■解説（VISION Vol. 22, No. 1, 49–59, 2010）

Envisioning the Material World

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The appearance of materials is of critical importance in many fields, yet formal models of material perception are limited. This paper presents three related projects that leverage the power of computer graphics technology to investigate and quantify material perception.

1. Introduction

Efforts to understand human vision have largely focused on our abilities to perceive the geometric properties of objects and have neglected the perception of materials. However correctly perceiving materials is at least as important as perceiving object geometry, and human vision allows us to tell if objects are hard or soft, smooth or rough, clean or dirty, fresh or spoiled, and dead or alive. Understanding the perception of material properties is therefore of critical importance in many fields. In three sections, this paper presents three related projects that leverage the power of computer graphics technology to investigate material perception. In the first section we describe a series of experiments to develop a psychophysical model of surface gloss that relates the physical reflectance properties of surfaces to their visual appearances. In the second section we introduce the concept of visual equivalence and develop metrics that can predict when two visibly different images are equivalent as representations of object appearance. Finally, in the third section we introduce the tangiBook, a tangible display system that supports natural modes of interaction with virtual objects and materials.

2. A psychophysical gloss model

Color and *gloss* are two fundamental attributes used to describe surface appearance. Color is related to a surface's *spectral* reflectance properties. Gloss is a function of its *directional* reflectance properties. Many models have been developed for describing color, from simple RGB, to the more sophisticated Munsell, XYZ, and CIELAB models that have grown out of the science of *colorimetry*. Colorimetric models make it easier to describe and control color because they are grounded in the psychophysics of color perception. Unfortunately similar psychophysically-based models of gloss have not been available.

We have developed a new model of glossy surface appearance that is based on psychophysical studies of gloss perception[1,2]. In two experiments, we have used multidimensional scaling to reveal the *dimensionality* of gloss perception and to find *perceptually meaningful axes* in visual gloss space, and numerical rating to place metrics on these axes and predict *just noticeable differences* in gloss.

Stimuli for the experiments were generated

2009 年夏季大会シンポジウム講演.

using physically-based image synthesis techniques. Our test environment consisted of a simulated painted sphere enclosed in a checkerboard box illuminated by an overhead area light source. Images were rendered with a Monte Carlo path-tracer incorporating an isotropic version of the Ward light reflection model:

$$\rho(\theta_i,\phi_i,\theta_o,\phi_o)=\frac{\rho_d}{\pi}+\rho_s\cdot\frac{\exp[-\tan^2\delta/\alpha^2]}{4\pi\alpha^2\sqrt{\cos\theta_i\cos\theta_o}}$$

where $\rho(\theta_i, \phi_i, \theta_o, \phi_o)$ is the surface's *bi-directional reflectance distribution function* (BRDF) that describes how light is scattered by the surface. In addition to angular dependencies (θ, ϕ, δ), the Ward model uses three parameters to describe the BRDF: ρ_d–the surface's diffuse reflectance; ρ_s–the energy of the specular lobe, and α–the spread of the specular lobe. By setting each parameter to three levels we generated the 27 stimulus images shown in **Fig. 1**.

In the first experiment, subjects viewed pairs of images and judged how different they appeared in gloss. We analyzed these gloss difference judgments with multidimensional scaling to recover the visual gloss space shown in Fig. 1. The figure shows that under our test conditions, apparent gloss has two dimensions related to the *contrast of the reflected image* (c) and the sharpness or *distinctness of the reflected image* (d).

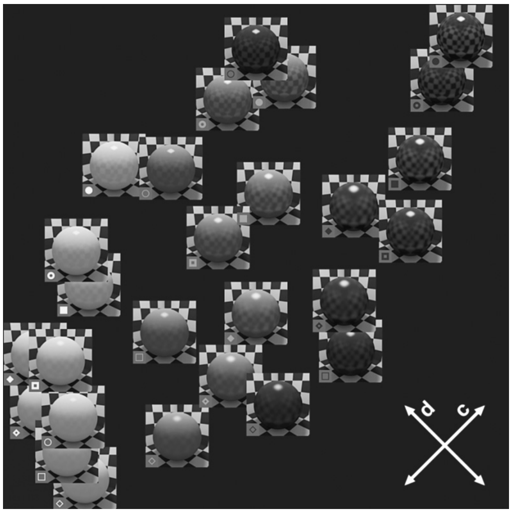


Fig. 1. Visual gloss space with its (c) contrast and (d) distinctness dimensions.

