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. In the first system, a 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 physically-based 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. We have also developed a second-generation system to improve the fidelity of the virtual surfaces rendered to the screen. With a higher quality display and greater processing capabilities, this system allows for more realistic and color accurate reproductions of virtual surfaces during interactive viewing. Tangible displays offer a meaningful way to present virtual objects in a real-world context. With its enhanced capabilities, the second-generation system will better support a range of appearance perception applications.

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. 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 to observe the changing patterns of surface reflections. To support these types of natural interactions in computer-based studies, we are developing a class of display systems, termed tangible (or situated) displays, that integrate display orientation tracking and observer viewpoint tracking with specialized rendering methodologies. The user experience with a tangible display is akin to holding a physical 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, as shown in Fig. 1.

Figure 1: Image sequence showing a model of a painting being displayed on a tangible display system. The tangiBook type of system is based on an off-the-shelf laptop computer that incorporates an accelerometer and a webcam as standard equipment. Custom software allows the orientation of the laptop screen and the position of the observer to be tracked in real-time. Tilting the display system or moving in front of the screen produces realistic changes in surface lighting and material appearance.
When viewing standard computer graphics simulations on a display screen, a user is typically a step removed visually and physically from the virtual objects they are interacting with. The display screen acts as a window separating the real and virtual worlds, and the user typically does not interact directly with the virtual objects, but instead uses indirect means, such as a keyboard and mouse, to manipulate the objects or shift the point of view.

Our objective is to remove these barriers between the real and virtual worlds by developing tangible interfaces that give users much of the same experience they would have if the virtual object were situated in a real environment. Instead of providing a view into a virtual world, this system presents the virtual object, situated in the real world, at the physical location of the display. It supports natural interaction with the object, through direct manipulation of the object’s orientation by rotating the display, and dynamic viewpoint changes through observer tracking. The material properties of the object can also be changed in real-time.

2. RELATED WORK

Computer graphics simulations are often been displayed on standard computer screens and manipulated using indirect input devices. However, there has been an interest in developing more natural interfaces to virtual environments since Sutherland and colleagues’ pioneering work on see-through head-mounted displays (HMDs) [Sutherland 1968] and 3D input wands in the 1960’s and 1970’s [Vickers 1974]. Since that time, significant advances have been made in both display systems [Callahan 1983; Fisher et al. 1986; State et al. 2005] and 3D input devices [VPL; Sensable; Ascension] for interacting with virtual environments. With these types of systems, a real environment is augmented with virtual content shown on a see-through HMD, or the user is immersed entirely within a virtual environment shown on the display.

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 [Cruz-Neira et al. 1993] projected virtual content onto multiple projection screens to immerse the user within a virtual environment. The shaderLamps and iLamps systems developed by Raskar et al. [2001, 2003] 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 in the scene to create real world objects whose appearance could be varied under computer control. The dynamic shaderLamps system [Bandyopadhyay et al. 2001] included tracking sensors on the objects to allow them to be moved and still retain their projected appearance content. Bimber and colleagues have also been early innovators in this area, focusing on applications in digital paleontology [Bimber et al. 2002] and augmented artwork and museums [Bimber et al. 2005], as well as basic technology development (see [Bimber and Raskar 2005] for a comprehensive review of the field).

A third approach to creating natural interfaces for computer graphics simulations is to use spatially-aware display systems that serve as tangible interfaces. In the Chameleon system, Fitzmaurice et al. [1993] coupled a six degree-of-freedom tracking device with a handheld display screen to create a display that updated its content based on its position and orientation in the environment. The Boom Chameleon system [Tsang et al 2003] used a larger LCD display attached to a motion-tracked boom arm. To change the point-of-view for a virtual 3D model shown onscreen, the user manipulated the physical position of the LCD screen. The Virtual Mirror System [Alexandre et al 2002] took the spatially-aware display a step further by using the display to simulate the behavior of a physical object in the user’s environment. The virtual mirror included tracking devices and a camera pointed back toward the user to create the impression that the display was a real physical mirror. This device was also used as part of an art exhibition to display virtual daugherotypes that showed ambient reflections from the user’s environment [Lazarri et al 2002].

