Tangible display systems: direct interfaces for computer-based studies of surface appearance

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ABSTRACT

When evaluating the surface appearance of real objects, observers engage in complex behaviors involving active manipulation and dynamic viewpoint changes that allow them to observe the changing patterns of surface reflections. We are developing a class of tangible display systems to provide these natural modes of interaction in computer-based studies of material perception. A first-generation tangible display was created from an off-the-shelf laptop computer containing an accelerometer and webcam as standard components. Using these devices, custom software estimated the orientation of the display and the user's viewing position. This information was integrated with a 3D rendering module so that rotating the display or moving in front of the screen would produce realistic changes in the appearance of virtual objects. In this paper, we consider the design of a second-generation system to improve the fidelity of the virtual surfaces rendered to the screen. With a high-quality display screen and enhanced tracking and rendering capabilities, a second-generation system will be better able to support a range of appearance perception applications.

Keywords: tangible display, interactive rendering, material appearance, surface texture, augmented reality

1. INTRODUCTION

Over the past decade, the study of surface appearance has been greatly facilitated by advances in computer graphics and electronic display technologies that have enabled experiments to be conducted using high fidelity rendered images of surfaces with complex illumination, geometry, and material properties.[1,2,3] However, a significant limitation of current methods is that the stimuli are typically presented as static images or in pre-calculated motion sequences that are passively viewed by experiment observers. When presented with a real object, to better understand its surface properties, observers often engage in complex behaviors involving active manipulation and dynamic viewpoint changes. By engaging in these behaviors, the user is able to observe the changing pattern of surface reflections as the object is moved relative to lighting and the observer's own viewpoint. We are developing a class of display systems, termed tangible displays, that support these types of natural interactions in computer-based studies. These systems combine tracking information on the display's orientation and the observer's viewpoint with specialized rendering methods to create a user experience akin to holding a real surface in one's hands and being able to actively tilt it and observe it from different directions to see the changing patterns and properties of surface reflections (shown in Figure 1).

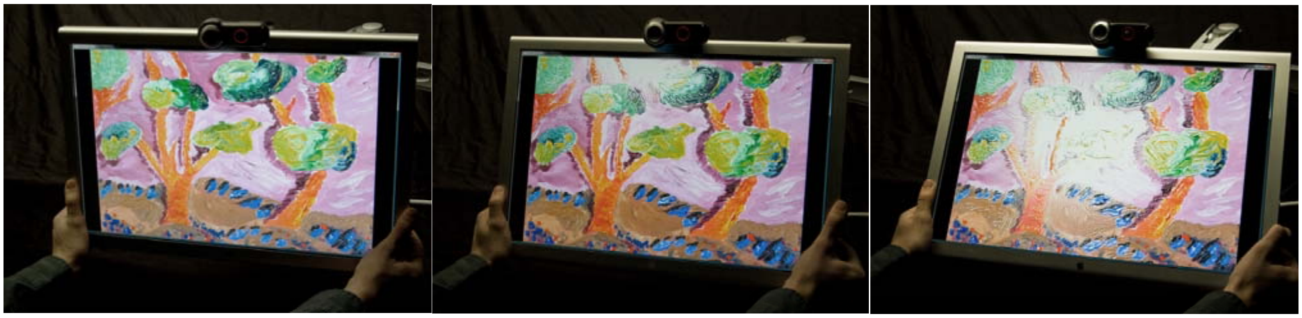

Figure 1: Sequence showing a painting model on a tangible display. Custom software allows the orientation of the screen and the position of the observer to be tracked in real-time. Tilting the display (as shown) or moving in front of the screen produces realistic changes in surface reflections and appearance, simulating the experience of interacting with a real object.

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A tangible display system requires three primary components: tracking devices for the display and user, a display screen, and an interactive rendering module that generates a realistically shaded view of the virtual surface based on the tracking information. Our first tangible display system, the tangiBook[4], was developed using an off-the-shelf laptop computer containing a triaxial accelerometer and a webcam as standard components. The triaxial accelerometer was used to provide data on the orientation of the display, and the webcam was used with computer-vision head-tracking to estimate the location of the observer's viewpoint. Custom software integrated the tracking information with a custom OpenGL shader, executed on the laptop's GPU, to generate a realistically shaded view of a surface to the laptop's LCD display.

In this paper, we describe the design considerations for a second-generation tangible display system and conduct a preliminary evaluation of candidate display screens. The objective of the initial tangiBook system was to build a tangible interface using only the components from an off-the-shelf laptop computer, to provide a means for users to experience a tangible display without the need to acquire specialized equipment. In the second-generation system, we consider the enhancements that are possible by synthesizing the system from a set of selected components: dedicated tracking devices, a powerful desktop computer, and high color-quality display screen. With the flexibility of a component-based system, and enhanced performance from more powerful hardware, a second-generation system will allow for more realistic and color accurate virtual surface reproductions to better support a range of appearance perception applications.

2. RELATED WORK

Computer graphics simulations are often displayed on standard computer screens and manipulated using indirect input devices, like a mouse or joystick. However, there has been an interest in developing more natural interfaces to virtual environments since the pioneering work on see-through head-mounted displays[5] (HMDs) and 3D input wands[6] in the 1960's and 1970's. Since that time, significant advances have been made in both display systems[7,8,9] and 3D input devices[10,11,12] for interacting with virtual environments. With these systems, a real environment is augmented with virtual content shown on a see-through HMD, or the user is immersed within a virtual environment shown on screen.