In the second experiment we used a rating procedure to place metrics on these dimensions. Subjects viewed single images from the stimulus set and rated how glossy the objects appeared. We analyzed these ratings with regression techniques to derive metrics for the dimensions that relate changes in apparent gloss to variations in the physical properties of the surfaces

$$c=\sqrt[3]{\rho_s+\rho_d/2}-\sqrt[3]{\rho_d/2}$$
$$d=1-\alpha$$

We used these metrics to rewrite the parameters of the *physically-based* Ward light reflection model in *perceptual* terms. The result is a new *psychophysically-based light reflection model* that relates the physical dimensions of glossy reflectance and the perceptual dimensions of glossy appearance. The following sections demonstrate how the new model can be used to describe and control the appearance of glossy surfaces.

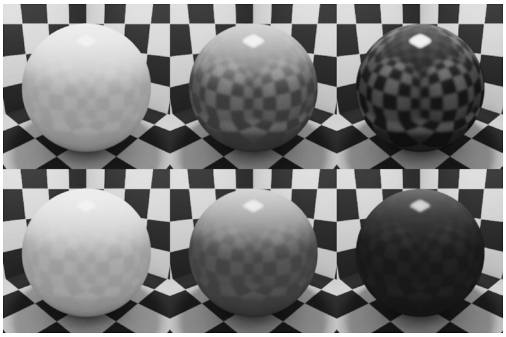


Fig. 2. Matching apparent gloss: white, gray, and black objects having the same physical gloss parameters (top row) and visual gloss parameters (bottom row).

2.1 Gloss matching

Many studies have noted that apparent gloss is affected by a surface's diffuse reflectance. This effect is illustrated in the top row of **Fig. 2** where the white, gray, and black objects have the same physical gloss properties (ρ_s=0.099, α=0.04), but the lighter ones appear less glossy than the darker ones due to differences in contrast gloss. The bottom row of Fig. 2 shows the results produced with our new model. Here the objects have been given the same visual gloss properties (c=0.057, d=0.96), and they appear similar in gloss despite their lightness differences. Using the parameters provided by the new model should make it much easier to create objects that match in apparent gloss.

2.2 Just noticeable differences in gloss

Just noticeable difference (JND) metrics can be used to predict acceptable tolerances in measurement and manufacturing processes. We have attempted to estimate JNDs in gloss for a subset of the surfaces we tested. Our findings indicate: 1) it is harder to see gloss differences in lighter surfaces (high ρ_d) than darker ones (low ρ_d); 2) it is easier to see gloss differences in high gloss surfaces (high ρ_s) than in lower gloss ones (low ρ_s); and 3) for the range of materials we tested gloss differences were constant with respect to α, the spread of the specular lobe. These results may lead to new methods for establishing visual tolerances in the measurement and manufacturing of glossy materials.

2.3 Summary

In many ways this work parallels early studies done to establish the science of colorimetry. We hope it inspires further research toward developing psychophysical models of the goniometric properties of surface appearance to complement widely-used colorimetric models.

3. Visual Equivalence

Measuring image differences is an important aspect of image quality testing, and a variety of metrics have been developed for this purpose. *Numerical metrics* measure physical differences between a reference image and test image. Well known numerical metrics include mean squared error (MSE) and peak signal to noise ratio (PSNR). Although these metrics are easy to compute, they often do not correlate well with observers' judgments of image differences. For this reason, *perceptual metrics* incorporate computational models of human visual processing. In these metrics visual models are used to represent an observer's responses to the reference and test images and then these responses are compared to identify visible differences. Popular perceptual metrics include Daly's Visible Differences Predictor (VDP) and the Lubin/Sarnoff model. These metrics typically do a better job at predicting perceived image quality. However current perceptual metrics have an interesting limitation that is illustrated in **Fig. 3**.