A significant feature of spatially-aware 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, pioneered by Ishii and Ullmer [1997] and Buxton [2008]. The advantage of tangible interfaces is that the affordances of the object (such as lifting, tilting, and rotating the display) provide rich and natural modes of interaction with the virtual world. The goal of the tangible display systems that we are developing is to provide these types of natural interaction when interacting with realistic simulations of complex materials.
3. SYSTEM ARCHITECTURE

A tangible display system requires three primary components: tracking capabilities for the display and user, a display screen to show the rendered images, and an interactive rendering module that generates a realistically shaded view of the virtual surface based on the tracking information.

3.1 Tangible display systems: laptop and workstation architectures

We have developed a set of tangible display systems that are based on two different architectures (shown in Figure 2). The first architecture, the tangiBook, is based on an off-the-shelf laptop computer (Apple MacBook Pro 15”) that incorporates 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 only the standard components in 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 architecture, we considered the enhancements that were possible by synthesizing the system from a set of selected components: tracking devices, a powerful desktop computer workstation, and high color-quality display screen. The workstation computer (Falcon Northwest Mach V) contains dual NVIDIA GeForce GTX 295 video cards, which together provide approximately 30 times the parallel processing capabilities of the GeForce 9600M GT card built in to the MacBook Pro laptop. The LCD screen used in the workstation-based system is an Apple Cinema HD 20” display, which features greater colorimetric stability and reduced viewing-angle dependent color shifting as compared with the LCD screen in the MacBook Pro. To help support the heavier weight of the Apple Cinema LCD, the screen was 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 continues, the customizable nature of the workstation-based system will allow for more advanced tracking hardware, such as a six degree-of-freedom magnetic system, to be used in place of the current tracking devices.

![Tangible displays are being developed for two different architectures. Left, the tangiBook, was developed from an off-the-shelf laptop computer. Right, a second type of tangible display system was created from a desktop computer and high-quality display.](image)

Currently, in both tangible display systems, a triaxial accelerometer is used to estimate the orientation of the display, and a camera is used to estimate the observer’s viewing position with computer vision-based head tracking. This information is used within a custom 3D shader to dynamically render a realistically shaded view of the virtual surface to the display screen. By integrating these components in a custom software system, virtual surfaces can be observed and manipulated in the same manner as real surfaces, such that tilting the display or moving in front of the screen produces realistic changes in surface appearance.
3.1.1 Interaction
Coordinate Systems

Two coordinate systems are used for performing calculations and representing interactions with the tangible display systems (Figure 3). The first is the world coordinate system, where the \( x, y, \) and \( z \) 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 3: 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 laptop’s initial state. Right, the laptop has been rotated relative to the world coordinate system.](image)

In the tangiBook system, with the laptop in its initial state, resting on a horizontal surface (Figure 3, left), the screen’s \( uvw \) axes are aligned with the \( xyz \) axes of the world coordinate system. As the laptop is manipulated, the \( uvw \) axes are rotated relative to the \( xyz \) axes (Figure 3, right). Because the system does not track translation of the screen, it is convenient to maintain a common origin point between the two systems and represent orientation changes as rotations relative to that origin.

**Orientation tracking**

The orientation-tracking component of the system provides information on how the screen has been rotated by the user. In the tangiBook system, tracking is implemented using the accelerometer in the laptop’s Sudden Motion Sensor (SMS) and the open source SMSLib library [Suitable Systems]. The SMS accelerometer provides the necessary information for tracking the laptop’s orientation (relative to the world) by relating the laptop’s three affixed axes (\( u, v, \) and \( w \)) to the direction of gravity (the y axis of the world coordinate system). For the workstation-based system, an ActionXL Wired Motion sensor FP100W was attached to the back of the workstation’s display screen. The ActionXL FP100W contains a triaxial accelerometer and provides the same type of tracking information as the SMS.

