Real-time Control of Appearance on an Object Using a High-Luminance PC Projector and Graphics Hardware

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Abstract

In the present paper, we propose a technique to control the appearance on an object in real time using a high-luminance PC projector and graphics hardware. We have previously proposed an image projection technique to reproduce the appearance of a real object on a mock object using a high-luminance projector. By controlling the projected image, the reflected radiance on the mock object is matched to that on the real object. However, in our previous study, only preliminary experiments were performed by matching the appearance empirically. The present paper uses ray tracing to reproduce the distribution of the reflected radiance for appearance matching. It is necessary to measure the bi-directional reflectance distribution function of the objects and the geometry between the projector and the observer's eyes. Since the observer's eyes move with the head in evaluating the appearance of the object, we performed a real-time reproduction of gloss appearance with the movement of the observer's position. The observer's position is detected by an electromagnetic position sensor. Graphics hardware is used in the real-time reproduction to calculate the ray tracing at high speed and render the appearance according to the observer's eye position in real time. Observer rating revealed that little difference in appearance was perceived between the real object and the projected mock object.

Introduction

In reproducing the appearance of real objects in industrial design, a digital mock-up is sometimes created using a 3D computer aided design system and computer graphics techniques. However, accurately reproducing the appearance of real objects using a conventional display is basically difficult because the dynamic range and contrast of the reproduced objects are not sufficient, compared with the real-world environment. Therefore, real mock-ups of design objects are still used to accurate reproduce the appearance of gloss, graininess, color and texture.

Recently, projector display systems have been developed that produce high-dynamic-range and high-contrast images, compared with conventional CRT displays. Several researchers have investigated the possibility of using such projectors for mixed-reality reproduction, in which real objects are combined with computer graphics.[1,2] Such projector display systems can project images onto any object, and the image can be recognized as a reflected object. This is consistent with the visual sensation of real objects. By making the best use of this feature, we expect to reproduce the real appearance by precisely controlling the radiance and color via the projection system.

In previous studies, we constructed a display system using a high-luminance projector that enabled exact matching of radiance and appearance between a real object and a mock object.[3,4] This display system, which is referred to as the Appearance-based Display, used the color matching method for appearance matching. Using this method, the accurate appearance of a real object was reproduced on a mock object constructed of a different material. However, in the previous studies, the reproduction of specular glossiness was empirically modeled and was performed at fixed positions of the observer's eyes. For the exact reproduction of specular glossiness, it is necessary to measure both the bi-directional reflectance distribution function (BRDF) of the objects and the geometry between the projector and the observer's eyes. However, this process is very difficult to perform in actual application because the observer's eyes move with the head while evaluating the appearance of an object.

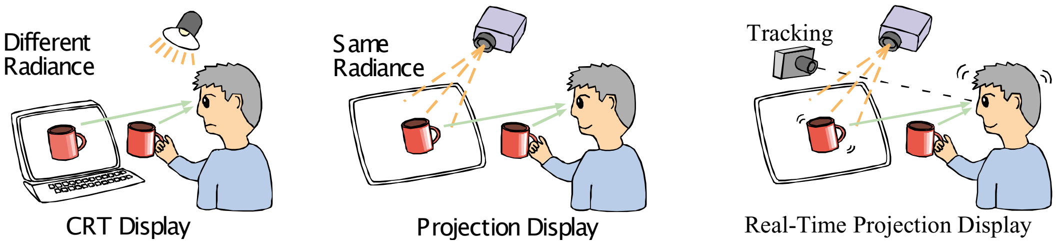


Figure 1. Summary illustration of the proposed display system

In the present paper, we propose a technique by which to control the appearance on an object in real time by using a high-luminance PC projector and graphics hardware. To change the projected appearance according to the observer's position, it is necessary to establish a method of calculating and rendering the projected image at high speed. In the present study, we performed appearance matching by ray tracing and achieved real-time rendering using graphics hardware.[5,6] The observer's position is detected by a 3D head tracking system, since the observer's eyes move with the head while evaluating the appearance of the object. We evaluate the results of an appearance matching experiment taking into account the observer's position.

