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Realization of Virtual Photometric Environment by Photometric Pattern Projection

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Abstract

In this paper, we introduce the *Virtual Photometric Environment* which is one of mixed reality systems. The *Virtual Photometric Environment* enables arbitrarily control over the lighting directions and reflection properties of objects. The environment is realized by photometric pattern projection onto screen objects. Reflection properties of the photometric patterns are acquired from real objects. As an application, a demonstration system was constructed which reproduces the reflection properties of Japanese ceramic arts on a white plaster vase with changing lighting direction.

1 Introduction

Mixed reality is a concept in which virtual information generated by computer graphics is mixed with real scenes[1]. Since mixed reality systems can be used as man-machine interface as well as for collaboration among users, a lot of systems have been proposed for mixing virtual objects with real scenes[2][3].

Head mounted displays (HMD) are often used as equipment for realizing mixed reality systems. HMD are classified into two types; optical see-through and video see-through displays. In optical see-through displays, virtual images are optically mixed with a real scene. Although the real scene is directly observed through a glass, the virtual image is late superimposed onto the real scene. In video see-through displays, in contrast, virtual images are mixed with real images captured by camera, and the user observes the mixed image on a monitor. Although the virtual image and real image are synchronized, latency exists between the mixed image and head motion. That is, mixed reality systems based on HMD have problems that users feel less realism.

To cope with these problems, new mixed reality systems using a projector have been proposed[4]. Virtual images generated by a computer are directly projected onto real scenes. By using a projector, users do not have to wear special devices such as HMD. The problem of delay is solved, because the virtual image is independent of head motion as long as the projector and real scenes are fixed.

Projectors have the capability of both overlaying virtual objects on real scenes and of changing the appearance of real objects by projecting appropriate photometric patterns[5][6]. These systems can be used for a variety of applications, such as lighting design simulations and virtual museums. However, photometric appearance changes such as reflection properties have not been treated in earnest in projector-based mixed reality systems. In this paper, we introduce a system called the *Virtual Photometric Environment* which enables us to arbitrarily control lighting directions as well as reflection properties of objects. The environment is realized by photometric pattern projection onto screen objects. Geometric information in the real world and photometric information in the virtual world are mixed in the real world. Because users can see the real world without any device, the realism can be improved.

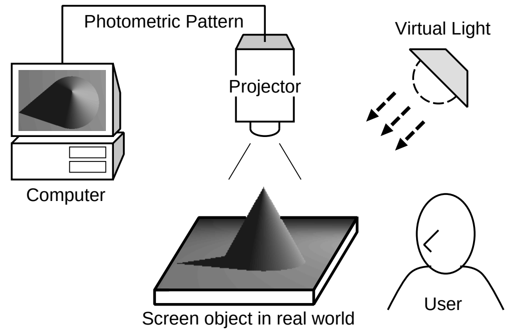

Figure 1: Principle of the Virtual Photometric Environment.

This paper is organized as follows: Section 2 describes the principle of the *Virtual Photometric Environment* and presents basic experimental results using a prototype system. Section 3 describes a method for acquiring reflection properties from real objects to improve realism. Some experimental results using Japanese ceramic arts are presented in Section 4. Finally, some conclusions are presented in Section 5.

2 Virtual photometric environment

2.1 Principle

The *Virtual Photometric Environment* is a new concept that handles photometric properties such as lighting directions and surface reflectance in the framework of mixed reality. In the environment, photometric properties can be arbitrarily controlled by mixing geometric information in the real world and photometric information in the virtual world. As shown in Fig. 1, this environment is realized by pattern projection onto 3-D screen objects. Projected patterns are generated according to virtual light and virtual reflection properties. The screen object is assumed to have a Lambertian white surface, with no ambient light.

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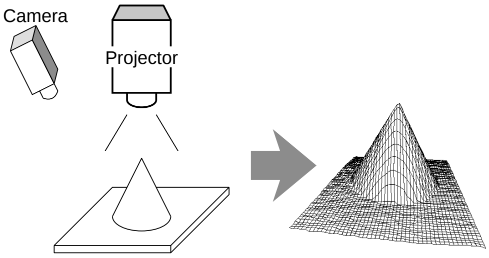


Figure 2: 3-D shape measurement of the screen object.

