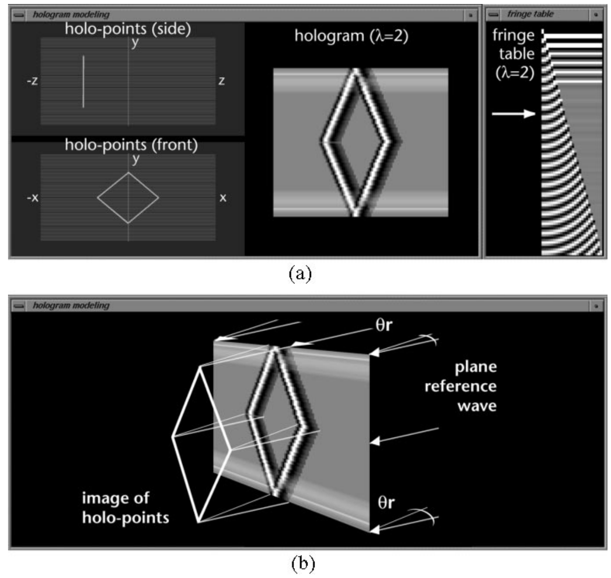

Fig. 16. Method of incremental computing and update of holograms.

0 and 50 mm. Then, as the depths of the haptic model's control points changed due to user interaction, the depths of their associated holo-points were updated, and incremental changes were made to the state hologram by subtracting and adding elemental fringes (more detail is given in [36]). Ideally, then, from the user's point of view, *Poke*'s multimodal springy surface would be felt to slowly deform as it was pressed by the stylus, with the holographic image responsively tracking these changes.

B. Poke System

Poke's system architecture is slightly different from that of *Lathe*; there were two distinct subsystems providing the haptic and holographic simulations. The *haptics module* performed force modeling and controlled the Phantom; the *holovideo module* used the precomputed hologram elements mentioned above to interactively compute rapid local hologram updates, and also to provide a simple computer graphic rendering of the holo-points and stylus position as the underlying model was deformed; and a display service called *holoPut* updated the hologram in Cheop's framebuffer as required. The *holovideo module* received user-applied haptic model changes through a client connection to the *haptics module*, updated the hologram, and sent it via a high-speed HIPPI link to *holoPut*, running on Cheops. The system diagram is shown in Fig. 17.

C. Interacting

In the workspace, *Poke* presented a person with a holographic rectangular sheet of points which floated in front of the holovideo's output plane. Upon inspection with the Phantom's stylus, a person could feel friction between the stylus tip and the continuous implied surface, and springy resistance as she pressed into it. When poked anywhere with more force, the sheet was felt to deform responsively, and

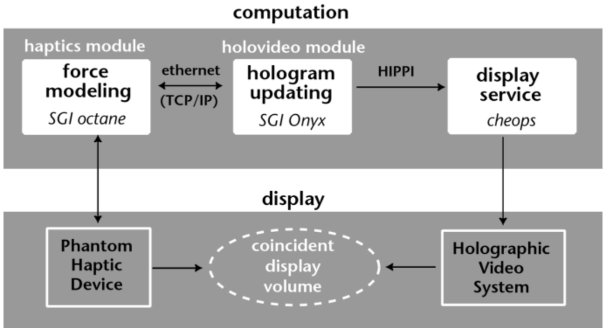

Fig. 17. *Poke* system diagram.

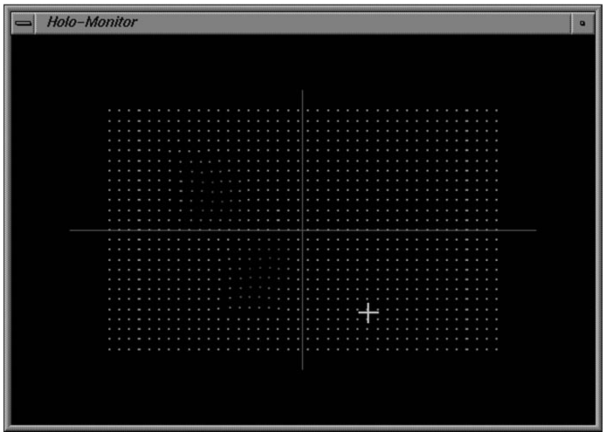

Fig. 18. Simple computer-graphic rendering of deformable surface and stylus position.

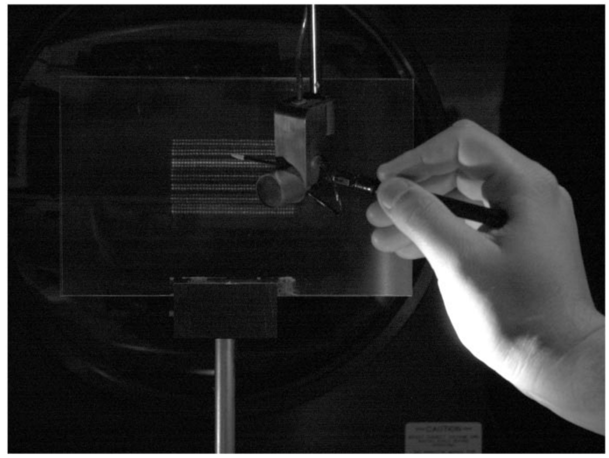

Fig. 19. Interacting with *Poke*'s haptic hologram.