Data from the triaxial accelerometers define a vector \( s \) that has known coordinates in both the \( uvw \) and \( xyz \) systems. The three coordinates \( (u_s, v_s, w_s) \) of \( s \) in \( uvw \) are reported by the sensor, and are known to correspond to the \( y \) axis, \( (x_s, y_s, z_s) = (0, 1, 0) \), of the world coordinate system. The \( xyz \) coordinates of these screen-affixed vectors are also known for the initial state, prior to any rotation (represented by a vector \( r \)). Because the two coordinate systems are aligned for the initial state, the vector \( r \) has the same \((x,y,z)\) components as \( s \) has \((u,v,w)\) components:

\[
 r = (x_r, y_r, z_r) = (u_s, v_s, w_s). \tag{1}
\]
The relationship between \( r \) and \( s \) in \( \text{xyz} \) is used to calculate a 4 x 4 matrix \( R \) that defines the current orientation of the screen-object frame in terms of world coordinates (the underlying mathematics can be found in [Strang 1993]). The \( \text{xyz} \) space homogeneous coordinates of the screen’s three axis vectors in their initial state, \( \mathbf{u}_0 = (1,0,0,0) \), \( \mathbf{v}_0 = (0,1,0,0) \), and \( \mathbf{w}_0 = (0,0,1,0) \), are multiplied by \( R \) to specify the screen’s current orientation in world coordinates:

\[
\mathbf{u} = R \mathbf{u}_0, \quad \mathbf{v} = R \mathbf{v}_0, \quad \mathbf{w} = R \mathbf{w}_0.
\]  
\( (2, 3, 4) \)

A limitation of using a triaxial accelerometer like the SMS or ActionXL FP100W to track orientation is that it is invariant to rotations around the axis aligned with gravity (y-axis). This limitation is partially overcome by dynamic viewpoint tracking, which responds to changes in the viewing angle between the eye-point and screen normal as the laptop is rotated. This maintains some dynamic interactivity, though of a different kind, for rotations around the y-axis.

**Viewpoint tracking**

Webcam-based viewpoint tracking is used in conjunction with orientation tracking to provide enhanced 3D interactivity. As the observer moves, the head tracking system estimates the observer’s viewing position relative to the display screen. This information, along with information about the camera’s orientation and position determined from orientation tracking, is used to estimate the position of the eye-point in world coordinates. The tangiBook system uses the laptop’s built-in webcam for viewpoint tracking while the workstation-based system uses an external Logitech Quickcam Pro 9000 camera that is attached to the Apple Cinema display screen.

The position of the head center and the head radius in each webcam image is determined using Lienhart’s Haar cascade algorithm from OpenCV [Lienhart & Maydt 2003]. The location of the eye-point in the image is estimated by offsetting the head center position by a percentage of the head radius. The size of the head radius in the image is also used as an approximate method for estimating the physical distance of the viewer from the screen.

The first step in estimating the 3D world coordinates of the eye-point from the camera data is to determine the camera’s position in \( \text{xyz} \). The physical distance from the origin point to the camera, \( d_{\text{cam}} \), has been measured, and the camera falls on the \( \text{v} \)-axis (Figure 4), allowing the camera position (\( \mathbf{p}_{\text{cam}} \)) to be found by:

\[
\mathbf{p}_{\text{cam}} = d_{\text{cam}} \mathbf{v}. \tag{5}
\]

Starting from the camera position, the eye-point position in 3D space is determined from the camera tracking data using an ideal pinhole camera model [Klette et al. 1998]. The distance along the camera’s principal ray to the perpendicular plane containing the eye-point is estimated from the size of the viewer’s head radius in the camera image, \( d_{\text{rad, pix}} \). Using the effective focal length of the camera in image pixels (\( f_{\text{pix}} \)), calculated from calibration data, and an estimate of the physical vertical radius of the viewer’s head (\( d_{\text{rad, cm}} \)), the distance along the principal ray to the plane (\( d_{\text{plane, cm}} \)) is determined from the head size in the image using the pinhole camera equation:

\[
d_{\text{plane, cm}} = d_{\text{rad, cm}} \left( f_{\text{pix}} / d_{\text{rad, pix}} \right). \tag{6}
\]