Other approaches for presenting computer graphics simulations have utilized projection-based display systems to create immersive environments or to augment the appearance of objects in real scenes. The CAVE system[13] projected virtual content onto multiple screens to immerse the user within a virtual environment. The shaderLamps[14] and iLamps[15] systems used projection-based displays to enhance the appearance of objects within a real scene. In these systems, images were geometrically warped and projected onto three-dimensional objects to create real world objects whose appearance could be varied under computer control. Tracking sensors on the objects allowed them to be moved and still retain their projected appearance content.[16] Bimber and colleagues have also been early innovators in this area, focusing on applications in digital paleontology[17] and augmented artwork,[18] as well as the technology for augmented reality.[19]

A third approach to creating natural interfaces for computer graphics simulations is the use of spatially-aware display systems. The Chameleon system[20] coupled a six DOF tracking device with a handheld computer to create a display that could update its content based on its location in the environment. The Boom Chameleon system[21] used a larger LCD display attached to a motion-tracked boom arm and allowed the user to change the view shown of a virtual 3D model by manipulating the physical position of the LCD screen. The Virtual Mirror System[22] took the spatially-aware display a step further by using it to simulate the behavior of a physical object in the user's environment. Using tracking devices and a camera pointed toward the user, the system rendered images to the display to give the impression that it was a real physical mirror. This device was also used as part of an art exhibition to display virtual daugerrotypes.[23] A significant feature of all these systems is the ability to grasp the display and directly manipulate the point of view on virtual scenes and objects. This quality, where a physical object serves as a direct interface between the physical and virtual worlds, is a central feature in the concept of tangible interfaces.[24,25] The advantage of these interfaces is that the affordances of the object (lifting, tilting, or rotating the display) provide rich and natural modes of interaction with the virtual world.

3. TANGIBLE DISPLAY CAPABILITIES

The objective for our tangible display systems is to create realistic reproductions of complex virtual surfaces and provide an interactive visual experience similar to manipulating and observing a real physical object. Toward this goal, our system supports direct manipulation of the virtual object's orientation by rotating the screen and dynamic viewpoint changes by tracking the observer's head position. With these capabilities, the tangible display responds to the two types of interaction that result in changing surface reflections when viewing a real object. Our tangible display systems also provide an important capability not possible with a real object, because the system supports interactive rendering, the material properties can be changed in real-time.

3.1 Dynamic manipulation of orientation

As shown in Figure 1, tangible display systems support dynamic natural interaction with the virtual surfaces displayed on screen. As the display is rotated or tilted by the user, the changes in its physical orientation are detected and used to dynamically update the surface reflections rendered to the virtual object. The updated rendering shows the reflections from the user's viewpoint that would be visible for the virtual object's new orientation relative to the specified virtual lighting environment. This is illustrated in figure 1, where the display is tilted from its orientation in the left image to its orientation in the far right image. As the display is tilted, the direction of the surface normal of the display (and the virtual painting) changes. Highlights are rendered to the virtual surface when the new direction of the painting's surface normal causes the viewing position to near the specular angle with respect to a virtual light's position.

3.2 Dynamic viewing

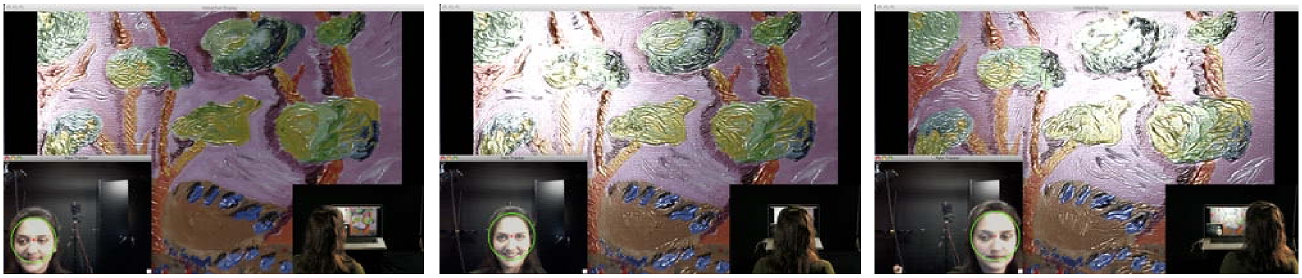


Figure 2: Image sequence illustrating the dynamic viewpoint control capabilities of tangible display systems. The insets show the observer's position (lower right) and the output of the head-tracking software (lower left) as the observer moves in front of the screen. The large images show the corresponding movement of the rendered surface reflections.

Tangible display systems also provide the capability to dynamically track observers' viewing positions as they move in front of the display and view it from different directions. To determine the correct reflections for the virtual surface, it is necessary to know the viewing position of the observer in addition to the surface orientation and lighting positions. As shown in Figure 2, as the viewer's head position moves from left of the display, to centered, to the right of the display, the reflections rendered to the painting's surface move with her, as they would when moving in front of a real physical object. The tangible display updates the highlights to reflect the new relationship between the viewpoint, surface normal, and the virtual illumination environment.