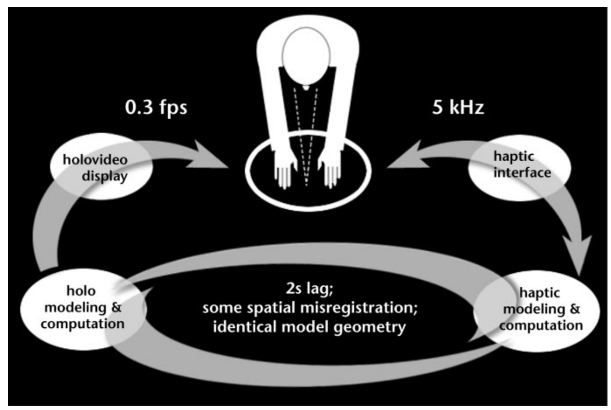

Fig. 20. *Poke* system in context.

after a noticeable lag the image was also seen to update properly. In light of the simple visual representation used by *Poke*, the computer graphic and holographic renderings were absent of rich pictorial cues to depth and layout. *Poke*'s holographic pliable surface was implied by an array of bright reconstructed points; the shape of this surface was clearly visible with binocular vision and motion parallax, but was not as strongly evident to a monocular, unmoving viewer. As it turns out, the simple visual representation used and the shallow depths represented were more forgiving of the intermittent spatial misregistration that occurs due to lag. The system's computer graphic representation of the deforming surface is shown in Fig. 18, and an image of a person interacting with the Poke system is shown in Fig. 19.

The performance of the entire system had much to do with the various computational platforms used in its implementation, and of course the demands put upon them. The *haptics module* ran on a 195-MHz SGI Octane, computed the haptics simulation, and served updated control point information to the *holovideo module*. The haptics servo loop ran at an average rate of 5 KHz, and we could dial the frequency with which updated control points were delivered to the holovideo module for recomputation. These data were sent roughly 30 times/s, but were restricted to include no more than 100 points per transfer. As in *Lathe*, if more than this quota of points changed, their update would not be propagated to the hologram until perhaps the next time they were modified. As long as 100 or fewer control points were changed within an update interval, the hologram matched the haptic model very well.

The *holovideo module* ran on a 250-MHz dual processor SGI Onyx, established a client connection to the *haptics module* over Ethernet using TCP/IP, and then used both processors to perform hologram updates based on the haptic model changes it received. Given that the *holovideo module* was never called upon to update the contribution of more than 100 holo-points at a time, and that many of these points were guaranteed to be on the same hololine, hologram recomputation could be accomplished relatively quickly (usually in less than 1 s). The *holovideo module* then delivered updated holograms to the holovideo display server *holoPut*, running on the Cheops Imaging System, via a 100-MB/s HIPPI link. Since we transferred the entire 36-MB hologram to Cheops for every update in this implementation (instead of sending just the updated portion), each HIPPI transfer required a fixed cost of 0.6 s. Consequently, the system exhibited a substantial delay between a user's poking input and the visual update. While appropriate changes to the haptic model were immediately felt, the total lag between user input and visual update was about 2 s on average, as indicated in Fig. 20.

D. In Context

Added to the suite of holo-haptic demonstrations, *Poke* let an interacting person flexibly deform a freestanding multimodal surface. This demonstration that holovideo could provide visual display in a more meaningful modeling task marked another important step for electroholography. It relied heavily upon the notions of constructing holograms from primitive elements, and modifying them locally and incrementally, in order to approach interactive visual update rates. Despite what *Poke* achieves, however, Fig. 19 indicates that as compared to *Lathe*, it has traded system response, visual update rate, and visual rendering complexity as well, for the important ability to effect more arbitrary changes in the underlying model.

These three demonstrations, *Touch*, *Lathe*, and *Poke*, together represent an interesting snapshot of current technical challenges and the future possibilities offered by combining haptics and holography in interactive multimodal applications. Being able to combine the full-parallax output and pictorial realism offered by *Touch*, the responsiveness of *Lathe*, and the more meaningful interaction of *Poke* would provide an extremely powerful demonstration with much room still for improvement. In the short term, reasonable next steps in our work are to improve data transfer schemes in our holovideo system, and to reimplement the *holovideo module* more efficiently on a higher performance computer, or perhaps with hardware assistance.

VI. Discussion and Longer View

A. Computational Plastic

We have long watched visitors to our laboratory apply the "touch test" to aerial images generated by many flavors of spatial displays, and we have observed their apparent delight when finding nothing with their fingertips. We have also heard automotive designers say that while observing light play across a body design was important, feeling the shape with gloved, moving hands and moving arms was also crucial to their understanding. Thus, we began to investigate adding haptic properties to our images. Finally, after experimenting with the combination of holo-haptic displays and computational modeling, the surfaces we assembled began to take on a decidedly *material* quality: visible, touchable, and also *programmable*, and the notion of computational plastic seemed quite obvious.