The position in world coordinates where the principal ray intersects the plane containing the eye-point is found by moving along the principal ray direction (which corresponds to the \( \text{w} \)-axis) a distance \( d_{\text{plane, cm}} \) from the camera:

\[
\mathbf{p}_{\text{pr, plane}} = \mathbf{p}_{\text{cam}} + d_{\text{plane, cm}} \mathbf{w}. \tag{7}
\]
Figure 4: Diagram of the geometry for viewpoint tracking. The camera position \( \mathbf{p}_\text{cam} \) is located a known distance \( d_{\text{cam}} \) from the origin along the \( \mathbf{v} \) axis of the screen coordinate system. The principal ray emanating from the camera points in the same direction as the \( \mathbf{w} \) axis. The point \( \mathbf{p}_\text{plane,cm} \) where the principal ray intersects the perpendicular plane containing the eye-point, is found by moving along the principal ray a distance, \( d_{\text{plane, cm}} \), determined from the pinhole camera equation. The viewpoint \( \mathbf{p}_\text{view} \) is found by moving away from the intersection point in the \( \mathbf{u} \) and \( \mathbf{v} \) directions, based on the offset of the eye-point in the captured image relative to the image center.

In the final step, the position of the eye-point in the camera image is used to determine the eye-point position in the world. The up-vector of the camera coincides with the direction of \( \mathbf{v} \), and is the physical direction corresponding to a vertical offset from center in the camera image. The \( \mathbf{u} \) vector is the physical direction corresponding to a horizontal offset from center in the camera image. The eye-point offsets in image pixels are scaled to physical units using the pinhole camera equation and are applied as physical offsets from the principal ray-plane intersection point, giving a final viewing position, \( \mathbf{p}_\text{view} \), of:

\[
\mathbf{p}_\text{view} = \mathbf{p}_\text{plane,cm} + d_{\text{plane, cm}} \left( \left( x_{\text{img,eye}} - x_{\text{img,ctr}} \right) f_{\text{pix}} \right) \mathbf{u} + d_{\text{plane, cm}} \left( \left( y_{\text{img,eye}} - y_{\text{img,ctr}} \right) f_{\text{pix}} \right) \mathbf{v}.
\]  

(8)

3.1.2 Modeling and Rendering

Using the orientation and viewpoint tracking information, the tangible displays render a realistically shaded view of a virtual surface to the screen. 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 (geometry, texture, material)

The geometry of the virtual object is modeled as a rectangular surface that coincides with the physical surface of the display screen in the world coordinate system. The surface normal for the rectangular virtual object is aligned with the \( \mathbf{w} \) axis. Spatially varying object-space normal maps are used to adjust this surface normal to provide mesoscale texture [Cohen et al. 1998]. The \((ix, iy)\) image positions of the map are associated with locations on the surface by anchoring the corners of the map image to the object vertices. At each \((ix, iy)\) image position, the object space normal map provides a set of scalars describing the mesoscale normal in \( \mathbf{uvw} \) coordinates \((u_{\text{map}}(ix,iy), v_{\text{map}}(ix,iy), w_{\text{map}}(ix,iy))\). After applying the map, the spatially varying normal vector for the object’s surface \((\mathbf{n}_{(ix,iy)})\), in world coordinates, becomes:

\[
\mathbf{n}_{(ix,iy)} = u_{\text{map}}(ix,iy) \mathbf{u} + v_{\text{map}}(ix,iy) \mathbf{v} + w_{\text{map}}(ix,iy) \mathbf{w}.
\]  

(9)
In addition to mesocale texture, spatially varying material properties can also be specified 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 [Ward 1992]: $\rho_d$, $\rho_s$, and $\alpha$.

**Illumination and Shading**

A custom OpenGL shader was developed to render the object’s surface with its specified material properties and mesoscale texture. The surface is shaded to show the reflections that an observer would see from his or her current viewing position, for the laptop’s current orientation relative to virtual environmental illumination. Our shader, based on the Ward model shader described by Rost [2006], implements an isotropic form of the Ward model:

$$
\rho_{\text{iso}}(\theta_i, \phi_i, \theta_r, \phi_r) = \rho_d + \rho_s \frac{1}{\sqrt{\cos \theta_i \cos \theta_r}} \frac{e^{-\tan^2(n_i, n_r)}}{4\pi \alpha^2}
$$

where $\rho_d$ is the diffuse reflectance parameter, $\rho_s$ is specular reflectance, $\alpha$ is the standard deviation of surface slope, and $\theta_h$ is the angle between the surface normal vector ($\mathbf{n}$) and the halfway vector ($\mathbf{h}$) defined by the bisector of the surface-to-light source and surface-to-viewing point vectors. $\theta_i$ represents the angle between the surface normal and a vector from the surface to a light source. $\theta_r$ is the angle between the surface normal and the vector to the viewing position.