3.3 Dynamic control of material properties

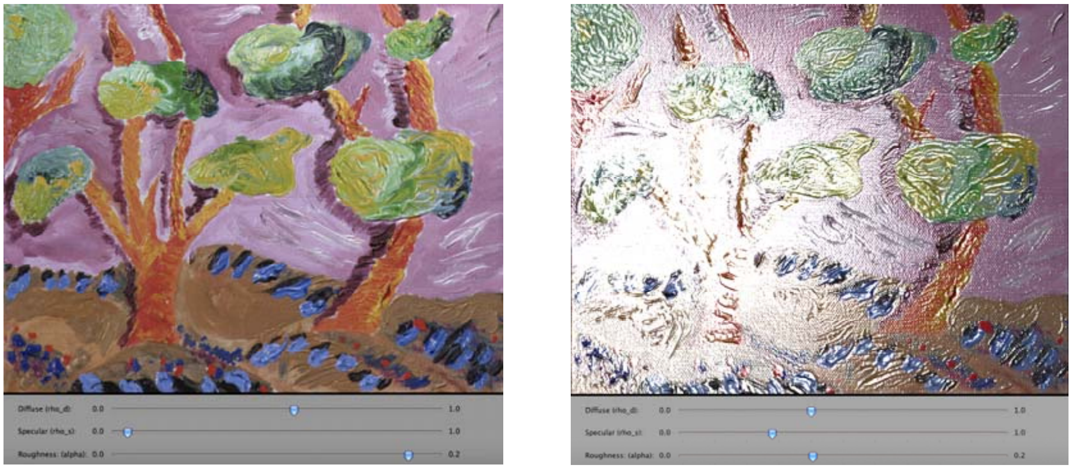


Figure 3: The two renderings of the painting illustrate the ability to dynamically change the material properties of a displayed surface. Using the sliders, the painting's material parameters have been altered from the matte surface on the left to produce the glossy surface seen on the right.

Unlike a real object, the use of a tangible display system provides the capability to change the properties of the material dynamically. The interactive rendering capabilities of tangible display systems allow for dynamic control of the diffuse reflectance, specular reflectance, and specular lobe roughness of the object's surface. These parameters can be adjusted while the user is interacting with the virtual surface and will immediately produce changes to the surface's appearance. As shown in Figure 3, a surface can be changed from matte to glossy by adjusting material parameters with a set of slider bars. The matte surface on the left in Figure 3 has a low value for specular reflectance and a large roughness (alpha) value. Increasing the specular reflectance and decreasing the roughness produces the glossy surface on the right.

4. TANGIBLE DISPLAY SYSTEM DESIGN

Figure 4: Tangible displays are being developed for two different architectures. Left, the first-generation tangiBook was developed from an off-the-shelf laptop computer. Right, a second-generation prototype is being developed using a desktop computer, external tracking devices, and an Apple Cinema HD display.

To recreate the visual experience of interacting with a physical surface, a tangible display system requires three main capabilities: accurate tracking of the display's orientation and user's position, high-fidelity real-time rendering that incorporates the tracking information, and accurate color and luminance output from the display screen. Providing these capabilities requires multiple hardware components and a specialized software system to integrate and support the tracking, rendering, and display modules of the tangible display.

4.1 Tangible display systems: laptop and custom-component architectures

We are developing tangible display systems for two different hardware architectures (shown in Figure 4). The initial architecture, the tangiBook, was based on an off-the-shelf laptop computer (Apple MacBook Pro 15") that incorporated all the components necessary to create a tangible display system: an LCD display, an accelerometer, and a webcam. The objective of the tangiBook system was to build a tangible interface using just the components contained within an off-the-shelf laptop computer. For our second-generation tangible display, we are in the process of designing a system from selected components: tracking devices, a powerful desktop computer, and high color-quality display screen. The development of a component-based system provides the flexibility to evaluate a range of hardware and select components that specifically meet the needs of a tangible display.

The second-generation system is being developed on a high-performance desktop computer, a Falcon Northwest Mach V system with an Intel Core i7 950 3.06 GHz processor and dual NVIDIA GeForce GTX 295 video cards in an SLI configuration. Together the GTX 295 cards provide 960 parallel pixel-shader pipelines and 4 GPU chips. The GeForce 9600M GT card used in the tangiBook, while relatively powerful for a laptop, has 32 parallel pipelines and a single GPU. The desktop-based system uses an Apple Cinema HD 20" display, which features greater colorimetric stability across different viewing angles as compared to the MacBook Pro screen. To help support the screen, it has been attached to a flexible Ergotron arm that allows the display to be tilted and rotated in three dimensions. In the current versions of both systems, similar types of hardware are used to track the user's position and orientation of the display screen. As development of the second-generation system continues, the customizable nature of the desktop-based architecture will allow for more advanced tracking hardware to be used in place of the current tracking devices.

4.2 Tracking and dynamic interaction module

The tracking and dynamic interaction module of the system is responsible for detecting changes in the orientation of the display and user's viewpoint and representing them in a form that can be used later in the rendering module.

Coordinate systems

Two coordinate systems are used to perform calculations and represent interactions with the tangible display systems (Figure 5). The first is a world coordinate system, where the **xyz** axes remain fixed relative to the physical direction of gravity. The second is the screen-object coordinate system **uvw**, which is affixed to the display and has its axes defined by the directions: normal to the screen (**w**), from bottom-to-top of the screen (**v**), and from left-to-right on the screen (**u**).