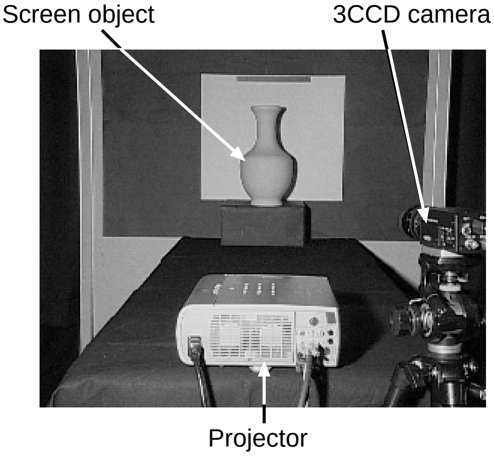


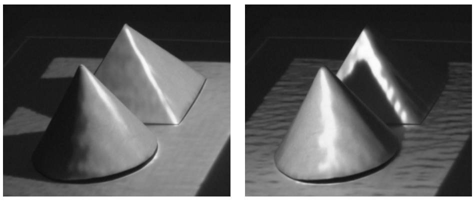
Figure 3: Prototype system.

2.2 Photometric pattern generation

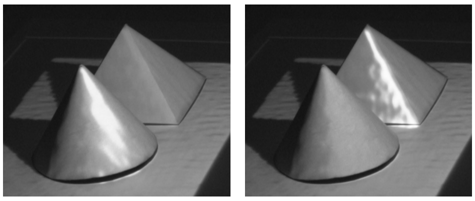
If the 3-D shape of a screen object is known, photometric patterns can be generated by usual computer graphics methods. The lighting position and reflection properties of the screen object can be controlled arbitrarily. We assume that the screen object has a textureless Lambertian white surface. The 3-D shape is therefore difficult to measure stably by stereo methods. In our system, the 3-D shape of the screen object is measured using a rangefinder, as shown in Fig. 2. Several slit patterns are projected onto the screen object and the scene is captured by a camera. The 3-D shape can be easily measured based on the principles of triangulation[7].

To add virtual specular reflections to a screen object, the viewing position of the user also needs to be detected, because the power of specular reflections depends on viewing direction. The 3-D position of the user can be measured by tracking a marker attached to the user using a pair of cameras. To precisely measure head motion, a magnetic field sensor can also be used.

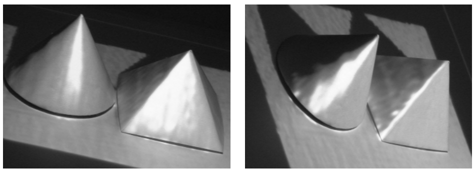
Note that if we give only Lambertian reflection properties to the screen object, the viewing position of the user does not have to be detected because Lambertian reflection is independent of viewing direction. This means that a lot of users can simultaneously see the *Virtual Photometric Environment* and that latency never occurs because the photometric pattern does not have to be updated due to movement of users.



(a) Changes to virtual light position.



(b) Changes to reflection property.



(c) Changes to viewing position.

Figure 4: Examples of the virtual photometric environment.

2.3 Prototype system

To demonstrate the principles of the *Virtual Photometric Environment*, a prototype system was constructed, as shown in Fig. 3. This system consists of a projector for projecting photometric patterns and a camera for rangefinder. To simplify the system, the distance between the screen object and the user is assumed to be constant. Therefore, the viewing position of the user is roughly detected by single camera.

First, experimental results are presented in which lighting direction and reflection properties are arbitrarily controlled. In this experiment, a screen object including a cone and a pyramid made of paper was used. Figure 4(a) shows photometric appearance changes due to changes in virtual lighting position. While reflection properties and camera position are fixed, the virtual lighting position is moved. We can see that appropriate photometric patterns including diffuse reflections, specular reflections and cast shadows are projected according to the virtual lighting position. Figure 4(b) shows changes in reflection properties. The left and right images show results in which virtual specular reflections are given to the cone and pyramid, respectively. Figure 4(c) shows results of viewing position changes. We can see that appropriate specular reflections are projected according to viewing direction.