Shading calculations are performed in the $xyz$ world coordinate system. The known screen-object space positions of the surface’s vertices are transformed into world coordinates in the vertex shader, and the resulting interpolated positions of the surface fragments in $xyz$ coordinates are sent to the custom fragment shader where the reflectance calculations are performed. Each interpolated surface position is subtracted from the tracked viewing position, $\mathbf{p}_{\text{view}}$, to find the Ward model’s surface-to-viewing point vector. The surface normal at each fragment position is found using the object-space normal map and the $\mathbf{u}$, $\mathbf{v}$, and $\mathbf{w}$ vectors from orientation tracking. The properties of the material are provided to the shader with either single values of $\rho_d$, $\rho_s$, and $\alpha$ to describe a surface with uniform properties, or maps of these parameters are provided to specify values at each fragment position to describe materials with spatially varying BRDFs.

Two methods can be used for illuminating the surface. For applications where complex patterns of illumination are critical, such as soft-proofing of a glossy print, the surface is illuminated with image-based cubic environment maps [Heidrich and Seidel 1998]. The surface normal and the direction from the surface to viewpoint are used to calculate the direction of the specular reflection. A small number of angles around the specular reflection direction are then uniformly sampled, used to index the cubic environment map to find the illumination color at that location, and the contribution of each to the overall sum, based on its direction, is calculated with the Ward model. A diffuse cubic map of the environment is also used and indexed by the surface normal. The amount of diffuse light reflection is weighted relative to specular reflectance and the light from the two is summed to determine the fragment color.

Due to sparse sampling of the specular lobe, the reflections calculated using the environment map technique may not be accurate enough for certain applications, such as psychophysical testing. In this case, a discrete set of lights specifying the direction and color of points of illumination may be used.

**Viewing Position for Rendering**

When rendering to the display, we want to treat it as a physical object with virtual material properties and not as a window into a virtual scene. Therefore, it is necessary to use a different viewing position for calculating the fragment colors in the shader than is used for rendering the surface to the screen’s viewport. When shading, the dynamically-tracked viewing position and its true relationship to the laptop’s current orientation needs to be used to calculate the light reflecting toward the viewer from each position on the virtual object’s surface. However, a different viewpoint must be used for rendering. To treat the display as a physical object, the virtual object’s surface must stay affixed to the viewport on the screen. This requires that the camera point for rendering always remains a fixed distance from the virtual object’s surface, along a ray normal to the object that intersects the center of the object’s surface.
3.2 System Capabilities

The tangible display systems provide a unique set of capabilities that create a powerful and flexible tangible interface tool for interacting with virtual objects. They support direct manipulation of the virtual object’s orientation by rotating the screen and dynamic viewpoint changes by tracking the observer’s head position. They also provide the capability to specify the material properties of the surface in terms of diffuse reflectance, specular reflectance, and surface roughness, and change them dynamically while the user is interacting with the system. These capabilities are illustrated in the following sections.

3.2.1 Dynamic interaction

As shown in Figure 1, tangible display systems support dynamic, natural interaction with virtual surfaces. As the screen is manipulated by the user, the changes in its physical orientation are tracked and used to dynamically update the rendering of the virtual object. The updated rendering displays the surface reflections for the virtual object’s new orientation relative to the specified lighting environment. As the laptop is tilted from its orientation in the left image (of Figure 1) to its orientation in the far right image, the painting’s surface catches the reflection from one of the virtual lights when the change in the direction of the painting’s surface normal causes the viewing position to near the specular angle with respect to the light’s position.