Fig. 3a and 3b show two computer-generated images of a tabletop scene. Fig. 3a was rendered using path tracing, a physically accurate but computationally intensive graphics algorithm. Fig. 3b was rendered using environment mapping, a fast but approximate rendering algorithm that uses an image of the surround rather the surround itself to illuminate the objects on the tabletop. One consequence of environment mapping is that illumination features such as surface reflections are warped. This can be seen by comparing the images reflected by the two teapots.

If we take the path traced image as the reference, and the environment mapped image as the test, and process the images with Daly's

a) Path traced image b) Environment mapped image c) visible differences map

Fig. 3. a, b) Computer graphics images rendered with different reflection algorithms and c) the output of a VDP metric showing areas of visible difference. Note that while the images are visibly different, they are similar in quality, and convey equivalent information about object appearance.

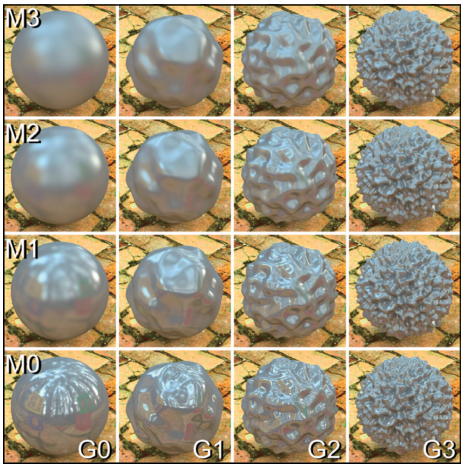


Fig. 4. The geometries and materials of the objects used in the experiments. Parameters were chosen to be perceptually uniform in both surface "bumpiness" and surface reflectance.

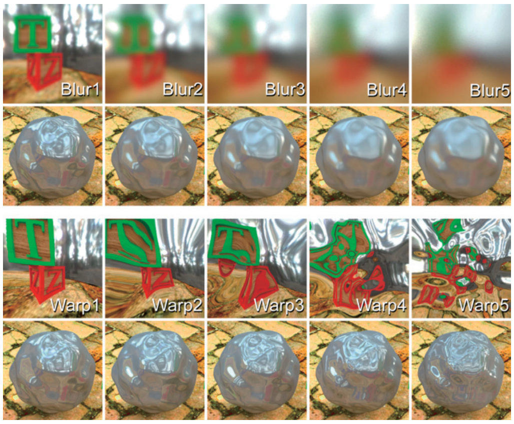
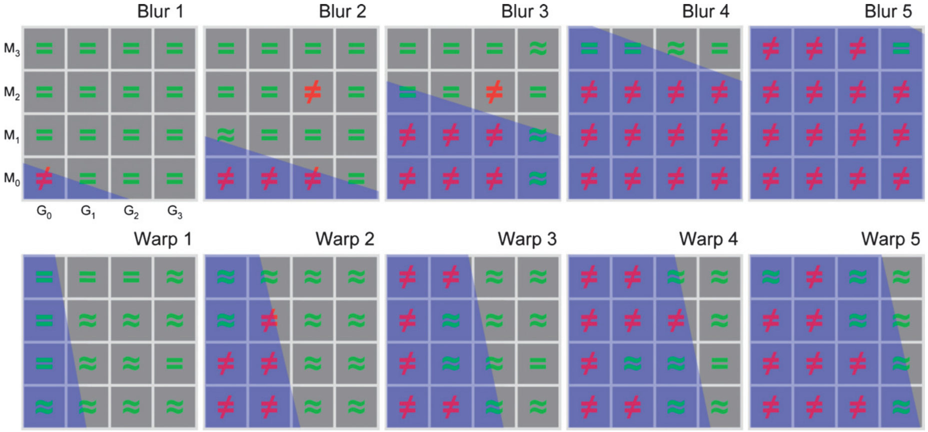


Fig. 5. The two classes of illumination transformations used in the experiments (blur and warp). The upper and lower panels show direct views of the blurred and warped illumination maps and their effects on the appearance of a representative object (G1/M0).