In the next section, we briefly introduce the projected reality display, which was proposed in a previous paper,[3] and explain the concept of calculating and rendering the projected image. In Section 3, the ray tracing technique is introduced into the system to calculate the exact appearance of the object. In Section 4, the proposed system is implemented using graphics hardware and an electromagnetic position sensor.

Appearance-based Display

The purpose of our research is to generate on a mock object the appearance of a real object. Figure 2 shows the schematic process of appearance matching using the projector. The luminance emitted from the projector is radiated onto the real and mock objects. The observer recognizes reflected light from both objects as tristimulus value XYZ. Accurate reproduction is possible if the radiances of the reflected light from both objects can be controlled to be identical.

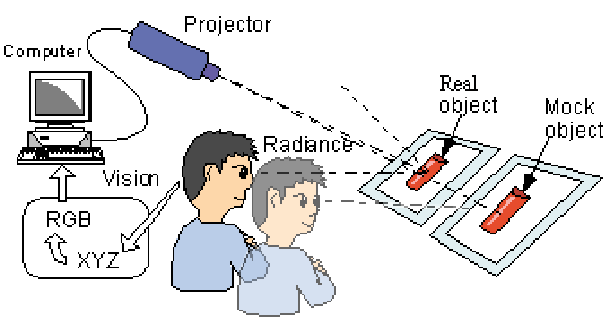


Figure 2. Schematic illustration of the Appearance-based Display system

The relation between the light from the projector and the reflected radiance is expressed as

$$L_r(x, y, \omega') = f_r(x, y, \omega', \omega) \cdot E_r(x, y, \omega), \quad (1)$$

where Lr is the reflected radiance from the objects, fr is the BRDF, Er is the irradiance of the projector, x and y indicate the position on the reflected surface, and ω' and ω indicate the direction of the incoming and outgoing radiances on the surface, respectively. If the BRDF on each object can be measured, then the reflected radiance XYZ can be controlled by the irradiance of the projector, which is decided by the RGB input value of the projector. Similarly, if the shape and the BRDF of the object can be measured, then the ray tracing method can be used to calculate the distribution of the reflected radiance.

Although control of the radiance and the reflected distribution might be possible using a conventional CRT display, the proposed projection method has the following advantages.

- The projector display system can project the images directly on any object and the observer can compare objects on the same display.
- The mode in observing the color can be made to correspond to the real object because the reproduction of the reflected object is possible by using the projector, which is different from an object displayed on a CRT.
- Detail texture on the object can be reproduced if the mock object is made of the same material as the real object.

Appearance Matching by Ray Tracing

Figure 3 shows a geometric illustration of the projected image. Both objects are set at the same position on the screen. The projector illuminates the objects, and the observer evaluates the appearance while viewing the screen from various angles. If the origin point of this geometry is decided to be in front of projector, then the reflected point on the object is calculated by the position of the screen and the shape of the object. An angle for the ray tracing calculation is obtained by measuring the position of the observer's eye.

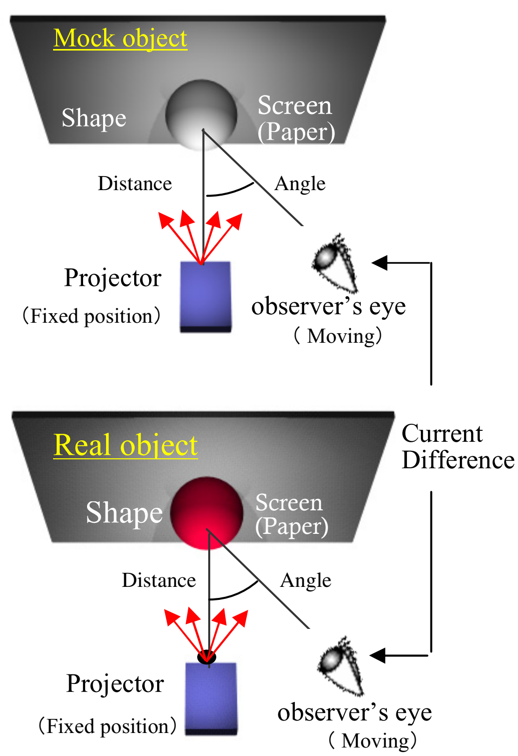


Figure 3. Geometric illustration of Appearance-based Display system

The difference in appearance of the objects should be compensated by controlling the projected image so that the appearances of the objects match. In the present paper, we control the projected image onto the mock object corresponding to the appearance of the real object. Therefore, the projected image is changed based on the current difference of the appearance on both objects. The current difference is calculated using the ray tracing technique as follows.

