

Tangible display systems: bringing virtual surfaces into the real world

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ABSTRACT

We are developing tangible display systems that enable natural interaction with virtual surfaces. Tangible display systems are based on modern mobile devices that incorporate electronic image displays, graphics hardware, tracking systems, and digital cameras. Custom software allows the orientation of a device and the position of the observer to be tracked in real-time. Using this information, realistic images of surfaces with complex textures and material properties illuminated by environment-mapped lighting, can be rendered to the screen at interactive rates. Tilting or moving in front of the device produces realistic changes in surface lighting and material appearance. In this way, tangible displays allow virtual surfaces to be observed and manipulated as naturally as real ones, with the added benefit that surface geometry and material properties can be modified in real-time. We demonstrate the utility of tangible display systems in four application areas: material appearance research; computer-aided appearance design; enhanced access to digital library and museum collections; and new tools for digital artists.

Keywords: advanced display systems, tangible user interfaces, digital painting systems.

1. INTRODUCTION

When observers interact with objects they typically engage in a complex set of behaviors that include active manipulation and dynamic viewing. These behaviors allow observers to experience how objects look from different viewpoints and under different lighting conditions, which provides rich visual information about object shape and material properties. Modern computer graphics systems have the ability to render both static and dynamic images of objects with high fidelity, but the ability to interact with these objects is typically indirect, through trackballs, mice and similar devices. To address this limitation we are developing a new class of *tangible display systems*¹⁻³ that combine the capabilities of modern mobile devices with the power of computer graphics to create rich digital representations of objects that can be viewed and manipulated as naturally as real ones, with the added benefit that object shapes, material properties, and lighting can be changed under real-time user control.

In this paper we describe the design, development, and applications of several classes of tangible display systems, the first-generation tangiBook system was based on a standard laptop computer that incorporated a webcam and accelerometer as standard equipment. The tangiDesk system uses a more powerful tower computer, inertial and optical tracking systems, and a large display to achieve high-fidelity rendering and interaction. The tangiPod and tangiPad implementations take advantage of these devices' form-factors, graphics hardware, integral gyroscopes, and touchscreens to provide direct interaction with virtual surfaces.

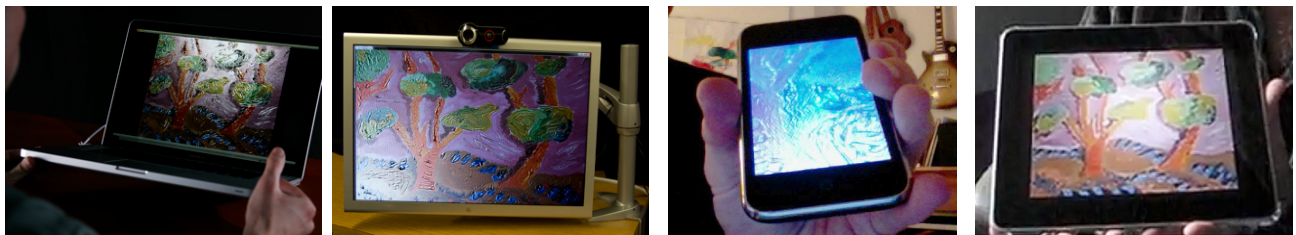


Figure 1: Tangible display systems are being developed for several different architectures. (Left to right) The first-generation tangiBook system developed from an off-the-shelf laptop computer; A high-performance system developed using a desktop computer, external tracking devices, and an Apple Cinema display; Consumer-oriented systems developed for the iPod and iPad devices.

2. RELATED WORK

Advances in computer graphics technologies have led to the development of realistic image synthesis techniques, where images of virtual objects can be rendered that are indistinguishable from images of real objects⁴. The ability to create realistic images of virtual objects has supported advances in a variety of application domains including the film and game industries, computer-aided design and manufacturing, medical imaging, and digital libraries and museums.

With standard computer graphics systems, a user is a step removed visually and physically from the virtual objects they are interacting with. The screen acts as a window separating the real and virtual worlds, and the user does not interact directly with the objects, but instead uses indirect means, such as a mouse or keyboard, to manipulate the objects or shift the point of view.

There has been a strong interest in developing natural interfaces for interacting with virtual objects since Sutherland and colleagues' pioneering work on see-through head-mounted displays (HMDs) and 3D input devices^{5,6}. Significant advances have been made since that time in both HMDs⁷⁻⁹, and 3D input¹⁰⁻¹² for virtual environments.

