Material and Color Design Using Projectors

Jonathan Konieczny and Gary Meyer
University of Minnesota, Department of Computer Science and Engineering, Digital Technology Center
Minneapolis, Minnesota, USA

Abstract

A novel front projection system is introduced for the purpose of material and color design. The system explores techniques for simulation of color on real objects lit by projectors. Choice of size, shape, and color of the target projection object is considered. Ambient lighting conditions are controlled, and a second projector is used as the light source. This permits the target projection object to be "cut out" from the light source, allowing for a realistically lit scene without "washing out" the simulated color. The surrounding environment is captured using high dynamic range environment maps in order to realistically simulate glossy materials. Metallic colors are emphasized, but the principles and conclusions also extend to the simulation of other materials.

Introduction

Recent advances in computer graphics hardware have made it possible to accurately simulate the color appearance of an object in real time. The pixel shading hardware that facilitates this can be programmed to model complex surface reflection properties, and these "shaders" can be modified in real time to change the color of the object. The result of this important development is that new paints and coatings can be designed using a computer graphics program without having to fabricate a prototype [8]. One of the limitations of this approach is that the color appearance must be evaluated by looking at a two dimensional picture on an LCD or a CRT monitor. It is well known that there are differences in judgments made while looking at an image of an object rather than observing the actual artifact itself.

This paper describes research that has been done to provide the user with a simulation that corresponds more closely to viewing a real object instead of a picture of that object. The goal is to show the user a simple practical setup: a three dimensional shape sitting on a table illuminated by a single light source. The color appearance of the object is determined by the reflection properties specified for its surface and the position of the light source. The object must exhibit a correctly located specular highlight, and it should reflect the environment that surrounds it. If the light source or the observer's position change the simulation should be modified accordingly.

The simulation of a real object with the desired color appearance is achieved by "painting" the surface of the object with light from a video projector. The desired reflection properties for the object are determined by employing an interactive automotive paint design program. Using the light source position and the requested surface reflectance a shading calculation is performed. An image is computed and projected onto the surface so that the object assumes the correct appearance. A second video projector that displays light on surrounding surfaces, but not on the object itself, is used to introduce the effect of the light source. High dynamic range photography and environment mapping techniques are employed to simulate the reflection of the surrounding environment on the object. Tracking the observer's position permits
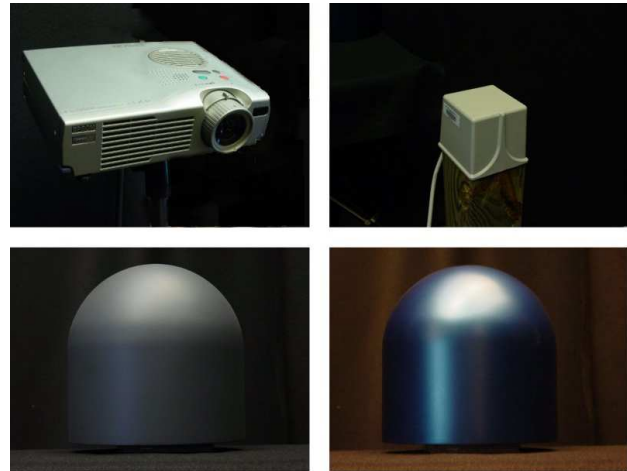

Figure 1. *The system setup: Projectors (top left) are used both to project a desired color onto a neutrally colored shape (bottom left), as well as to provide lighting for the environment (see Figure 3). A magnetic tracker (top right) is used to input the user's viewpoint as well as the light source position. A pre-painted shape (bottom right) is used for comparison and calibration between real paint and the simulated colors*

the color appearance and environmental reflections to be updated as necessary.

The work reported in this paper introduces several important advances in using video projectors to paint color appearance onto three dimensional objects. First, an accurate surface reflection model for metallic paints is used. This makes it possible to perform direct comparisons between the simulations and a real painted object. Second, an interactive program is employed to adjust the surface reflection properties. The result is that the system can function as a paint and surface coating design tool. Third, the color of the object was carefully chosen for video projection. This made it possible to render specular surfaces like automotive metallics. Fourth, high dynamic range photographs were used to simulate surface reflections from surrounding environments. This is important for accurately modeling high gloss surfaces. Finally, a second projector was used to include the effect of the simulated light source on the surfaces that surround the object. This insures that the appearance of the object is consistent with its environs.

Relevant Work

The concept of using projectors to provide material properties for objects was introduced by Raskar et al [6]. Raskar's paper describes the techniques required for projection onto non-planar objects, in addition to accounting for separation of user and rendering viewpoints. The work reported here builds on these basic concepts.