The technique used to decide the luminance distribution of the projector shown at the observer's position for the mock object can be calculated by ray tracing (Figure 4-a). Moreover, the luminance distribution of the real object at the position of the mock object is calculated using the same method by switching the BRDF in the computer (Figure 4-b). The difference between the two luminance distributions can be calculated, and this difference can be used to compensate the projected image onto the mock object. Since the difference is acquired at the observer position, it is necessary to inversely calculate the difference as the luminance distribution at the projector position. Therefore, the luminance distribution of the projector is calculated by tracing the ray from the observer position to the projector position (Figure 4-c). The appearances of the two objects are expected to be matched by controlling the luminance distribution of the projector at each pixel based on this difference.

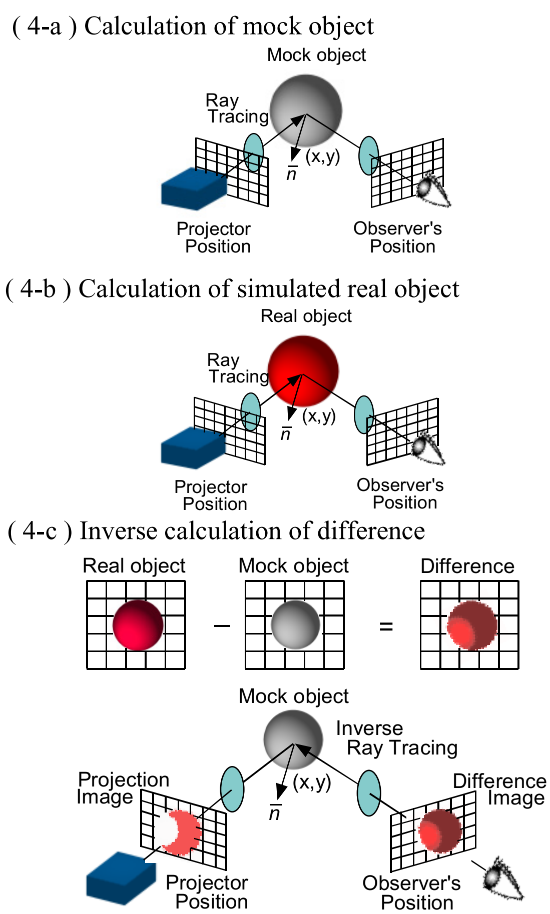


Figure 4. Schematic illustration of ray tracing

Implementation

Figure 5 shows the experimental system using a projector, and Figure 6 shows both objects under white illumination. The reproduced appearance is evaluated by the observer in order to demonstrate the effectiveness of the proposed method. The evaluation is performed under the same conditions as described in Section 3. Both objects are on the same screen. One object is a real object, and the other is a mock object that has different reflectance. Although the shapes of both objects are identical, the real object is covered by colored paper and the mock object is covered by white mat paper. Before the experiment, we measured the shapes of the objects and the BRDFs of both papers and fixed the position of the projector and the screen. A center of the projection image is corresponding to the center of the screen, and central positions of both objects are measured as a distance from the center of screen.