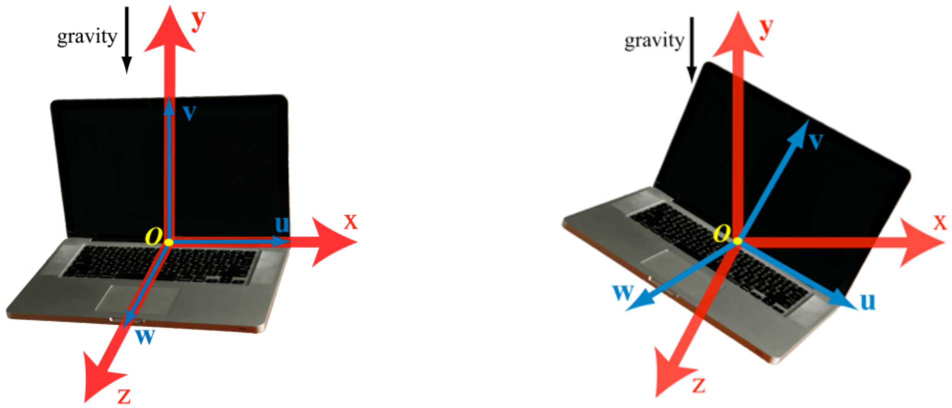


Figure 5: The xyz axes define a world coordinate system that is fixed with respect to gravity. The uvw axes define an object space coordinate system that is fixed with respect to directions on the screen. Left, the two coordinate systems are aligned in the screen's initial state. Right, the screen coordinate system has been rotated relative to the world coordinate system.

In the system's initial state, with the screen in a vertical orientation (Figure 5, left), the screen's **uvw** axes are aligned with the **xyz** axes of the world coordinate system. As the display is manipulated, the **uvw** axes are rotated relative to the **xyz** axes (Figure 5, right). Because the current prototypes do not track translation of the screen, a common origin is maintained for the two systems and orientation changes are represented as rotations around that point.

Orientation tracking

The orientation-tracking component provides real-time data on how the screen has been tilted or rotated by the user. In the initial tangiBook system, tracking was implemented using the triaxial accelerometer in the laptop's Sudden Motion Sensor (SMS) and the open source SMSLib[26] library. The SMS accelerometer provides the necessary information for tracking the display's orientation relative to the world by relating the three screen axis directions (**uvw**) to the direction of gravity (the **y** axis of the world coordinate system). To provide similar functionality for the desktop-based system, an ActionXL Wired Motion sensor FP100W containing a triaxial accelerometer was mounted to the Apple Cinema display.

It is convenient to use triaxial accelerometers for orientation tracking because they are inexpensive and readily available in a range of device, but they do have an important limitation. Because they detect orientation relative to the direction of gravity, they are not able to detect rotations of the display that are made around the axis aligned with gravity (the **y**-axis). The accelerometer can detect if the display is tilted backward or rotated in plane so that the screen is upside-down, but does not detect when the screen is turned to face in a new compass direction. This limitation is partially overcome by the viewpoint-tracking component because turning the display will result in a change in the observer's viewing direction relative to the screen. This maintains some dynamic interactivity for these rotations, though of a different kind.

In future work, as we continue developing the second-generation tangible display system, we plan to evaluate the performance of more complex tracking devices to see which tracking technology would be the most appropriate replacement for the accelerometers. Options include three degree-of-freedom orientation sensors that include magnetometers to detect rotation around the axis of gravity, or complete 6 degree-of-freedom tracking devices that will also provide translation information.

Viewpoint tracking

In addition to tracking the orientation of the display, it is also necessary to know the viewing position of the observer to calculate the surface reflections that should be rendered to the virtual object. In the original tangiBook system, the location of the user was tracked using the laptop's built-in webcam and computer-vision-based head-tracking. In the desktop-based system, an external Logitech Quickcam Pro 9000 camera has been attached to the display screen to provide similar capabilities. The location of the head in the stream of camera images, along with information about the camera's physical orientation and position determined from orientation tracking, is used to estimate the position of the eye-point in world coordinates. In both current systems, the position and size of the head in each image is determined using the Haar cascade algorithm from OpenCV.[27] The location of the eye-point in the image is estimated by adding an offset to the head center position. The size of the head radius in the image is used to estimate the approximate distance of the viewer from the screen. The eye position in three-dimensional space is determined by relating directions in the image plane to the **uvw** coordinate system and using an ideal pinhole camera model to estimate physical distances.

4.3 Modeling and rendering

The modeling and rendering component of the system uses the information collected by the tracking module to render a realistically shaded view of a virtual surface to the screen. It includes custom software to integrate the tracking information into the rendering process and 3D shaders to allow for real-time rendering of complex surfaces using realistic image-based lighting. To simulate the visual experience of interacting with a real object, the virtual surface is modeled in such a way that it appears to be at the physical location of the screen, and it is rendered from a camera position that makes it respond to orientation and viewpoint changes as a physical surface would.

Surface modeling

The tangible display software incorporates three types of modeling to create virtual objects: polygonal geometry to give the shape of the surface, normal maps to provide the small scale surface texture, and bidirectional reflectance distribution function (BRDF) models to represent the color and gloss properties of the material.