Yamamoto et al. [9] have also proposed using projectors to perform color matching. In this paper, a single projector was
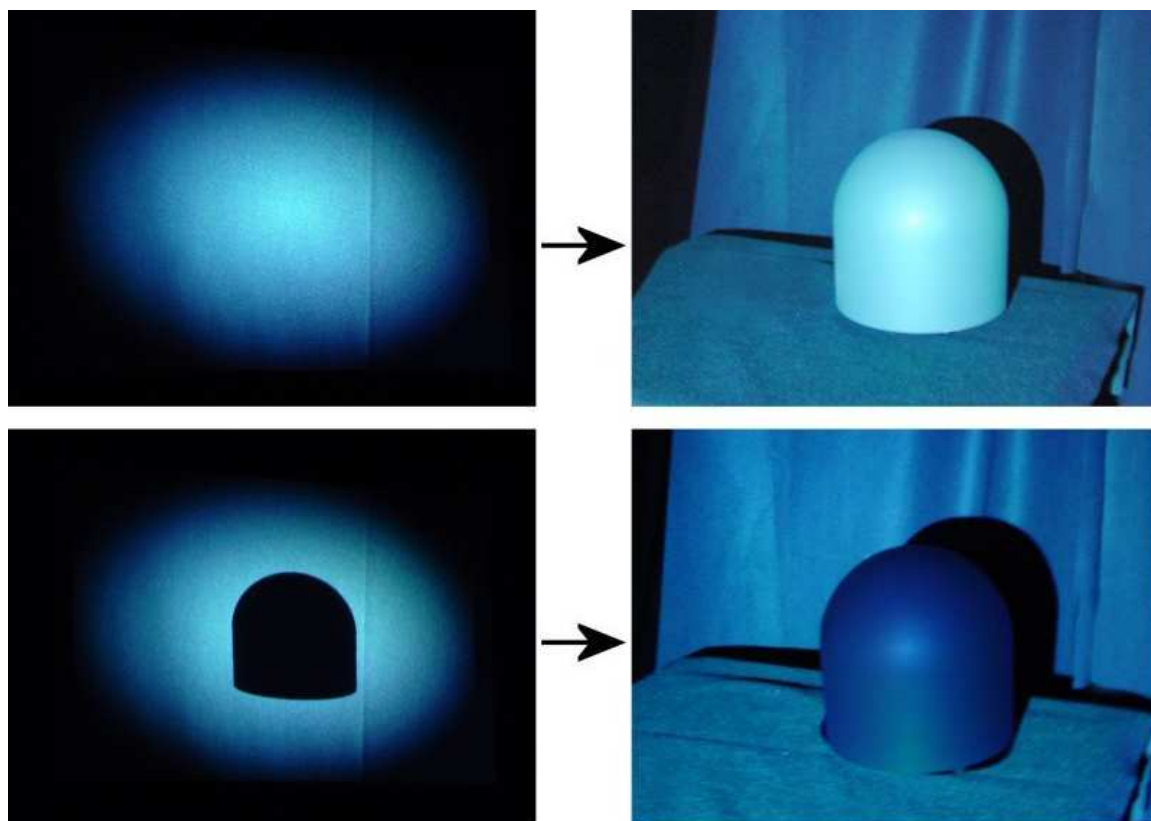
Figure 2. *Top Left: A projector is used as a light source Top Right: The result of the top left image when used on the neutrally colored shape shown in Figure 1. Note how the shape is brightly lit by the emitted light. Bottom Left: The same light pattern as before, but with the shape being "cut out" from the lit area Bottom Right: The result of the bottom left image when used on the shape. The shape is now only slightly lit by the source source, preventing the simulated color from being washed out.*

used to simulate a flat color, as well as a single specular highlight on a curved object. However, color matching was not combined with gloss simulation, and the environment was not taken into account (only a single specular highlight created by a light source was simulated). Our system combines color and gloss, simulates real material properties instead of just single diffuse colors, and does this in conjunction with an interactive design tool.

The environment acquisition technique used in this paper was pioneered by Debevec [1], in which pictures of a reflective sphere are taken with different exposure times and compiled together to form a single high dynamic range photograph. This technique is used for environment capture in this paper.

Basic Setup and Projection

Our basic system setup is similar to that given by Raskar et al. in "Shader Lamps [6]." First, a projector is calibrated to a target object. Then the image is pre-warped to account for distortion caused by projection onto a non-planar object [5]. For the setup presented in this paper, the object is placed at the projector's minimum focal distance in order to achieve the highest possible pixel resolution on the object. In addition to this, the projector's minimum focal distance is reduced by adding another lens. This allows a high number of pixels to be projected onto a small target area for the best possible image quality.