Next, experimental results for a white plaster vase are shown in Fig. 5. Figure 5(a) and (b) show the vase and its 3-D shape, respectively. The shape is almost correctly measured except for the back of the vase, where slit patterns cannot be projected. Figure 5(c) and (d) show results with the virtual light located on the left and right side, respectively. Reflection properties are set to be Lambertian, and the texture was manually drawn. Figure 5(e) and (f) show different virtual reflec-

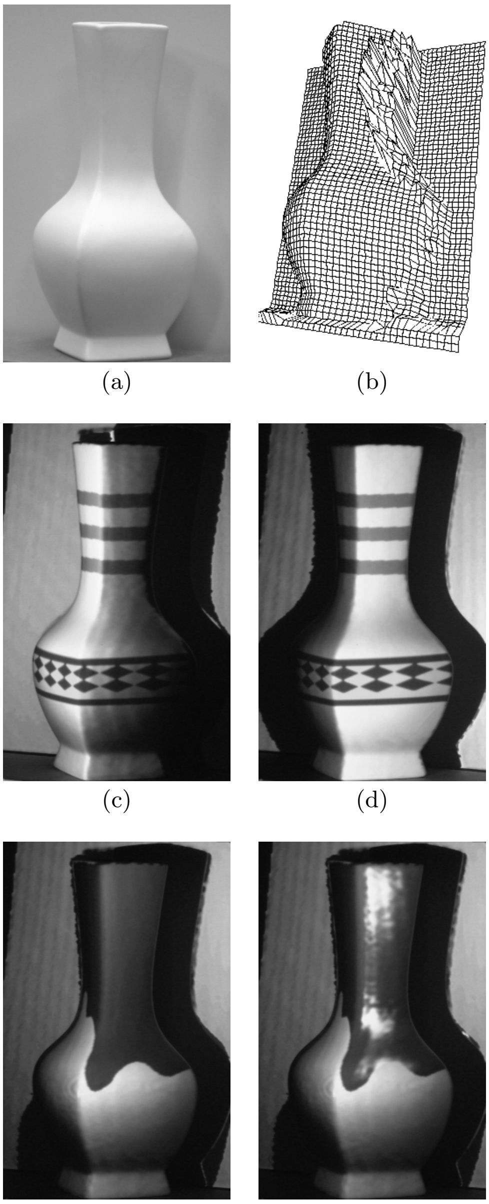

(a) (b) (c) (d) (e) (f)

Figure 5: Results of pattern projection onto a vase. (a): Screen object. (b): Measured 3-D shape. (c) and (d): Appearance changes due to virtual light position. (e) and (f): Appearance changes due to virtual reflection properties.

tion properties. Virtual specular reflections are added to (f), while (e) has only Lambertian reflection properties. We confirmed that the appearance of objects can be arbitrarily controlled by projecting virtual photometric patterns.

Screen objects contain regions that photometric patterns cannot be projected, and thus virtual photometric information cannot be given to those region. For the same reason, pseudo cast shadows are always observed. Although these problems cannot be solved in the current prototype system using a single projector, they could be solved by using multiple projectors.

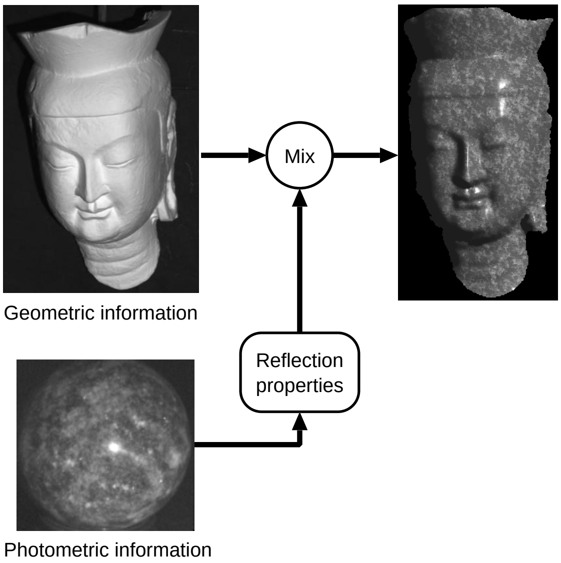


Figure 6: Acquisition of reflection properties from real objects.