Blur 1

	G_0	G_1	G_2	G_3
M_3	=	=	=	=
M_2	=	=	=	=
M_1	=	=	=	=
M_0	≠	=	=	=

Blur 2

	G_0	G_1	G_2	G_3
M_3	=	=	=	=
M_2	=	=	≠	=
M_1	≈	=	=	=
M_0	≠	≠	≠	=

Blur 3

	G_0	G_1	G_2	G_3
M_3	=	=	=	≈
M_2	=	=	≠	=
M_1	≠	≠	≠	≈
M_0	≠	≠	≠	≈

Blur 4

	G_0	G_1	G_2	G_3
M_3	=	=	≈	=
M_2	≠	≠	≠	≠
M_1	≠	≠	≠	≠
M_0	≠	≠	≠	≠

Blur 5

	G_0	G_1	G_2	G_3
M_3	≠	≠	≠	=
M_2	≠	≠	≠	≠
M_1	≠	≠	≠	≠
M_0	≠	≠	≠	≠

Warp 1

	G_0	G_1	G_2	G_3
M_3	=	=	=	≈
M_2	=	≈	≈	≈
M_1	=	≈	≈	=
M_0	≈	≈	≈	≈

Warp 2

	G_0	G_1	G_2	G_3
M_3	≈	≈	≈	≈
M_2	≈	≠	≈	≈
M_1	≠	≠	≈	≈
M_0	≠	≠	≈	≈

Warp 3

	G_0	G_1	G_2	G_3
M_3	≠	≠	≈	≈
M_2	≠	≈	≈	≈
M_1	≠	≈	≈	=
M_0	≠	≠	≈	≈

Warp 4

	G_0	G_1	G_2	G_3
M_3	≠	≠	≈	≈
M_2	≠	≠	≠	≈
M_1	≠	≈	≈	=
M_0	≠	≠	≈	≈

Warp 5

	G_0	G_1	G_2	G_3
M_3	≈	≠	≈	≈
M_2	≠	≠	≈	≈
M_1	≠	≠	≠	≈
M_0	≠	≠	≠	≈

Fig. 6. Results of the experiments: Each panel represents the objects tested (G0–G3, M0–M3) (see Fig. 4). The upper and lower strips show the results for different levels of the blur and warp illumination transformations. Overall the results fall into three categories: equality, non-equality, and equivalence.

VDP, it produces the difference map shown in Fig. 3c which correctly indicates that the images *are* visibly different (green and red pixels 75% and 95% probability of detection respectively). However a key question is: *are these meaningful image differences?*

When we look at images we don't see pixels. Rather, we see objects with recognizable shapes, sizes, and materials, at specific spatial locations, lit by distinct patterns of illumination. From this perspective the two images shown in Fig. 3 are much more similar than they are different. For example, the shapes, sizes, materials and locations of the objects appear the same in both images, and the scene lighting looks the same. Although the images are *visibly different* they are *visually equivalent* as representations of object appearance. The existence of images like these has prompted us to develop a new kind of image difference/quality metric that can predict when different classes of image transformations produce images that are visually equivalent[3,4].

3.1 Experiments

An object's appearance is based on the images it reflects to our eyes, and these images are determined by the object's geometry, material, and illumination properties. To begin to quantify the phenomenon of visual equivalence we decided to study image equivalence across two kinds of illumination transformations (blurring and warping) for objects with different geometric and material properties.

Stimuli: We first created a set of computer graphics stimulus images that would allow us to systematically explore the visual interactions between object geometry, material, and illumination. **Fig. 4** shows representative images from our stimulus set which showed a bumpy ball-like test object on a brick patio flanked by two pairs of children's blocks. The four object geometries (G0–G3) were judged in pre-testing to be equally spaced with respect to surface "bumpiness". The four materials (M0–M3) represented rolled aluminum with different degrees of microscale roughness.