3.2.2 Dynamic viewing

The tangiBook and workstation-based tangible display systems also provide the capability to dynamically track the observer’s viewing position relative to the display and update the rendered image accordingly. As shown in Figure 5, as the viewer’s head position moves relative to the display, the rendered reflections off the painting’s surface change to reflect the new relationship between the viewpoint, surface normal, and the virtual illumination environment.

![Figure 5: Dynamic viewing](image)

3.2.3 Dynamic control of material properties

The interactive rendering capabilities of the tangible display systems allow for dynamic control of material properties specified in terms of the diffuse reflectance, specular reflectance, and roughness of the object’s surface. These parameters can be adjusted dynamically, while the user is interacting with the virtual surface, and will immediately produce changes to the surface’s appearance. This is demonstrated in Figure 6, where the material being rendered is changed from matte to glossy while the tangiBook is actively being used.
3.3 Display Evaluation

Beyond the benefits provided by the more powerful graphics rendering hardware, a key advantage of the workstation-based system over the tangiBook is the ability to incorporate a screen that better satisfies the performance requirements of a tangible display system. The properties of the display, in particular viewing-angle dependent shifts, are an important consideration for a tangible display systems intended for surface appearance evaluations. A tangible display system, by its nature, results in off-axis viewing of the display screen, given its purpose of simulating the experience of dynamically viewing a real surface from different directions. With the tangiBook LCD, color shifting and luminance fall-off were evident when looking at the screen from wide angles.

When selecting a display for the workstation-based system, we collected colorimetric measurements as a function of viewing angle to evaluate the angular-varying display performance of candidate LCD screen. Two high color quality screens were considered, the Apple Cinema HD 20” display and HP DreamColor. These two screens, in addition to the MacBook Pro screen of the tangiBook, were measured using a PR650 spectro-radiometer mounted on a gonio-arm apparatus. The measurement apparatus is shown in Figure 7.
The results of the viewing-angle measurements indicate that the candidate displays for the work-station system, the Apple Cinema 20” and HP DreamColor, both exhibit greater colorimetric stability, higher contrast ratios, and a reduced rate of luminance falloff as a function of viewing angle as compared to the MacBook Pro laptop display from the tangiBook system. As shown in Figure 8, the MacBook Pro display has a rapid decline in luminance when viewed at an angle of more than 15 degrees from the normal. The HP DreamColor and Apple Cinema displays have more gradual declines in luminance as a function of viewing angle.
Both candidate display also exhibit greater colorimetric stability (smaller deviation in u’v’ chromaticity) as a function of viewing angle than the MacBook Pro screen in the tangiBook. 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 9), effectively limiting the display color gamut. The HP DreamColor display exhibited the smallest degree of chromaticity shifting as a function of viewing angle (Figure 10).

Figure 9. Chromaticity shift as a function of viewing angle for the MacBook Pro display screen. The chromaticities of the display primaries (red, green, and blue dots) and the white point (cyan dots) are plotted for measurements taken at 5 degree intervals from normal viewing to 80 degrees away from normal.
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. The HP DreamColor and Apple Cinema display exhibited similar performance, with slightly better colorimetric stability found in the HP DreamColor. Ultimately, the Apple Cinema display was selected for the workstation-based system because its lighter weight allowed for easier manipulation and tilting of the screen in tangible display applications.
4. APPLICATIONS

The capabilities of our tangible display systems enable a wide variety of applications where natural interaction with virtual objects is desired. In the following section we provide examples of three application domains: the psychophysical study of material appearance, visualization and soft proofing of coatings and printed materials, and interactive access to digital library and museum collections.

4.1 Psychophysics of material appearance

Understanding the psychophysics of material appearance has important implications for both basic science and industry [Adelson 2001; Hunter and Harold 1987]. Traditionally, a major impediment to material appearance research has been the difficulty of creating physical sample stimuli that vary systematically in the parameters of interest. Recently, the study of material appearance has been facilitated by the ability to use 3D computer graphics techniques to create and display physically accurate simulations of objects with complex geometries and material properties in realistic illumination fields [Nishida and Shinya 1998; Pellacini et al. 2000; Fleming et al. 2003, tePas and Pont 2005; Dorsey et al. 2008]. However a significant limitation of computer-based studies is that the stimuli are typically images or movie sequences from a fixed viewpoint. Images on a screen do not allow for the complex natural modes of interaction that we typically use when evaluating material properties, such as direct manipulation and differential viewing. Another limitation of most computer graphics methods for psychophysics is the inability to dynamically control material properties, which has prevented the use of fast, easy, and reliable material adjustment and matching procedures in experiments. Both of these limitations can be overcome using the capabilities of a tangible display.