3 Acquisition of reflection properties

3.1 Acquisition from real objects

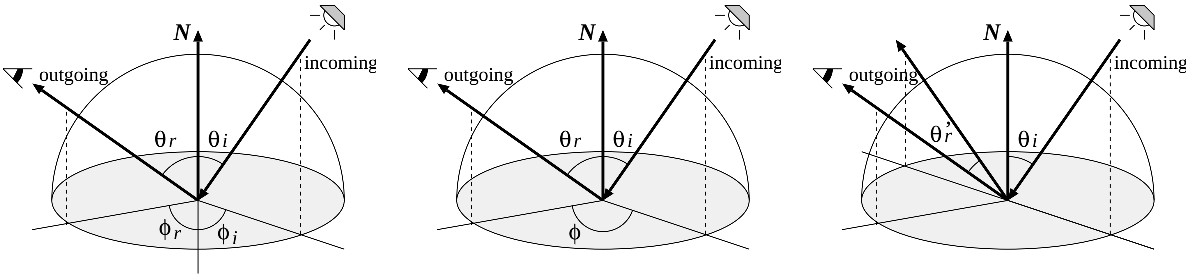
In the prototype system described in the previous section, reflection properties given to the screen object were defined manually. The appearance of the screen object therefore tends to be artificial. However, improving the realism is very important for practical use of the system. For this, reflection properties of real objects are acquired and reproduced on the screen object, as shown in Fig. 6. By changing the real objects from which reflection properties are acquired, a variety of photometric information can be given to the screen object. Since reflection properties are acquired from real objects, realism of the system can be improved[8].

3.2 Representation by BRDF

To represent reflection properties, several reflection models, such as the Phong model[9] and Torrance-Sparrow model[10], are often used. These models formulate reflection properties using a small number of parameters, and are suitable for hardware rendering. However, decision of parameters of these reflection models is often unstable. Perfect reproduction of the reflection properties of real objects is therefore difficult.

In our method, formula-based reflection models are not used. Instead, real intensities observed by camera are directly used as values in the reflection function without needing parameter estimation. To represent reflection properties, the bidirectional reflectance distribution function (BRDF) is used. The BRDF f_4 represents the ratio of outgoing radiance in the viewing direction (θ_r, ϕ_r) to incident irradiance from a lighting direction (θ_i, ϕ_i). (θ_r, ϕ_r) and (θ_i, ϕ_i) are relative angles to the surface normal $\boldsymbol{N}$, as shown in Fig. 7(a). By assuming that the surface is illuminated by a point light source whose irradiance is L, the observed radiance i can be expressed by

$$i = f_4(\theta_i, \phi_i, \theta_r, \phi_r)L. \tag{1}$$



(a) BRDF with four parameters (b) BRDF with three parameters (c) BRDF with two parameters

Figure 7: Angle parameters of BRDF.

If BRDFs could be acquired for each surface point, the photometric pattern to be projected onto the screen object can be generated easily. Photometric patterns are generated based on Eq. (1), with viewing direction, virtual lighting direction, and lighting power parameters. That is, texture mapping can be applied even if the 3-D shape is different between the screen object and the real object from which reflection properties are acquired.

3.3 Angle parameters of BRDF

To perfectly acquire the BRDF specified by four angle parameters, a complex mechanism is necessary to control the position of both camera and light[11]. Moreover, huge memory is required to store the complete BRDFs for every point on the surface. However, the four angle parameters are often redundant. The number of parameters can be reduced.

When a surface rotates around the surface normal, the appearance of the center point of the rotation does not change for most materials. Therefore, the angles ϕ_i and ϕ_r are thus assumed to be redundant, and the BRDF is defined with three parameters, θ_i, θ_r, and ϕ. ϕ denotes the sum of ϕ_i and ϕ_r, as shown in Fig. 7(b). The BRDF can be approximated by the function f_3 with three angle parameters, and the observed radiance i is expressed by

$$i = f_3(\theta_i, \theta_r, \phi)L. \tag{2}$$

Moreover, the angle parameter ϕ is also redundant for a lot of materials[12]. The BRDF is thus approximated by the function f_2 with two angle parameters θ_i and θ'_r. θ'_r denotes the angle between the surface normal and the mirror direction of the incident light, as shown in Fig. 7(c). Observed radiance i is then given by

$$i = f_2(\theta_i, \theta'_r)L. \tag{3}$$

It is desirable for the BRDF to correctly express reflection properties using only a small amount of memory. In consideration of the tradeoff between the amount of stored data and the ability for reproducing reflection properties, reflection properties are acquired by the function f_2 in our method.

3.4 Interpolation of BRDF

To acquire BRDFs, both light source and camera need to be rotated around the target object. However, when the camera is rotated, the correspondence of points between images needs to be found. This is quite difficult, and so the camera is not rotated. The camera and target object are fixed, and only the light source is rotated.

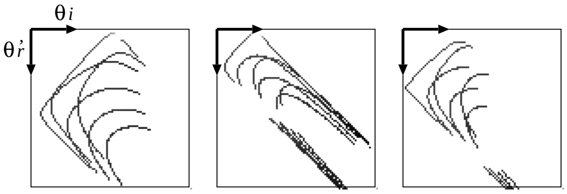


Figure 8: Examples of acquired reflection properties.