An alternative approach is represented by the CAVE system¹³ that surrounds a user with projection screens on which virtual content is displayed. Further innovations in projection-based approaches include the shaderLamps and iLamps systems¹⁴⁻¹⁶ that project pre-warped images on real three-dimensional objects to create physical objects whose appearance can be changed under computer control. Bimber and colleagues¹⁷ have also been early innovators in this area.

A third major approach to bridging real and virtual worlds incorporates spatially aware displays and tangible interfaces. The Chameleon systems^{18,19} coupled 6 DOF trackers with computer displays to create a spatially aware display whose content changes depending on its context and position. The Virtual Mirror system²⁰ took the spatially aware display concept a step further by incorporating a video camera pointed toward the user to create the impression of a real mirror. The device also allowed interactive viewing of reflective daguerreotype images²¹. A significant feature of these systems is the capability to grasp and directly manipulate the display to change the viewpoint on the virtual environment. The virtue of tangible interfaces such as these is that the affordances of the systems (in these cases lifting, tilting, and rotating the display) support rich and natural modes of interaction with the virtual objects^{22,23}.

3. SYSTEM DESIGN

To recreate the experience of interacting with physical surfaces, tangible display systems require three main capabilities: accurate tracking of the display's orientation and the user's viewpoint; 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 that integrates and supports these functions. The following sections describe the design of our tangible display systems.

3.1 Hardware platforms

We have developed tangible display systems for several different hardware architectures (shown in Figure 1). The initial system, the tangiBook, was based on an off-the-shelf Apple MacBook Pro laptop computer that incorporated all the necessary components: an LCD display, graphics rendering hardware, an accelerometer, and a webcam. Our high-end desktop system is also built from off-the-shelf components including a powerful tower computer with gaming graphics cards, a precision accelerometer, an infrared head tracking system, and an Apple Cinema display. In addition we are developing consumer-oriented tangible display software for the iPod and iPad architectures that take advantage of the elegant form-factors of these devices and the built-in gyroscopes, webcams, and touchscreens.

3.2 Tracking and dynamic interaction

Regardless of the hardware platform, tracking the orientation of the device and the observer's viewpoint are key components of the systems. The discussion below describes tracking in the tangiBook system. Though implementation details vary, similar concepts apply to all the systems.

Coordinate systems

Figure 2 shows the coordinate systems used to represent interactions with the tangible display. 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). In the system's initial state, with the screen vertically oriented, 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. Because the current systems do not track translation, a common origin is maintained for the two systems and orientation changes are represented as rotations around that point. A viewpoint coordinate system is also defined, where camera position ($pcam$) is located a known distance ($dcam$) from the origin along the v axis of the laptop coordinate system. The principal ray emanating from the camera points in the same direction as the w axis. The point $ppr,plane$, where the principal ray intersects the perpendicular plane containing the eye-point, is found by moving along the principal ray a distance, $dplane$, determined from a pinhole camera equation. The viewpoint ($pview$) is found by moving away from the intersection point in the u and v directions, based on the offset of the eye-point in the captured image relative to the image center.

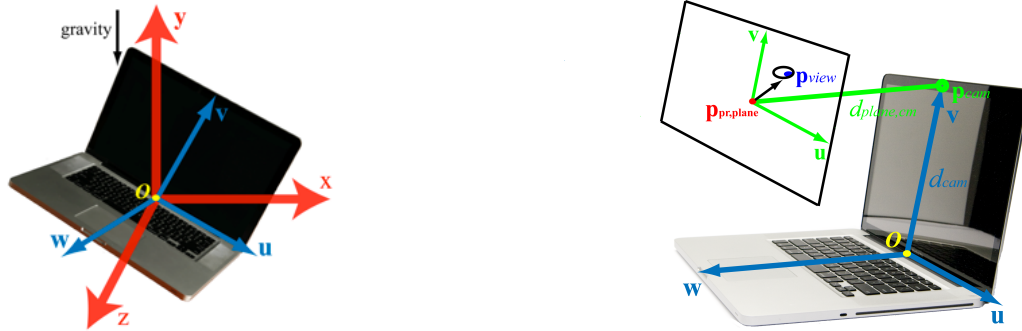


Figure 2: (left) Orientation tracking: The xyz axes define a world coordinate system that is fixed with respect to gravity. The uvw axes define an object space coordinate system that is fixed with respect to directions on the screen. (right) Viewpoint tracking: The observer's viewpoint (p_{view}) is defined in a coordinate system constructed relative to the uvw axes of the screen. The three-dimensional position of the viewpoint is found with reference to head-tracking information provided by the system's camera.