To allow the virtual object onscreen to be manipulated like a real object, the geometry for the virtual object is modeled as a rectangular surface with the size and location of the physical display screen in the world coordinate system. The geometric surface normal for the virtual object is set to the **w**-axis direction, the real normal to the physical display. Spatially varying normal maps are then used to adjust the geometric surface normal to provide mesoscale texture.[28] Spatially varying material reflectance properties are specified to provide gloss and color for the virtual object. The diffuse, specular, and roughness properties of the material are specified by a set of maps corresponding to the three components of the Ward BRDF model[29]: ρ_d, ρ_s, and α. In the current software, these parameters are specified in three channels to provide diffuse color information and allow for colored specular highlights when simulating metals.

Illumination and shading

A custom OpenGL shader was developed to incorporate information from the tracking module and render the object's surface with its specified material properties and texture. The current shader is based on the Ward model shader described by Rost[30] and implements an isotropic form of the Ward model:

$$\rho_{brdf}(\theta_i,\phi_i,\theta_r,\phi_r) = \frac{\rho_d}{\pi} + \rho_s \frac{1}{\sqrt{\cos\theta_i \cos\theta_r}} \frac{e^{-\tan^2(\theta_h/\alpha^2)}}{4\pi\alpha^2} \tag{1}$$

where ρ_d is the diffuse reflectance, ρ_s is the specular reflectance, α is the standard deviation of surface slope, θ_h is the angle between the surface normal and the half vector of the light source and viewing directions, θ_i is the angle between the surface normal and light source vector, and θ_r is the angle between the surface normal and the viewing vector.

The shading calculations are performed in the **xyz** world coordinate system. The orientation information from the tracking module is used within the custom vertex shader to update the position of the virtual object as the display is rotated. The user's estimated viewing position from the tracking module and the interpolated surface positions from the vertex shader are used in the fragment shader to determine the surface-to-viewing point vector in the Ward model's reflectance calculations. The surface normal at each fragment position is specified by the spatially-varying normal map. The properties of the material are provided to the shader using either single values of ρ_d, ρ_s and α per channel to describe a surface with uniform properties or specified with maps to describe materials with spatially varying BRDFs.

Two methods are available for illuminating the surface. For applications where complex patterns of illumination are critical, the surface can be illuminated with image-based cubic environment maps.[31] To light the surface, the specular reflection direction is calculated from the surface normal and viewing direction. A small number of angles around the specular direction are sampled and used to index the cubic environment map to find the illumination color for those directions. The contribution of each direction is weighted by its value in the Ward model and added to diffuse lighting to determine the final color at each surface position. Due to the sparse sampling of the specular lobe, the reflections calculated using this technique may not be accurate enough for certain applications. In this case, a discrete set of lights specifying the direction and color of points of illumination may be used. In the second-generation system, the discrete lighting option may no longer be needed. The processing power of the desktop-based system will allow for significantly more directions to be sampled and will improve the accuracy of the environment-mapped lighting option.

4.4 Display screen evaluation

Another advantage of the desktop-based system over the laptop-based tangiBook is the ability to select a screen that is better suited to the requirements of a tangible display. The properties of the display screen, in particular viewing-angle dependent shifts, are an important consideration for tangible display systems intended for surface appearance evaluations. A tangible display system, by its nature, results in off-axis viewing of the display screen, as it is intended to simulate the experience of viewing a surface from different directions. With the tangiBook LCD, color shifts and luminance fall-off were evident when looking at the screen from wide angles.

Two high color-quality screens were considered for the second-generation system, the Apple Cinema HD 20” display and the 24” HP DreamColor LP2480zx. To aid in the selection of a screen, colorimetric measurements were taken to evaluate their luminance and color consistency when viewed from a range of different angles. These two screens, in addition to the MacBook Pro screen from the tangiBook, were measured at 5 degree intervals over an 80 degree range in the horizontal plane using a PhotoResearch PR650 spectro-radiometer mounted on a gonio-arm (shown in Figure 6).