We imagine a good prototype of computational plastic to have several basic properties: it should allow us to interactively shape and reshape a surface, should admit programmable appearance and behavior, should be available to the senses just like a physical material, and when fashioned (or when being fashioned) into an object, should offer some unique physical affordances for use. Taken as a whole, the demonstrations reported in this paper allow us to inspect and modify a simulation that may be regarded as a rudimentary, programmable, material surface. Certainly, the underlying technology itself presents many enormous challenges to address before we can truly begin to test the strength of this metaphor. We might advance from here along many interesting fronts: improving the palette of visual and haptic material qualities and behaviors we can ascribe to surfaces, improving image characteristics of our visual display, shrinking the obtrusive physical mechanisms of all displays, and developing new and efficient algorithms for hologram computation. For our holovideo system in particular, we should adopt faster and specialized computational subsystems, and allow both processor and framebuffer to share the same high-speed bus—and many of these efforts are already underway.

These holo-haptic demonstrations actually mark a turning point for electroholography. Within the last decade, the literature has reported that advances in display technology and computational methods have ushered interactive holographic technology to within steps of its consummate form. This may be more or less true, depending upon how one defines "interactive" and what one expects from a realistic display. In contrast, we would argue that holography still has a great distance to go. However, in this work, rather than just *displaying* a holographic image or *updating* that image as the engineering achievement, we have now pressed holography into actual service in primitive interactive applications, and have allowed it to assume the role of "supporting technology"; to catch a glimpse of its practical use is both meaningful and noteworthy.

B. Holographic Video

Computational holography is notoriously resource hungry. For example, *Poke*'s visual frame rate was too low and the lag between haptic and visual updates was unacceptable owing to the lack of greater computation, communication, and modulation bandwidth. These issues fairly well encapsulate the major *nonalgorithmic* challenges to building the next generation of holographic video displays.

Consider, for instance, that to build a 0.5×0.5-m full parallax display with an angle of view of 60° (a size and view angle analogous to high-end LCD computer monitors at the time of this writing) using a wavelength of 5×10^{-6} mm, a holographic fringe pattern would need to represent a maximum spatial frequency $f_{\max}$ of approximately $2\sin 30°/\lambda = 2 \times 10^6$ cy/mm. The required sampling frequency $f_{\rm s}$ would have to be at least twice that, at 4×10^6 cy/mm in order to avoid aliasing artifacts. Thus, the horizontal and vertical resolution of such a display would each be 2×10^9 samples, requiring every frame of holographic video to contain 4×10^{18} samples in total. Further, a full-color display would require that many samples *for each color channel*. And we would expect that, depending on which techniques are used to compute the fringe pattern and lightness curve correction, 1 B/sample may not be enough to represent, say, 256 distinct levels of grayscale in the final image.

All these considerations roughly put our requirement at a currently astonishing 10^{20} bytes per frame of holographic video! The spatial light modulator employed by this display system must be able to accommodate this enormous amount of data and the high sampling frequencies resident in the fringe patterns. Further, we need to update/refresh the display

30 times/s and, consequently, to move 3×10^{21} B/s through the computational, electronic, optoelectronic, or mechatronic subsystems that constitute this hypothetical display system. These numbers are obviously prohibitive in terms of contemporary consumer-grade technology.

In a practical sense, these discouraging computation, communication, and modulation bandwidth requirements might argue instead for the development of large format *stereogram* displays in the near term, with static, preprinted, or precomputed diffractive elements used to optically relay 2-D views to the viewer. In this case, for the same 0.5×0.5-m display, a very high-resolution stereographic frame composed of 1×1-k 2-D views, each containing about 10×10-k pixels (such that the image plane is sampled at roughly 500 dpi), could require on the order of 10^{14} B/frame—without giving up vertical parallax.

This does raise the intriguing question of whether it is worthwhile to pursue the development of true holographic video systems at all. What possible value could derive from the sustained investment of resources in future development after the concept has been proven and the target remains elusive? The answer to this question is at many levels. At the most fundamental level, a true holographic display is a generalized optical wavefront generator—this implies that it could be used to simulate or emulate any other kind of display. This makes holovideo an important tool in the design and analysis of future displays. Another *raison d'être* may be found by examining ongoing developments in supercomputing. IBM's Deep Blue caused a stir when it defeated the reigning world champion at chess. Blue Gene, currently being designed to investigate protein folding, will eventually be capable of 360 teraflops. It is inevitable that these and other supercomputing platforms will be used to generate data that is best visualized in 3-D. This puts holovideo in the role of a high-quality output device for high performance computing. Finally, study of holographic video lies at the confluence of several disciplines—physics, optical engineering, computation, and human perception. A continued push toward more ambitious holographic displays will likely promote compelling research in all these areas, while offering increasingly realistic and sensual output for designers of objects and information.

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