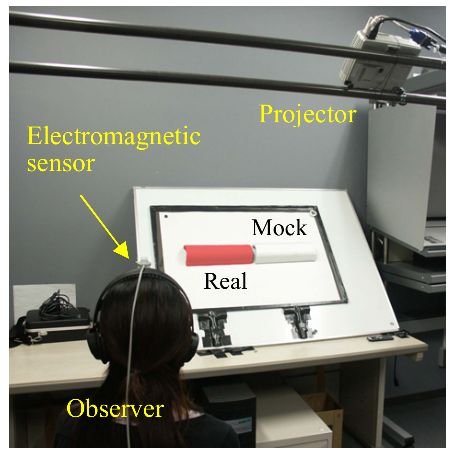


Figure 5. Experimental system using the projector and 3D tracking system

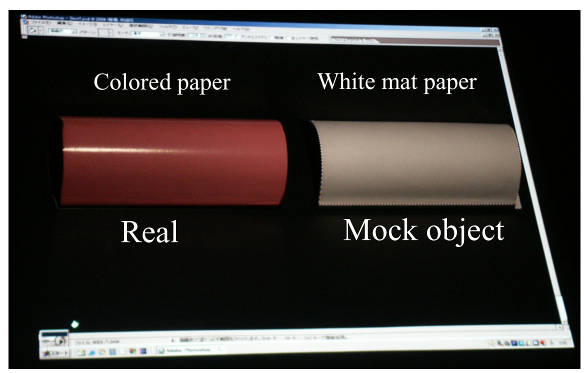


Figure 6. Experimental image of the objects under white illumination

In practical applications, the observer's eyes move with the head in evaluating the appearance of the object. Therefore, the observer's position is detected by an electromagnetic position sensor. In order to perform real-time reproduction of gloss appearance with the movement of the observer's position, the proposed system uses graphics hardware to accelerate the calculation. The graphics hardware has powerful calculation ability and significant frame memory and is suitable for real-time processing for the display. Figure 7 shows the rendering process implemented in the graphics hardware.