However, it is difficult to densely rotate the light around the target object. Figure 8 shows some examples of acquired data. Each image shows a visualized BRDF, which is specified by two parameters θ_i and θ'_r. In these examples, the light source is rotated around the target surface point with changing the height at six levels. White regions indicate that intensity cannot be acquired. If the sampling is sparse, almost of the data cannot be acquired.

In our method, undefined data are interpolated and extrapolated from the acquired data. Observed intensity can be expressed as the sum of diffuse reflection and specular reflection[13]. The power of diffuse reflections is assumed to be independent of viewing direction θ'_r and power of specular reflections is assumed to be independent of incident direction θ_i. Specular reflections are assumed not to be observed for large angles θ'_r. Based on these assumptions, complete BRDFs are obtained by interpolation and extrapolation of the acquired data, as shown in Fig. 9. First, diffuse and specular reflections are separated. Next, diffuse components and specular components are linearly interpolated along θ'_r and θ_i, respectively. Then, the uninterpolated regions are extrapolated. Finally, the complete BRDFs are obtained by integration of the diffuse and specular reflections.

4 Experimental results

In this section, we show some experimental results that reflection properties are acquired from real objects and the properties are reproduced on the screen object. To precisely control the lighting direction, a lighting control system was constructed, as shown in Fig. 10. This system consists of a camera for capturing images, a projector as a rangefinder, and six lights. The lights are installed on a bar, and the bar rotates around the target object. The rotation angle is arbitrarily controlled by computer. The 3-D position and power of the lights are calibrated in advance.

Keeping the camera and the target object fixed, the

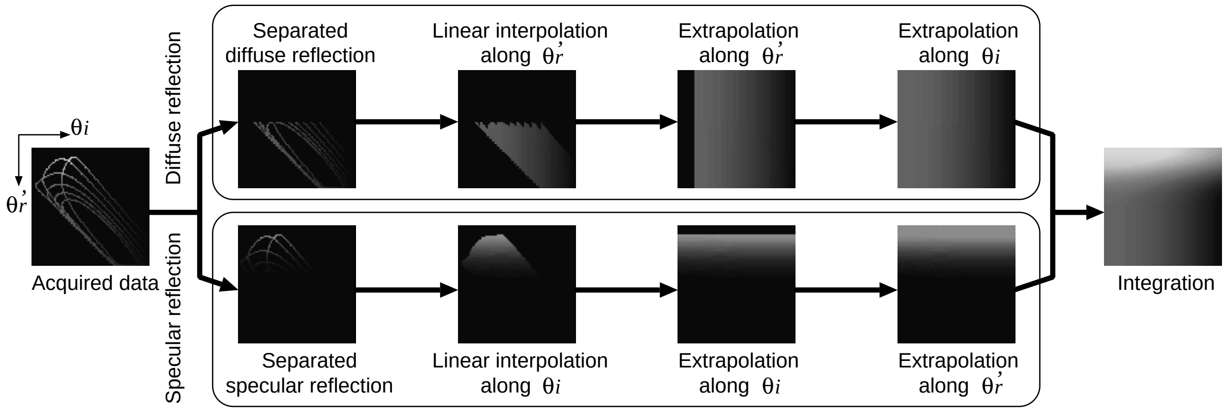


Figure 9: Interpolation and extrapolation of BRDF. Diffuse reflection and specular reflection are processed separately.

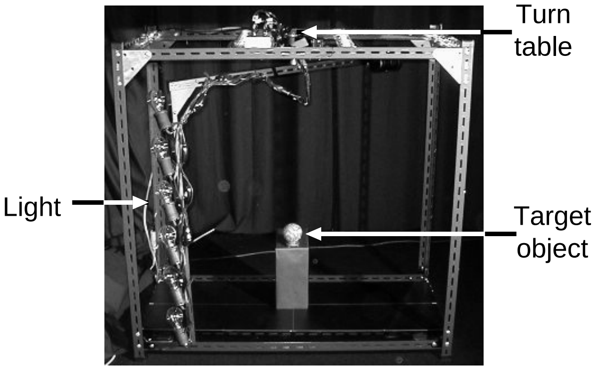


Figure 10: BRDF acquisition system.

bar with six lights is rotated by 1° from −100° to +100° (0° indicates the camera direction). The switches of six lights are independently controlled to be on or off. A total of 1206 images were then taken in a dark room for each target object.