The user's viewpoint is tracked using a magnetic tracker and a virtual light position is input to the program (if desired, the light position can be tracked as well). This allows for correct viewpoint dependant lighting effects.

For color simulation, the current system uses a metallic color design program introduced by [8]. This program both simulates the metallic color, and allows the user to dynamically alter the color.

Projection Based Lighting

Since the goal of this research is to present the user with a visually convincing reproduction of a desired material, it is important to prevent external light from interfering with the simulated color being projected onto the object. Therefore, ambient lighting must be kept to a minimum. We do this by placing the setup in a room that is covered in black felt. This reduces the ambient light to a minimum.

A traditional light source cannot be used to illuminate the object and its surroundings because it would "wash out" the projected color. However, without lighting the object's environs the object appears to "glow" in a manner that is not consistent with its surroundings. In order to correct this problem, a second projector is used as the light source. Employing a second projector for this purpose permits realistic lighting on the surfaces next to the object while the object itself is "cut out" from the lit area. In addition, the amount of light emitted by the projector can be very tightly controlled. This allows for the brightness of the simulated color to be calibrated precisely with the actual emitted light of the "light source" projector. This gives a convincing illusion of the object being lit by the light source projector. Secondary scattering from this light source is kept to a minimum by the black felt mentioned above.

The use of a second projector is a critical addition to the system and it solves a fundamental problem with nearly all com-
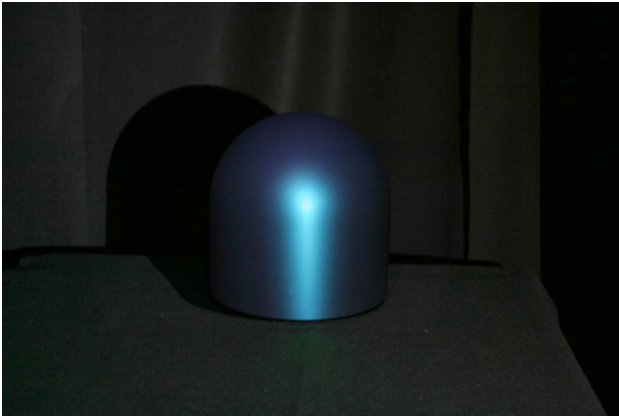
Figure 3. *A projector is used to "paint" a metallic blue color onto the shape shown in Figure 1*

puter graphics: the display showing the simulation is clearly an emissive light source. Since very few materials are actually emissive, perception that the display is emissive eliminates any chance of completely convincing a user that the displayed material is real. Use of a controlled projector light source enables a setup in which the user is unable to determine that an emissive light source is creating the material simulation. The only other method of making this illusion is to completely immerse the user: the user sees nothing but the display. Our method of projector based lighting is a cheaper and more practical solution to this problem, providing the potential to seamlessly add virtual objects to a real environment.

Object Properties

When using a projection system for color design and simulation, the choice of the target projection object is very important. In selecting the object material lightness, it was found that a darker surface gives a more convincing image. Projectors have a certain minimum darkness that they can project, and it is important that this be perceived as black. On the other hand, it was found that the projectors maximum lightness is not as important, except when simulating a specular highlight (see future work section). In addition, by using a light source projector, the incoming light can be calibrated to be within range of the color simulation projector's maximum brightness. Besides being dark, the object is neutrally colored (gray), as this allows the widest

range of possible colors to be simulated.

In addition to object material properties, the shape of the object was also explored. While a correct color simulation could be projected for any object shape, choice of shapes can alter the perception of an object's surface [3]. The first shape used in this system was a cylinder, similar to that currently employed as evaluation samples by car paint companies such as Dupont. However, it was found to be difficult, while using the cylinder, to keep both the specular highlight and a recognizable environment (see simulating gloss section) in view simultaneously. Therefore, the top of the cylinder was replaced with a hemisphere, allowing for the specular highlight and environment to be viewed at the same time.

Simulating Gloss

Gloss is an important part of many materials, including metallic paints. In the case of the paints that are simulated in the current system, a clear coat is added on top of the actual metallic pigment. This adds a specular highlight as well as reflecting the environment around it.

In order to simulate this effect as realistically as possible, we added an artificial environment around the target projection object so that it had something to "reflect." In particular, a checkerboard pattern was placed underneath it. Then high dynamic range photographs were taken of a reflective ball [1]. This ball is placed in the same location as the target projection object. This allows for environment mapping to be used to simulate glossy reflections. This environment map can then be pre-convolved to generate different levels of glossiness to the simulation. See [8] for details.