Orientation tracking

The orientation-tracking module provides real-time data on how the screen of the tangible display system has been tilted or rotated by the user. In the tangiBook system, tracking was implemented using the triaxial accelerometer in the laptop's Sudden Motion Sensor (SMS) and the open source SMSLib²⁴ 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).

While it is convenient to use triaxial accelerometers for orientation tracking because they incorporated as standard equipment in a range of devices, they do have an important limitation. Because they detect orientation relative to gravity, they are not able to detect rotations of the display around the vertical. Thus an accelerometer can detect if the display is tilted backward or rotated upside-down, but cannot detect when it is turned to face in a new compass direction. This limitation is partially overcome by viewpoint-tracking because turning the display will result in changes in the observer's viewing direction relative to the screen. A better solution is to use the gyroscopic trackers that are beginning to be incorporated in mobile devices that can signal rotations around all three principal axes.

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 surface reflections that should be rendered on the virtual object. In the tangiBook system, observer position was tracked using the laptop's built-in webcam and image-based head-tracking. The location of the head in the camera image stream, along with information about the camera's physical orientation and position determined from orientation tracking, were used to estimate the position of the observer's eye-point in world coordinates. Head location was determined using the Haar cascade algorithm in the OpenCV²⁵ library. The head radius was used to estimate the approximate viewer-to-screen distance. The location of the eye-point was estimated by adding an offset to the head center location. Finally, 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.

3.3 Surface modeling and rendering

The modeling and rendering component of tangible display systems uses information collected by the tracking component to render a realistically shaded view of a virtual surface to the screen. It includes custom software that integrates the tracking information into the rendering process and 3D shaders that support real-time rendering of complex surfaces using image-based lighting.

Surface modeling

The surface modeling component incorporates three kinds of modeling to simulate virtual surfaces: polygonal geometry to define the overall shape of the surface, normal maps to provide small scale surface texture, and BRDF models to represent material properties.

To allow the virtual surface to be manipulated like a real surface, it is modeled in the world coordinate system as a rectangle with the size and orientation of the physical display. The normal for this rectangle is set to the w -axis direction: the real normal to the physical display. Spatially varying normal maps are then used to modulate this surface normal to simulate mesoscale texture.²⁶ Surface reflectance properties are specified using a set of maps where each element represents one of the three components of the Ward BRDF model²⁷: ρ_d (diffuse reflectance), ρ_s (specular reflectance), and α (surface roughness). These parameters are specified in three channels each 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 realistically render an image of a surface with its specified material properties and texture. Our current shader is based on the isotropic Ward model shader described by Rost²⁸:

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

where ρ_d , ρ_s , and α are as specified above, 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. All shading calculations are performed in the xyz world coordinate system.

In the rendering pipeline, display orientation information from the tracking module is used within the vertex shader to update the position of the surface as the display is rotated. Viewing position information 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 information. 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.²⁹ To determine surface lighting, 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 environment map to find the light color for those directions. The contribution of each direction is weighted by its value in the Ward model and added to the diffuse lighting to determine the final color at each surface point. Due to the sparse sampling of the specular lobe, the reflections calculated using this technique might not be accurate enough for certain applications. In this case, a discrete set of colored point lights can be used.

4. SYSTEM CAPABILITIES

The goal of creating tangible display systems is to produce rich visual representations of complex surfaces that can be interacted with like real surfaces. The system components described in the previous section provide the functionality necessary to support this goal. The following sections describe some of the unique capabilities of tangible displays.



Figure 3: Image sequence showing a painting model being displayed on the tangiBook. The tangiBook 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 laptop (as shown) or moving in front of the screen produces realistic changes in surface lighting and material appearance.

4.1 Direct manipulation

As shown in Figure 3 (top), tangible displays support direct manipulation of virtual surfaces. The image sequence shows a model of an oil painting rendered and displayed on the tangiBook system. As the user tilts the display, the shading and reflections on the surface are updated in real-time and change the way the real surface would in the given lighting environment. This capability provides a compelling visual experience of the surface and also allows users to better understand surface texture and material properties through the dynamic and coordinated visual feedback produced by their manipulations.