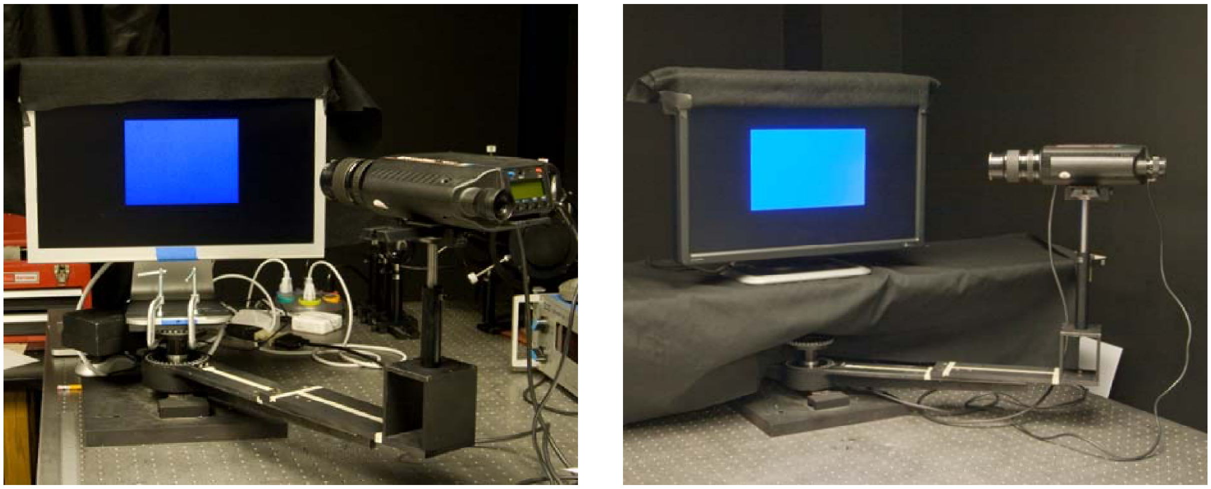


Figure 6: Gonio-apparatus for measuring viewing-angle dependent color properties of the candidate display screens. Left, the PR650 is being used to measure the Apple Cinema HD display and on the right, the HP DreamColor display.

As compared to the MacBook Pro screen used in the tangiBook, the measurement results indicate that both candidate displays for the desktop-based system exhibit greater colorimetric stability, higher contrast ratios, and a reduced rate of luminance falloff as a function of viewing angle. As shown in Figure 7a, the MacBook Pro display has a rapid decline in luminance when viewed at an angle of more than 15 degrees from the normal. While directing the display luminance this way may be advantageous for typical laptop usage, it is less suitable for use as a tangible display. The HP DreamColor and Apple Cinema HD displays both exhibit more gradual declines in luminance with viewing angle. Both candidate displays also exhibit greater stability in the chromaticity of their primaries as a function of viewing angle. As the viewing angle increases, the chromaticities of the RGB primaries in the tangiBook screen begin to shift toward the white-point of the display (Figure 7b). In comparison, the HP DreamColor (Figure 7c) and Apple Cinema (Figure 7d) displays show minimal shifting of the primaries over the same 80 degree range.