It is well known that the apparent gloss of a surface varies with its diffuse reflectance due to changes in the visual contrast of surface reflections [Hunter and Harold 1987]. Research has also shown that gloss affects the perceived lightness and colors of surfaces [Dalal et al. 1999]. Figure 11 shows screen shots from sample psychophysical experiments designed to investigate these phenomena implemented on the tangiBook. Figure 11a illustrates the effects of diffuse reflectance on perceived gloss. The two patches of the central target have the same physical gloss properties (Ward $\rho_s$ and $\alpha$), yet differ in apparent gloss due to differences in their diffuse reflectances ($\rho_d$). The experiment shown in the figure allows an observer to tilt the surface and observe it from different viewpoints, while interactively varying $\rho_i$.

Figure 11: Psychophysics of material appearance. Figure 11a (left) shows how a tangible display 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 ($\rho_s$ and $\alpha$) 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 $\rho_i$ until the patches match. A tangible display allows the observer to tilt and view the patches from multiple directions while performing the task.
and $\alpha$ to produce a visual gloss match. The experiment illustrated in Figure 11b explores the complementary condition, where the two target patches have been given different physical gloss properties ($\rho$, and $\alpha$) and the subject’s task is to adjust the diffuse reflectance ($\rho_d$) to produce an apparent lightness match. The interactive capabilities of the tangiBook enable a new level of naturalness and control in computer-based studies of surface appearance that should lead to a deeper understanding of material perception, more comprehensive psychophysical models, and more robust industrial metrics.

4.2 Computer-aided appearance design

In photographic printmaking and desktop publishing, it is useful to be able to simulate the appearance of a hardcopy image before printing by soft proofing on a computer display [Masia et al. 1985; Laihanen 1994]. Recently, soft-proofing systems have started to model the glossiness of photographic prints and render them in 3D graphics simulations [Gatt et al. 2006; Patil et al. 2004]. The simulated images are mapped to 3D planes and shown as objects on a standard display system. Limited interactivity is provided through Quicktime VR sequences created in an offline process.

Figure 12 shows a prototype of an interactive soft-proofing system for a tangible display. In addition to being able to select the gloss and texture properties of the paper in real time, the system allows the user to directly manipulate the simulated print and view it from different orientations to anticipate how it will look under different lighting conditions. The real-time control and natural interactivity provided by a tangible display should enhance the utility of soft-proofing applications.

![Figure 12](image)

**Figure 12**: Soft-proofing: The images illustrate a photographic soft-proofing application. Buttons in the interface allow an image to be proofed on simulated photo papers with different colors, textures, and gloss levels (canvas (left) and high gloss (right), respectively). A tangible display allows the simulated prints to be viewed from different angles and under different lighting conditions when selecting among paper types to find the one that gives a preferred appearance.

The ability to render accurate simulations of surfaces and materials viewed under realistic lighting conditions has fostered the field of Computer-Aided Appearance Design (CAAD) [Meyer 2000]. Researchers have developed interactive tools for specifying the reflectance properties of materials [Colbert et al. 2006] and custom augmented-reality display systems for viewing the rendered surfaces [Konieczny et al. 2005; Konieczny et al. 2006]. The tangiBook provides a low-cost, off-the-shelf, rendering and display system for CAAD. Figure 13 shows a screenshot of the system being used to simulate potential changes in appearance for a paint touch-up process. Note the changes in gloss caused by texture differences in the outer basecoat and central touch-up areas. Using the system a paint manufacturer could experiment with changes in BRDF and texture properties to find tolerances for visible differences to inform decisions about paint formulations and application methods.
Figure 13: Computer-aided appearance design: the images show the tangiBook applied to a paint touch-up application. Note the difference in appearance between the outer and central areas due to texture differences. The lightness (L), contrast gloss (c) and distinctness-of-image gloss (d) of the central region can be changed while tilting the surface and viewing it from different directions to assess the magnitude of the texture effects for paints with different properties.