One limitation of environment mapping on current graphics hardware is that the reflected environment is always assumed to be at infinity. In the case of our current setup - and many real environments - this is not a valid assumption. As the viewpoint alters, the objects that are farther away "move" more rapidly in the reflection than those that are closer. In order to account for this, the system allows a size and center for the cubic environment map to be entered. The environment map lookup in the pixel shader is then altered based on these dimensions to provide a more realistic reflection.

To adjust for the fact that the environment is not infinitely distant, within the pixel shader the environment center is subtracted from the fragment location to find a new origin point for the system. Then, the distance from the origin to each environ-
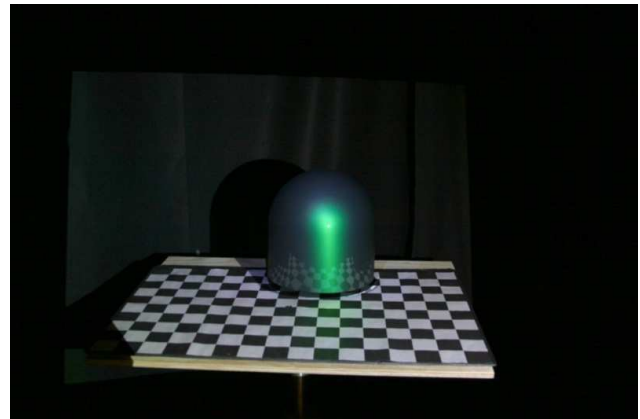

Figure 4. *Environment mapping is added to simulate the appearance of a clear coat. Here, the metallic blue simulation shown in Figure 3 is given a glossy finish.*

Figure 5. *The simulated color is easily adjusted by changing the parameters of the reflection model. Here the shape is used to simulate a glossy green paint.*

Figure 6. *The final system setup: a color simulation projector (left), magnetic tracker (middle), and projector light source (right).*

Figure 7. *The final system in use.*

ment box wall is computed to determine which wall, and where on that wall, the reflection will hit. Based on this, a new reflection vector is calculated and this vector is used by the pixel shader as an index into the environment map. The result is that a visually correct glossy reflection is generated in the simulation for every point of the object.

Future Work

There are several additions to the system that we are currently exploring. One is the importance of stereo to perception of gloss. The current system does not support stereo separation of the two eyepoints, and this could be added to provide further realism.

Another issue we wish to address is the limited dynamic range of the system. The current projectors have limited contrast and brightness. A specular highlight on a glossy image can become very bright in relation to the rest of the object. Lack of this intense highlight can detract from the illusion the system presents. We would like to add a bright focused light source to simulate this specularity. In addition the use of new display technology, such as high dynamic range displays [7], could give better overall dynamic range in the system.

As well as providing higher fidelity in the displayed image, we also wish to increase the interactivity of the system. For instance, the color design program could be placed on a PDA to allow the user to easily walk around the setup and alter or evaluate the color more quickly and interactively.

This system is also capable of providing compelling simulations of materials other than the currently used metallic paints. One particular field we would like to explore with this system is that of architectural material design and simulation. Bidirectional Texture functions (or similar methods) could be used in combination with this system to simulate materials with spatially varying material properties such as brick, marble, and wood. This could be of great value to architectural and interior designers.

A final possibility of the system is to add more controlled light sources. While the current system does an effective job of convincing a viewer that the simulated object is not emissive, and is being lit by the projector light source, the lighting environment created by a single projector is somewhat restrictive. The addition of more projector light sources or controlled lights could create a more natural lighting setup while still maintaining an effective illusion that the simulated object is actually a real material.
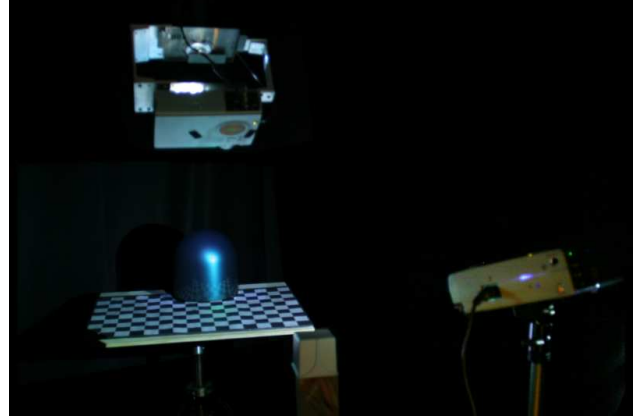
Conclusion

This paper has presented a system for realistic color design and simulation. It extends the concept of shader lamps by using a second projector as a light source and environment mapping to simulate gloss. The object itself is carefully selected, both for its material properties and shape. The surrounding environment is controlled to provide the best possible lighting situation, as well as to give a setting for interactive design of materials and color. To this end, a tracker is provided for the users viewpoint, as well as to easily set lighting coordinates. Finally, the system has been linked to a metallic paint design program to give the user an interface to alter the projected color and evaluate it in real time.