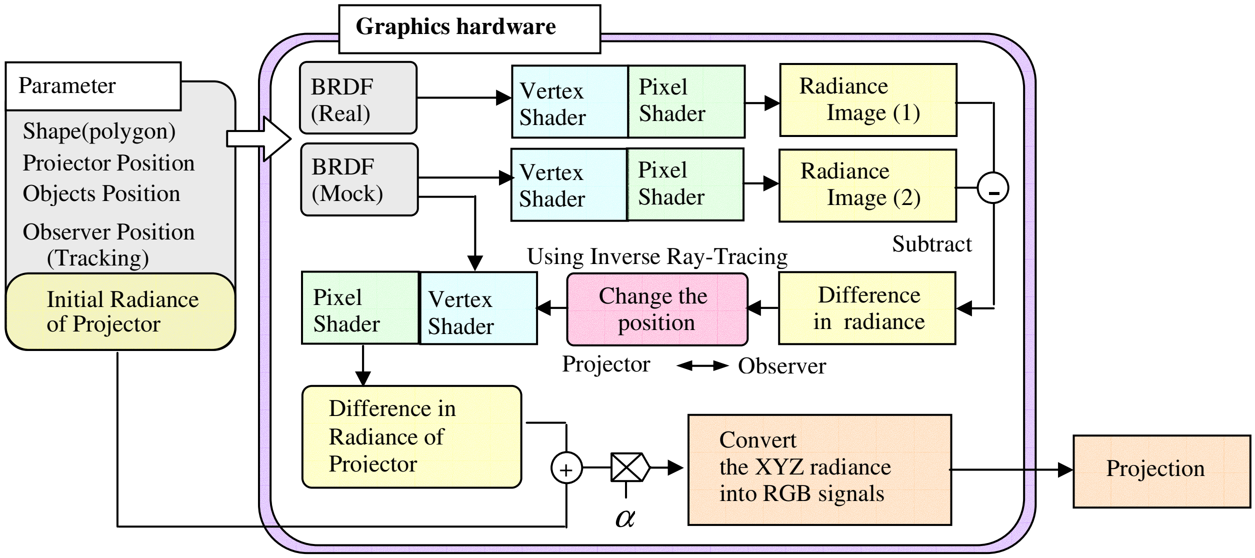


Figure 7. Rendering process performed with graphics hardware

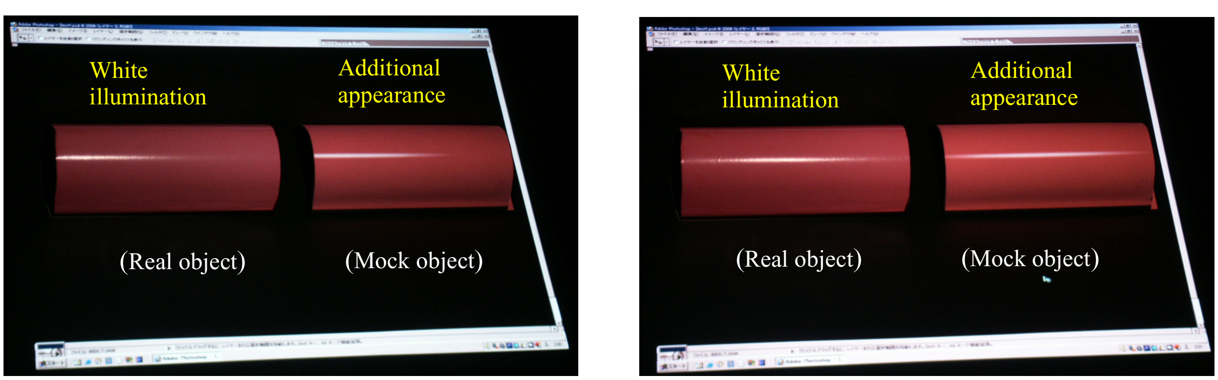
The appearance at the detected position of the observer's eyes is calculated using fixed parameters, such as shape and projector position. The graphics hardware easily generates the two images for the real and mock objects for the position of the observer, because this hardware is specifically designed to calculate computer graphics. The difference obtained from the subtracted radiance for both images is calculated as described in Section 3, and the result is stored in a new frame memory.

As the next step in the process, it is necessary to generate a final image that is projected on the mock-up using the difference in radiance. However, the ray is calculated from the position of the illumination to the observer via the graphics hardware. Therefore, we swap the position of the projector with the positions of the observer's eyes, and the difference in radiance for projector is calculated from the subtracted radiance for both images by using inverse ray tracing. The final image projected on the both objects is decided by adding the difference in radiance of projector into the initial radiance of projector.

If the real object has a strong gloss reflection on its surface, it is usually difficult to reproduce the absolute radiance and contrast on the mock surface because the brightness of the projector is limited. Therefore, we adapt the coefficients α after the final addition to match the relative contrast generated between the real object and the mock object. To adjust the power of illumination to the objects, we can display the appearance of strong secular reflectance relatively, since the power of radiance on gloss reflection depends on the illuminated radiance.

Experimental Result

Figure 8 shows the result of appearance matching using the proposed technique with movement of the observer's position. For the real object, our system projects white illumination, which is the original lighting used to calculate the appearance of the real object. For the mock object, the system projects the final additional radiance, which is calculated by the graphics hardware.



(About 30 degree against to normal vector of screen) (About 15 degree against to normal vector of screen)

Figure 8. Experimental results of the proposed display system

Subjective evaluation by ten observers revealed that the appearances of the real object and the projected mock object were difficult to distinguish. The proposed system was very effective in reproducing the gloss appearance with the movement of the observer's position. The image rendering was projected at a rate of 30 frames per second, enabling the proposed system to provide natural reproduction.

Conclusions

We proposed the improved Appearance-based Display, which provides exact matching of radiance and appearance between a real object and a mock object, even during movement of the observer's position. The proposed technique uses ray tracing to reproduce the distribution of reflected radiance for the appearance matching. By measuring the BRDF of the objects and the position of the observer's eyes, the proposed system performs real-time reproduction of gloss appearance with the movement of the observer's position. The observer's position is detected by an electromagnetic position sensor, and graphics hardware is used for real-time processing of the reproduction. In the experiment, little difference in appearance was perceived between a real object and a projected mock object. The image rendering is projected at a rate of 30 frames per second, and so the proposed system provides natural reproduction. Based on these results, the developed display system will provide a very useful tool for future industrial design applications, such as digital mock-ups.

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Author Biography

Shoji Yamamoto received his B.E. and M.E. degrees from the Department of Opt-Electro-Mechanics Engineering from Shizuoka University in 1989 and 1991 respectively. Now, he is the doctorate course student at Chiba University. He is interested in Multi-spectral imaging, Visual mechanism, and Mixed-reality. He is a member of the Institute of Image Electronics Engineers of Japan.