Since recent studies have demonstrated the importance of real-world illumination for the accurate perception of shape and material properties we lit our model using Debevec's "Grove" HDR environment map that captures the illumination field in the Eucalyptus grove at UC Berkeley. We chose this map in particular, because Fleming et al[5]. found that it allowed subjects to most accurately discriminate material properties. Starting with the original "Grove" map as the reference then generated two sets of transformed maps (blurred, warped). The top two rows in **Fig. 5** show the five levels of the blurred map set and its effect on the appearance of the G1/M0 object. The third and fourth rows show the warped map set and its effect on the same object.

Images were rendered at 484×342 as high dynamic range (HDR) floating point images using a custom-built physically-based Monte Carlo path tracer. The HDR images were tone mapped using a global sigmoid tuned to the characteristics of the display. Each image subtended approximately 12 degrees of visual angle.

Procedure: The images in the stimulus set were presented to subjects in pairs. In some conditions a third reference image was shown above the test pair. *In all cases the test pairs showed objects with identical shapes and material properties* (the G/M combinations shown in Fig. 4). In each case one of the images was rendered using the reference illumination map, and the other was rendered using one of the transformed maps (Blur1-5 or Warp1-5 as shown in Fig. 5). An experiment consisted of four related tasks/questions asked about the image pairs.

"Which test image is the same as the reference image?" The intent of this task was to determine when images rendered with the transformed maps were visibly different (in the VDP sense) than images rendered with the reference map.

"Are the left and right test objects the same shape?" The intent of this task was to determine if the transformed maps produced illusory changes in the apparent shapes of the objects.

"Are the left and right test objects made of the same material?" The intent of this task was to determine if the transformed maps produced illusory changes in the apparent material properties of the objects.

"Which test object is lit the same as the reference object?" The intent of this task was to determine if subjects could use surface reflection patterns to detect differences in scene illumination.

Overall 15 subjects (ages 20 to 50) participated in the experiments. Some had technical backgrounds, but none in imaging. All were naive to the design and purpose of the experiments and had normal vision.

Note that the four tasks can be divided into two conceptual categories. In the image difference task subjects are being asked to report on detectable *image* differences. In the shape, material, and illumination difference tasks subjects are being asked to report on detectable *object* differences. We chose these tasks because they should allow us to dissociate the effects of image differences on image and object appearance and quantify when different configurations of object geometry, material and illumination produce images that are visually equivalent.

Results: The results of the experiments are summarized in **Fig. 6**. Each panel shows the set of objects we tested (G0–G3, M0–M3), and the upper and lower strips show how observer's judgments changed for different levels of illumination map blurring (Blur1-5) and warping (Warp1-5). The results fall into three categories. In general green symbols are good and red symbols are bad.

Equal: When subjects reported that the reference and test images were indistinguishable we said that the images were equal (green equal signs in Fig. 6). Note that for low levels of blur the image differences were often undetectable and the images appeared identical.

Not-Equal: On the other hand when subjects reported that the reference and test images were visibly different, and also reported that the objects also looked different we labeled the images as not equal (red signs in Fig. 6). Note that the number of non-equal cases increases monotonically with the magnitude of the blur and warp transformations.

Equivalent: Finally, when subjects reported that the reference and test images were visibly different but also said that the objects represented by the images appeared the same (same geometry and material, no clear differences in illumination) we labeled the images as equivalent. Note that while there are few equivalent cases for the blur transformation, there are cases of equivalence at all levels of the warp transformation, even the most severe.

What these results show is that there is a significant class of conditions (indicated by green symbols) where the images rendered with the transformed illumination maps are either equal or equivalent as representations of object appearance. While existing visible difference metrics (VDPs) could predict the cases of equality, they would not identify the much larger set of visually equivalent images.

3.2 Visual equivalence predictor (VEP)

To take advantage of this newfound latitude in perceptually acceptable image distortions we developed a new kind of image metric: the *visual equivalence predictor* (VEP)

To achieve this we first used Support Vector Machines to classify the experimental results into “good” and “bad” categories. The classification planes are illustrated by the blue-shaded regions in Fig. 6.