4.3 Access to digital collections

Digitization has had an enormous impact on libraries and museums. Manuscripts, paintings, and other collections that were only accessible by physical visit, or were not accessible at all due to concerns about wear and tear, are now documented and accessible worldwide though digital images. The positive impact of digital libraries on teaching and research is widely acknowledged. However for many objects, still images are not enough. For example, a digital image of a painting does not fully convey its true appearance, because its appearance changes due to interactions of the materials used, the environmental illumination, and the observer’s own movements. The situation is similar with a wide range of cultural heritage objects.

Figure 14: A virtual illuminated manuscript: The images show sections from a manuscript model displayed on a tangible display. Note how the highlights in the gold leaf and vellum change as the display is tilted. Tangible displays can provide enhanced levels of access to digital library and museum collections.

The tangiBook can be used to provide enhanced digital access to collections of these objects. Figure 14 shows an example of an illuminated manuscript digitized by Gardner et al. [2003]. A museum visitor or library scholar could pick
up this page, move it around to see the glints off the gold leaf and look at it from different angles to see the texture of the vellum. In future versions it might be possible to view the page under daylight or smoky candlelight [Devlin et al. 2003], hold the page up to a virtual window to see its translucency [Jensen et al. 2001], and simulate the aging process to see how the page would have looked 600 years ago or how it will look 600 years from now [Dorsey et al. 2008]. Tangible displays provide a rich, natural interface that allows direct access to digital collections and suggests the advances in teaching and scholarship that might be possible if digital objects are available that can be viewed, analyzed, and manipulated like the objects themselves.

5. CONCLUSIONS

Over the course of this research project, we have developed tangible displays systems utilizing two different architectures. Both allow for realistic simulations of complex materials and provide the user the ability to directly manipulate virtual surfaces like they were real physical objects. The tangiBook is based on an off-the-shelf laptop computer that contains an accelerometer and a webcam as standard components. The workstation-based system is constructed from custom-selected components. Both incorporate software that registers the display’s orientation and the observer’s position in real-time to render accurately shaded images of surfaces with complex texture and material properties.

We have created prototypes applications to demonstrate how tangible displays can be used to advantage in a wide range of areas including psychophysics of material appearance, design and soft proofing of coatings and printed materials, and enhanced access to digital collections in libraries and museums. 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. With the development of the workstation-based system, we can now produce more realistic, color accurate depictions of virtual surfaces while still providing the same natural modes of interactivity afforded by the tangiBook system.

Although we think our tangible display systems have great current utility and greater promise, in the current implementations there are still some limitations that suggest future work. One current limitation is that the triaxial accelerometers used in both systems only register changes with respect to gravity. Therefore rotations of the display around a vertical axis produce no change in lighting. The customizable nature of the workstation-based system will allow us to incorporate more sophisticated tracking devices, such as six degree-of-freedom trackers to overcome this limitation in the future. Also, currently both types of tangible display systems use the relatively simple Ward BRDF model. With the added processing power of the workstation-based system we will now have the ability to incorporate more complex BRDF models and lighting environments to produce more realistic renderings of virtual surfaces.

Tangible interfaces offer a powerful and meaningful approach to merging the real and virtual worlds. The availability of commodity hardware with input, sensing, and display capabilities provides new opportunities to develop and use tangible interfaces in a wide variety of applications. We hope that diverse communities of users find the tangiBook and workstation-based system useful, and we look forward to seeing them used in a wide range of applications. We plan to continue these avenues of research to help realize the full potential of tangible display systems. We would like to thank Eastman Kodak and the RIT Chester F. Carlson Center for Imaging Science for their support of this research over the past year.
**Publications & Presentations Resulting From this work**


Ferwerda, J.A. (2009, October). Envisioning the material world. Keynote address, Procter and Gamble Imaging Community of Practice Symposium, Cincinnati OH.


**Proposals to External Agencies**

**Awarded**


**Pending**


**Prospective**

Procter and Gamble, Apple Computer
REFERENCES


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