Figure 12 (a) shows a Japanese ceramic art (Bizen-Hidasuki) from which reflection propertied are acquired. Figure 11 shows some results of acquiring reflection properties after interpolation and extrapolation. Figure 12 (b) shows the screen object on which reflection properties are reproduced. Figure 12 (c) shows the result of reproduction of reflection propertied acquired from the ceramic art. Reflection properties can be seen to have been almost correctly acquired with virtual lighting direction arbitrarily controlled.

Figure 13 (a) and (b) show more results of the acquisition and reproduction of reflectance properties. Left images show a real vase from which reflectance properties are acquired. Right images show the results of reproduction of the reflectance properties on the screen object. The detailed nuance of the reflections is reproduced on the screen object.

5 Conclusion

In this paper, we proposed a new mixed reality system called the *Virtual Photometric Environment* which mixes geometric information of the real world and photometric information of the virtual world. The environment is realized by photometric pattern projection

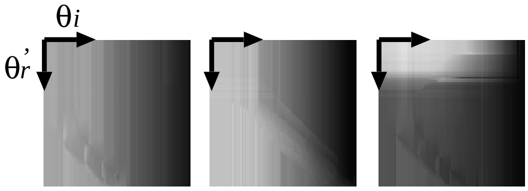


Figure 11: Results of interpolation and extrapolation of reflection properties.

onto a screen object. By experiments using a prototype system, latency and geometric mis-alignment, which are problems in HMD systems, were confirmed to be overcome using a projector. Virtual lighting position and virtual reflection properties were confirmed to be arbitrarily controlled in the *Virtual Photometric Environment*.

To improve the realism of the environment, a method for acquiring reflection properties from real objects was introduced. BRDF was used to represent reflection properties. BRDF, however, needs a huge amount of memory, as it is specified by four parameters. To reduce memory consumption, a two parameter function was used as an approximation to the complete BRDF. Experimental results demonstrated that acquired reflection properties can be reproduced on a screen object with a different shape to the real object from which reflection properties were acquired. Although the BRDF that we used is an approximation, reproduced reflections were confirmed to be almost correct, giving improved realism.

The surface of the screen object is assumed to be perfectly visible from the projector. The back of the screen object, however, cannot actually be projected onto. This problem can be solved by using multiple projectors. Now, attempts to develop a system so that objects of complex shapes can be used as screen objects are currently underway.

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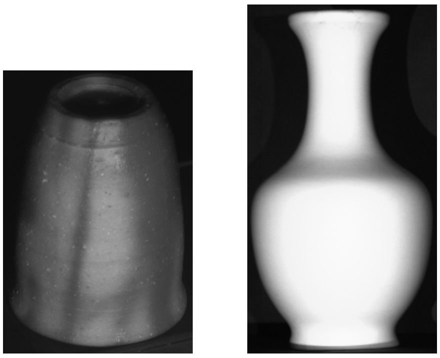
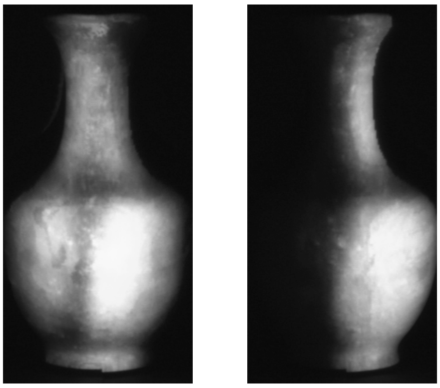


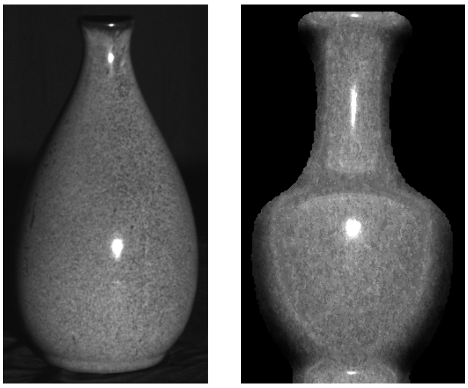
(a) Ceramic art (Bizen-Hidasuki)   (b) Screen object (plaster)



(c) Results of reproduction of the acquired reflection propertied on the screen object.

Figure 12: Experimental results of acquiring reflection properties from a real object and reproducting these on a screen object.

(a) Ceramic art (Bizen-Goma)



(b) Glossy ceramic art

Figure 13: Acquisition and reproduction of reflectance properties. The left images show the real vase from which reflectance properties are acquired. The right images show the results of reproduction of the reflectance properties on the screen object.

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