We now have a predictor that can determine visual equivalence for the images in our test set. To be useful however, we need be able to predict equivalence for images of novel objects and scenes. For novel geometries we characterized the average surface normal variation for the objects in our test set (G0–G3) and mapped the normal variations of new objects into this space. For novel materials, we fit surface reflectance data with the Ward light reflection model and cast the parameters into our M0–M3 material space. Finally for illumination, our only requirement is that the illumination field have “natural” image statistics ($\sim 1/f^2$ power spectrum).

To test the predictive power of the VEP, we ran a confirmatory experiment where we created reference and test images of 14 novel scenes, ran them through the predictor and also had subjects judge them using the same procedure used in the main experiment. Ten new subjects participated. The VEP correctly predicted the result in 13 out of 14 cases (being overly conservative in one case), and was able to predict both equivalence and non-equality. Selected results are shown in **Fig. 7**.

3.3 Summary

In this project we have introduced a new foundation for image difference/quality metrics: visual equivalence. Images are visually equivalent if they convey the same information about object appearance even if they are visibly different. We believe that visual equivalence is a novel approach to quantifying image quality that goes significantly beyond existing metrics by taking advantage of the limits of visual coding of object appearance and leveraging the fact that some classes of image differences do not matter to human observers.

4. Tangible display systems

When an observer interacts with an object to examine its shape and surface properties they typically engage in a complex set of behaviors that include active manipulation and dynamic viewing. These behaviors allow the observer to experience how the object looks from different viewpoints and under different lighting conditions, and provide rich visual information about object shape and surface properties.

Modern computer graphics has the ability to accurately simulate the shapes and surface properties of complex objects, and object design and analysis in a wide range of applications that include film and gaming, computer-aided design and manufacturing, medical imaging, and digital libraries and museums. However in typical interactive graphics systems the observer is one step removed from the object they are observing. The display screen serves as a window onto a virtual world, and the object is manipulated indirectly through mice, joysticks, trackballs or similar devices.

Our goal in this project is to develop a *tangible display system* that combines the power of computer graphics object modeling and rendering techniques with the rich and natural modes of interaction that we have with physical objects in the real world[6)].

Our solution is a system we call the *tangiBook* (for tangible MacBook) that is based on an off-the-shelf Apple laptop computer that

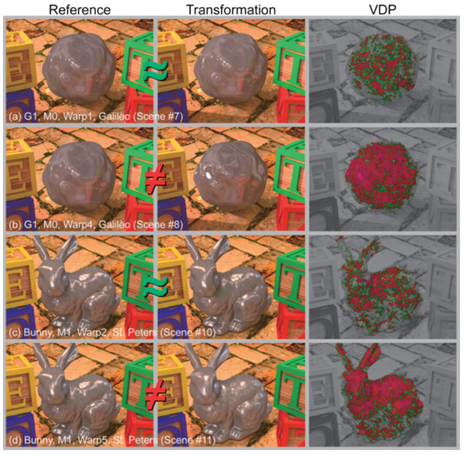


Fig. 7. Selected images from the validation experiment. The reference images (left), test images (middle), visible difference (VDP) maps (right). Symbols on each image pair indicate whether they were seen/predicted to be visually equivalent despite being visibly different.

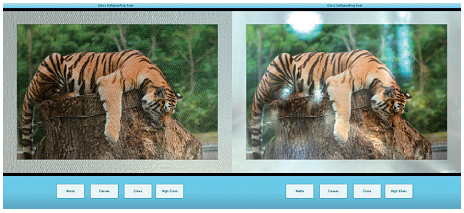
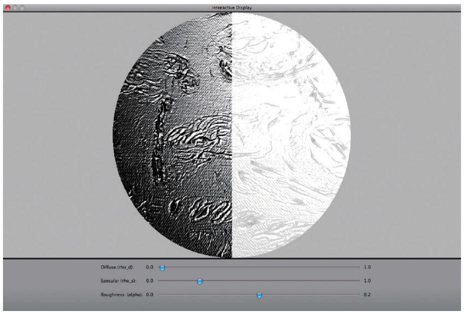


Fig. 10. Softproofing using the tangiBook.