Overall, this system holds up well to visual inspection, creating a compelling illusion of a metallic finish being on the object. At mid-long distances, many viewers are unable to determine that the projected metallic finish is not real. At closer distances (around 2 meters), the illusion begins to break down, possibly due to pixel resolution as well as the stereo and dynamic range issues discussed in the future work section. In order to create a direct comparison, a real metallic finish was added to a shape that is identical to the projection object. The side by side comparison between the real metallic finish and the simulation is shown in Figure 8.

The results this system has presented gives it the potential to be viable tool in the paint industry, as well as in other design areas. Since the actual color simulation and projection concepts can be separated, the move from metallic paint design tool to

Figure 8. *A direct comparison between a real painted cylinder (shown under diffuse lighting in Figure 1) and the metallic simulation.*

other design fields should be straightforward. In addition to being a useful tool now, the research presented in this paper gives a step toward the potential use of projectors to seamlessly add virtual objects into a real environment, for both augmented reality and design purposes.

Acknowledgments

References

[1] Paul E. Debevec and Jitendra Malik. Recovering high dynamic range radiance maps from photographs. In *SIGGRAPH '97: Proceedings of the 24th annual conference on Computer graphics and interactive techniques*, pages 369–378, New York, NY, USA, 1997. ACM Press/Addison-Wesley Publishing Co.

[2] J. Foley, A. van Dam, S. Feiner, and J. Hughes. Computer graphics: Principles and practice. *Addison-Wesley Publishing Co., ISBN 0-201-12110-7*, 1990.

[3] Bruce A. Hartung. *Computer Graphics and Perception: Reaching to Virtual Objects and Material Perception.* PhD thesis, University of Minnesota, 2003.

[4] Ramesh Raskar, Jeroen van Baar, Paul Beardsley, Thomas Willwacher, Srinivas Rao, and Clifton Forlines. ilamps: geometrically aware and self-configuring projectors. *ACM Trans. Graph.*, 22(3):809–818, 2003.

[5] Ramesh Raskar, Greg Welch, Matt Cutts, Adam Lake, Lev Stesin, and Henry Fuchs. The office of the future: a unified approach to image-based modeling and spatially immersive displays. In *SIGGRAPH '98: Proceedings of the 25th annual conference on Computer graphics and interactive techniques*, pages 179–188, New York, NY, USA, 1998. ACM Press.

[6] Ramesh Raskar, Greg Welch, Kok-Lim Low, and Deepak Bandyopadhyay. Shader lamps: Animating real objects with image-based illumination. In *Proceedings of the 12th Eurographics Workshop on Rendering Techniques*, pages 89–102, London, UK, 2001. Springer-Verlag.

[7] Helge Seetzen, Wolfgang Heidrich, Wolfgang Stuerzlinger, Greg Ward, Lorne Whitehead, Matthew Trentacoste, Abhijeet Ghosh, and Andrejs Vorozcovs. High dynamic range display systems. *ACM Trans. Graph.*, 23(3):760–768, 2004.

[8] Clement Shimizu, Gary W. Meyer, and Joseph P. Wingard. Interactive goniochromatic color design. In *Color Imaging Conference*, pages 16–22, 2003.

[9] S. Yamamoto, M. Tsurase, K. Ueda, N. Tsumura, T. Nakaguchi, and Y. Miyake. Reproducing an appearance of the objects using high bright projector. *Proceedings of 10th Congress of the International Colour Association*, pages 1043–1046, 2005.

Author Biography

Jonathan Konieczny received his BS in computer science from the University of Utah in 2003. He is currently seeking his PhD in computer science at the University of Minnesota. His primary research interests are in the area of color and material reproduction, as well as projector based graphics.

Gary Meyer is an Associate Professor in the Department of Computer Science and Engineering at the University of Minnesota. He has also been a Member of Technical Staff at Bell Telephone Laboratories. Meyer received a BS degree from the University of Michigan, an MS degree from Stanford University, and a PhD degree from Cornell University.