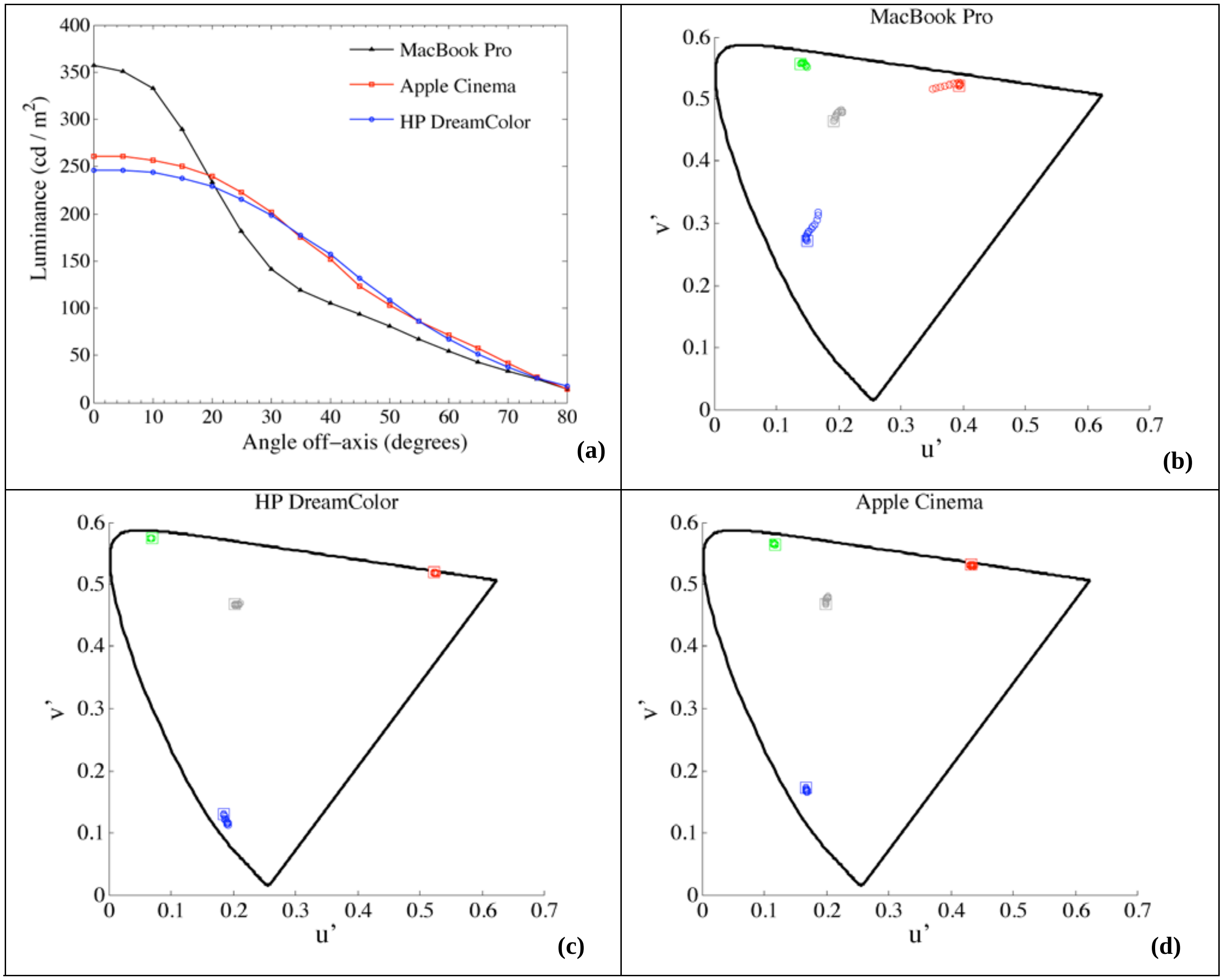


Figure 7: Comparison of luminance and chromaticity stability as a function of the viewing angle (horizontally). Upper left (a), the MacBook Pro exhibits a sharper decline in luminance in the first 30 degrees than the HP DreamColor and Apple Cinema displays. The chromaticities of the display primaries and the white point are plotted for measurements taken at normal viewing (shown as squares) and at angles from 5 to 80 degrees away from normal at 5 degrees intervals (dots) for the MacBook Pro (b), HP DreamColor (c), and Apple Cinema (d).

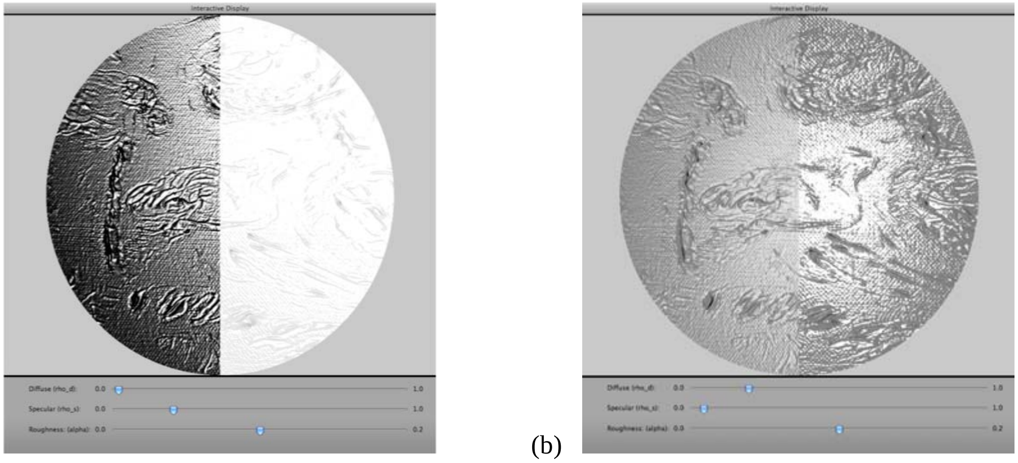
The greater colorimetric stability and reduced luminance falloff of the candidate displays will allow for color accuracy to be better maintained as the user interacts with the system and views it from different directions, so that the appearance changes the user sees are due to changes in the rendered virtual surface and not due to artifacts introduced by off-axis viewing of the display. We plan to use the Apple Cinema display in the second-generation system because its form factor makes it more suitable for use as a tangible display. The Apple Cinema HD display has smaller dimensions and weighs approximately 4 pounds less than the HP DreamColor screen, making it easier to grasp and manipulate.

5. APPLICATIONS

The capabilities provided by a tangible display system can enable a wide variety of surface appearance applications where natural interaction with virtual objects would be beneficial. In the following section we describe examples in three domains: the psychophysical study of material appearance, computer aided-appearance design, and soft-proofing of printed materials.

Understanding the perception of material appearance has important implications for both basic science and in industry.[32,33,34] Historically, conducting experiments on material appearance has been challenging due to the difficulty in creating physical sample stimuli that vary systematically in parameters of interest. More recently, the study of material appearance has been facilitated by the use of computer graphics simulations that allow researchers to create and display physically accurate simulations of objects with complex geometries and material properties in realistic lighting environments.[1,2,3,35,36] However, a significant limitation of many computer-based studies is that the stimuli are presented as static images or animated sequences rendered from a fixed viewpoint and are passively viewed by the observer. These stimuli presentations do not allow for the natural modes of interaction that are typically used when evaluating the properties of real materials, such as direct manipulation and differential viewing, to see the changing patterns of surface reflections. Another limitation of many computer graphics methods is the inability to dynamically control material properties, which has prevented the use of material adjustment and matching procedures in experiments. Both of these limitations can be overcome using the capabilities of a tangible display.

Research has shown that the apparent gloss of a surface varies with its diffuse reflectance due to changes in the visual contrast of surface reflections[33] and that gloss affects the perceived lightness and colors of surfaces.[37] A sample psychophysical experiment for investigating these phenomena using a tangible display is shown in Figure 8. Figure 8a illustrates the effects of diffuse reflectance on perceived gloss. The two patches of the central target have the same physical gloss levels (Ward ρ_s and α), yet differ in apparent gloss due to differences in their diffuse reflectance (ρ_d). The use of a tangible display allows an observer to tilt the surface and observe it from different viewpoints while interactively varying ρ_s and α to produce a visual gloss match. The experiment illustrated in Figure 8b explores the complementary condition, where the two target patches have been given different physical gloss properties (ρ_s and α) and the observer's task is to adjust the diffuse reflectance (ρ_d) to produce an apparent lightness match. The interactive capabilities of tangible displays will enable a greater level of naturalness and control in computer-based studies of surface appearance.