4.2 Dynamic viewing

Tangible displays can also provide richer experiences of surfaces through the visual feedback produced by user movement. Figure 3 (bottom) shows an image sequence where the user is moving from left to right in front of the oil painting model rendered and displayed on the tangiBook system. Note how the surface shading and highlights in the image change in concert with the users movement just as they would for a real surface. This capability also contributes to the visual experience and allows users to better understand surface texture and material properties through the visual feedback produced by their own movement.

4.3 Dynamic control of material properties

Finally, tangible displays provide a capability that is not possible with real surfaces: changing surface texture and material properties under user control. Because the imaged surface is virtual, by changing its underlying model it is possible to change its appearance. Figure 4 shows a pair of images of the oil painting model rendered on the tangiBook, and an interface has been called up that allows real-time control over surface material properties. By dragging the sliders the user can vary the ρ_d , ρ_s , and α Ward model parameters of the surface, producing the observed changes in surface gloss. Similar capabilities exist for changing surface texture. This functionality goes beyond reproducing the appearance of captured/modeled surfaces and opens possibilities for using tangible displays for surface and material appearance design.

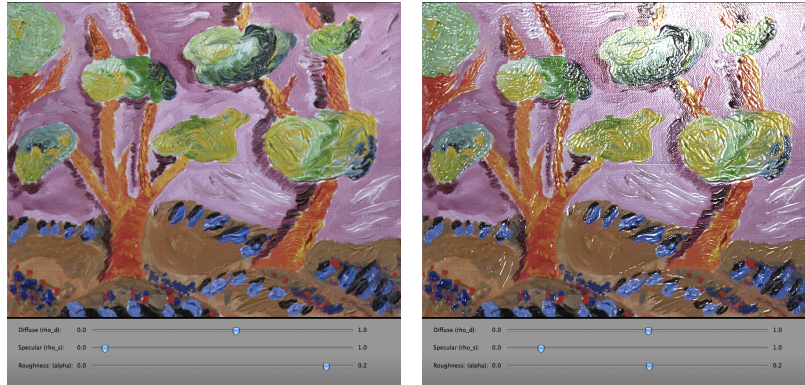


Figure 4: Dynamic control of material properties: The two renderings of the painting illustrate the tangiBook's ability to dynamically change the material properties of a displayed surface. The surface on the left has a relatively low specular reflectance (ρ_s) and a high roughness (α) giving a matte appearance. Using the sliders, these two parameters have been altered in the surface on the right to produce glossy reflections.

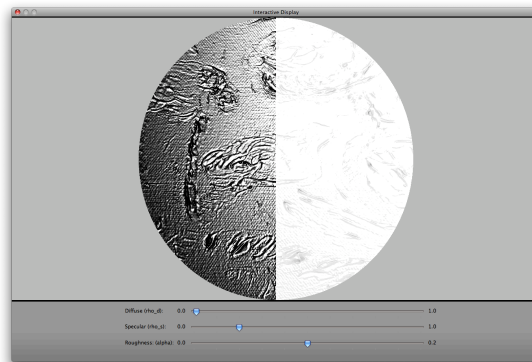


Figure 5: Psychophysics of material appearance. The screenshot shows how tangible displays can be used to study the effects of color on gloss perception. The left and right patches of the target have the same physical gloss properties (ρ_s and α) but differ in perceived gloss. The observer's task is to change the Ward parameters of the left patch until the two match in apparent gloss.

5. APPLICATIONS

The unique capabilities of tangible displays should enable a wide variety of applications where natural interaction with virtual objects is desired. In the following section we provide examples of four potential application domains: the psychophysical study of material appearance, computer-aided appearance visualization and design, enhanced access to digital library and museums, and new tools for digital artists.

5.1 Psychophysics of material appearance

Understanding the psychophysics of material appearance has important implications for both basic science and for industry³⁰⁻³². A major impediment to material appearance research has been the difficulty of creating physical stimuli that vary systematically in the properties of interest. Recently, the study of material appearance has been facilitated by the use of realistic 3D computer graphics^{33,34}, however a significant limitation of computer-based studies is that images on a screen typically do not support the natural modes of interaction that one uses when evaluating real surfaces and materials. Another limitation is the inability to dynamically control material properties, which has prevented the use of adjustment and matching procedures in experiments. Both of these limitations can be overcome with tangible displays.