Diffuse (rho_d): 0.0 1.0
Specular (rho_s): 0.0 1.0
Roughness: (alpha): 0.0 0.2

Fig. 9. TangiBook used to explore the psychophysics of material appearance.

Fig. 11. An illuminated manuscript visualized on the tangiBook. (model courtesy of Paul Debevec)

Fig. 8. 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.

incorporates a triaxial accelerometer and a webcam as standard components. Through custom software we have developed that accesses these devices, we are able to actively sense the orientation of the laptop's display and dynamically track the observer's viewpoint. This information is then used to drive a custom physically-based rendering algorithm that generates accurately oriented and realistically shaded views of a virtual surface to the laptop's display. Through the integration of these components the tangiBook allows the user to interact with the virtual surface in the same ways that they can with a real surface, with the added benefit of being able to change the material properties of the virtual surface in real-time. The capabilities of the system are illustrated in **Fig. 8**.

4.1 Applications

The unique capabilities of the tangiBook should enable a wide variety of applications where natural interaction with virtual objects is desired. In the following sections we provide examples of three potential application domains: psychophysical study of material appearance, soft proofing of digital prints, and enhanced access to digital library and museum collections.

Psychophysics of Material Appearance: Understanding the psychophysics of material appearance has important implications for both basic science and industry. 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 to create and display physically accurate simulations of objects and scenes with complex geometries, materials and illuminations. However computer-based studies typically do not allow for natural modes of interaction, such as direct manipulation and differential viewing, when evaluating material properties. 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 the tangiBook.

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. **Fig. 9** shows a screen shot from a sample psychophysical experiment designed to investigate this phenomenon using the tangiBook. The two patches of the central target have the same physical gloss properties (specular energy and roughness), yet differ in apparent gloss due to differences in diffuse reflectance. The tangiBook allows an observer to tilt the surface and observe it from different viewing positions, while interactively varying the surface parameters to produce a visual gloss match. These capabilities enable a greater level of naturalness and control in computer-based experiments of material appearance and should lead to a deeper understanding of material perception.

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. Recently such soft-proofing systems have started to model the glossiness of photographic prints and render them in 3D graphics simulations. **Fig. 10** shows a prototype of an interactive soft-proofing system implemented on the tangiBook. 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 geometries. The real-time control and natural interactivity provided by the tangiBook should enhance the utility of soft-proofing applications. More broadly, the system provides important functionality for Computer-Aided Appearance Design (CAAD) of paints, coatings, and textiles.

Digital Libraries and Museums: Digitization has had an enormous impact on libraries and museums. Manuscripts, paintings, and other collections that were only accessible by physical visit, 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, 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 the texture and reflectance properties of the materials used, the environmental illumination, and the observer's own movements. The situation is similar for a wide range of cultural heritage objects.

The tangiBook can be used to provide enhanced digital access to collections of these objects. **Fig. 11** shows an example of a digital model of a page from an illuminated manuscript. 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. The tangiBook provides a rich, tangible interface that allows direct access to digital collections and should enable advances in teaching and scholarship that follow from having digital objects that can be viewed, analyzed, and manipulated like the objects themselves.

4.2 Summary

Tangible interfaces offer a powerful and meaningful approach to merging the real and virtual worlds. The availability of commodity hardware with multimodal input, sensing, and display capabilities provides new opportunities to create tangible display systems for a wide variety of important applications. The tangiBook represents some promising first steps in this direction.

5. Conclusion

This paper has surveyed three projects that leverage the power of computer graphics to explore and model material appearance. There is still much work to be done, but the projects outline a research program of physical measurement, computer graphics modeling and rendering, and psychophysical experimentation that should both deepen our understanding of material perception and lead to new graphics, imaging, and display technologies that can efficiently produce realistic representations of complex surfaces and scenes.

Acknowledgements: This work was supported by National Science Foundation grants NSF IIS-0113310 and NSF CCF-0811032 to James Ferwerda.

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