(a) (b)

Figure 8: Psychophysics of material appearance. Left (a), an example showing how tangible displays can be used to study the effects of color on gloss perception. The left and right patches of the target have the same physical gloss properties (ρ_s and α) but differ in perceived gloss. The observer's task is to change the Ward parameters of the left patch until the two match in apparent gloss. Figure 11b (right) shows the complementary experiment where the gloss levels are different and the observer has to adjust the diffuse reflectance ρ_d until the patches match.

The ability to render accurate simulations of surfaces and materials under realistic lighting conditions has fostered the field of Computer-Aided Appearance Design (CAAD).[38] Researchers have developed interactive tools for specifying the properties of materials[39] and custom augmented-reality display systems for viewing the rendered surfaces.[40,41] Tangible displays will provide a new way to interact with virtual surfaces during CAAD. An example application on a tangible display for simulating potential changes in appearance for a paint touch-up process is shown in Figure 9. Note the changes in gloss caused by texture differences in the outer basecoat and central touch-up areas. Using an application like this, a paint manufacturer could experiment with changes in gloss and texture properties to find tolerances for visible differences to inform decisions about paint formulations and application methods.

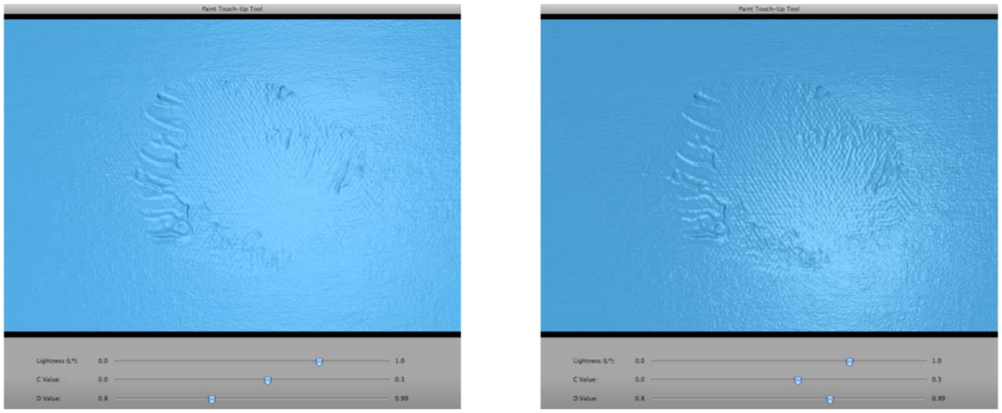


Figure 9: Computer-aided appearance design: the images depict a paint touch-up application on a tangible display. The lightness (L), contrast gloss (c) and distinctness-of-image gloss (d) of the central region can be changed with the slider bars while interacting with the surface and viewing it from different directions to assess the magnitude of the texture effects for paints with different properties.

It is useful in photo printing and desktop publishing to be able to simulate the appearance of a hardcopy by soft proofing on a computer display before making the physical print.[42,43] Recently, soft-proofing systems have started to model the glossiness of photographic prints in addition to their diffuse color properties and render them in computer graphics simulations on standard computer displays.[44,45] An example of an interactive soft-proofing application for a tangible display is shown in Figure 10. Buttons in the application allow the user to select between papers with different gloss and texture properties. A tangible display allows the simulated prints to be viewed for different angles and orientations relative to lighting when selecting among paper types. The real-time control and natural interactivity of a tangible display should enhance the utility of soft-proofing applications that simulate material properties beyond surface color.

Figure 10: Images illustrating a photo soft-proofing application. Buttons in the interface allow an image to be proofed on simulated photo papers with different textures and gloss levels (canvas, left and high gloss, right).

6. CONCLUSIONS

In this paper, we have described the design considerations for a class of systems, termed tangible displays, that support realistic simulations of complex materials and provide the user with the ability to directly manipulate virtual surfaces like they were real physical objects. These systems include sensors to track the orientation of the screen and the viewing position of the user. Custom software integrates this information with a real-time rendering module to display realistically shaded images of surfaces with complex texture and material properties on the screen. The initial system developed, the tangiBook, was designed to provide tangible display capabilities using only the components from an off-the-shelf laptop computer. We are now in the process of developing a second-generation system that will be created from a set of components selected to specifically meet the needs of a tangible display. As a starting point, a desktop-based prototype has been developed that reproduces the tracking and rendering capabilities of the tangiBook. The customizable nature of the second-generation system will allow us to incorporate more sophisticated tracking devices as development continues. The color accuracy of the display screen is also an important consideration for a second-generation tangible display intended for surface appearance studies. Two candidate screens were evaluated and as compared to the tangiBook display, both were found to exhibit greater luminance consistency and colorimetric stability as a function of viewing angle. Finally, the processing power of the high-performance desktop computer for the second-generation system will provide the ability to incorporate more complex BRDF and lighting models to produce more realistic renderings of virtual surfaces in the future.

Ultimately, the goal of tangible display systems is to recreate the experience of viewing a real object as closely as possible, while providing the advantages of computer-based studies of surface appearance, namely the ability to create a wide range of stimuli without having to physically construct them, and the ability to interactively change the properties of materials. The development of a second-generation system will allow for more realistic, color accurate depictions of virtual surfaces while maintaining the natural interactivity of the tangiBook. Tangible displays offer a meaningful way to present virtual objects in a real-world context. With enhanced capabilities, a second-generation system will be better able to support a range of appearance perception applications.

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