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 reflections³¹. Figure 5 shows a screen shot from a psychophysical experiment designed to

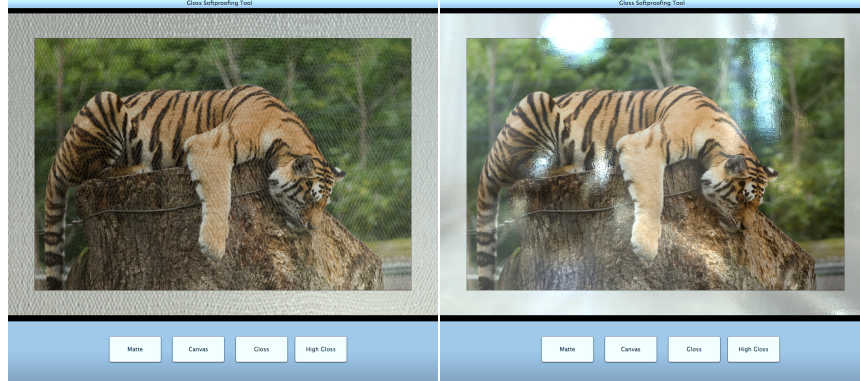


Figure 6: Soft-proofing: The images illustrate a photographic soft-proofing application. Buttons in the interface allow an image to be proofed on simulated photo papers with different colors, textures, and gloss levels (canvas (left) and high gloss (right), respectively).

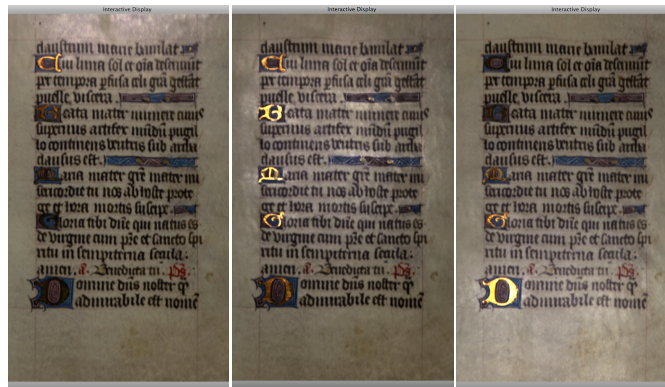


Figure 7: A virtual illuminated manuscript: The images show sections from a manuscript model rendered on a tangible display. Note how the highlights in the gold leaf and vellum change from the left image to the right image as the display is tilted.

investigate this phenomenon using the tangiBook. The two patches of the central target have the same physical gloss properties (Ward ρ_s and α), yet differ in apparent gloss due to differences in their diffuse reflectances (ρ_d). Running the experiment on a tangible display allows an observer to tilt the surface and observe it from different viewing positions, while interactively varying ρ_s and α to produce a visual gloss match. These capabilities enable a greater level of naturalness and control in computer-based experiments.

5.2 Softproofing and 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^{35,36}. Recently, soft-proofing systems have started to model the glossiness of photographic prints and render them in 3D graphics simulations^{37,38}. The simulated images are mapped to 3D planes and shown as objects on a standard display system. Interactivity is sometimes provided through Quicktime VR sequences created in an offline process.

Figure 6 shows a prototype of an interactive soft-proofing system implemented on the tangiBook system. In addition to selecting 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 tangible displays should enhance the utility of soft-proofing applications. More broadly, tangible displays could provide important functionality for the emerging field of Computer-Aided Appearance Design (CAAD) of paints, coatings, and textiles³⁹.

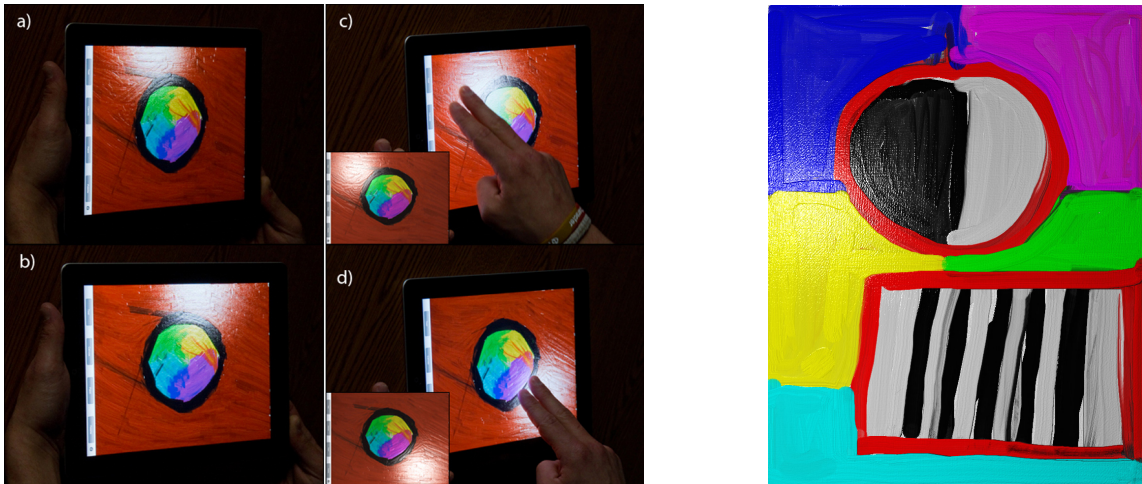


Figure 8: Screenshots of paintings created using the tangiPaint system. Note the gloss and relief of the brushstrokes and the texture of the underlying canvas. The system allows direct interaction with the “painted” surface both in terms of paint application and manipulation of surface orientation and lighting.

5.3 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 through digital images. 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, changes in illumination, and the observer’s own movements. The situation is similar for a wide range of cultural heritage objects.

Tangible displays can be used to provide enhanced access to digital collections of these objects. Figure 7 shows a model of an illuminated manuscript⁴⁰ rendered on the tangiBook. A museum visitor or library scholar could pick up the display, move it around to see the glints off the gold leaf and look at the surface from different angles to see the texture of the vellum. Tangible displays provide a new interface paradigm that supports enhanced access to digital collections. Examples like this suggest the advances in teaching and scholarship that might be possible if digital objects are available that can be viewed, analyzed, and manipulated more like the objects themselves.

5.4 Tools for digital artists

The development of computer-based digital art tools has had a huge impact on a wide range of creative fields. In commercial art, advertisements incorporating images, text, and graphic elements can be laid out and easily modified using digital illustration applications. In cinema, background matte elements can be digitally drawn, painted, and seamlessly integrated with live footage. In fine art, painters, printers, and engravers have also been embracing the new creative possibilities of computer-based art tools. The recent introduction of mobile, tablet-based computers with high-resolution displays, graphics processing units (GPUs) and multi-touch capabilities is also creating new possibilities for direct interaction in digital painting.

However a significant limitation of most digital painting tools is that the final product is just a digital image (typically an array of RGB color values). All the colors, textures and lighting effects that we see when we look at the digital painting are “baked in” to the image by the painter. In contrast, when a painter works with real tools and media, the color, gloss, and textural properties of the work are a natural byproduct of the creative process, and lighting effects such as highlights and shadows are produced directly through interactions of the surface with light in the environment.

We have recently developed tangiPaint³, a new tablet-based digital painting system that attempts to bridge the gap between the real and digital worlds. TangiPaint is a tangible painting application that allows artists to work with digital media that look and behave like real materials. Figure 8 shows screenshots from the tangiPaint application implemented on an Apple iPad2.

In Figure 8a an artist has painted a number of brushstrokes on a blank canvas. Note that in addition to color, the strokes vary in gloss, thickness, and texture, and run out just as if they were real paint laid down with a real brush. The paints also layer and mix realistically as they would on a real canvas.

Figure 8b shows that the system also incorporates the key capabilities tangible display systems. By tilting the device the artist can change the relationship between the digital painting and the virtual light source that illuminates it. This action reveals both the texture of the strokes and canvas and the gloss properties of the paints just as manipulating a real painting would. Figures 8c and 8d show that the artist can also position the light source with a simple hand gesture akin to moving a real light source. The tangiPaint system represents a significant first step toward developing digital painting tools that allow artists to work with digital art media that look and behave like real materials.

6. CONCLUSIONS

In this paper we have described the design, development, and applications of several classes of tangible display systems. The first-generation tangiBook system was based on a standard laptop computer that incorporated a webcam and accelerometer as standard equipment. The tangiDesk system uses a more powerful tower computer, inertial and optical tracking systems, and a large display to achieve high-fidelity rendering and interaction. The tangiPod and tangiPad implementations take advantage of those devices' form-factors, graphics hardware, integral gyroscopes, and touchscreens to provide direct interaction with rich digital representations of complex surfaces.

We have illustrated how tangible displays can be used to advantage in a wide range of applications including psychophysics of material appearance, soft proofing and appearance design, enhanced access to digital collections, and creating new tools for digital artists. The relatively low cost and commodity hardware base of tangible display systems should allow their widespread implementation and application.

Tangible display systems represent a powerful and meaningful new approach to merging the real and virtual worlds. The work described in this paper represents some promising first steps toward realizing this goal.

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