Texture Reproducibility Evaluation on BRDF Reproduction by Light Field Projection*

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Abstract

In recent years, spatial augmented reality (SAR) technology, which adds information through light projection, has been used in projection mapping. Kimura et al. proposed a method on SAR research to reproduce color changes due to viewpoint shifts by reflecting Bidirectional Reflectance Distribution Function (BRDF) data through light field projection, This method achieved adaptive BRDF representation under the assumption that surface normal vectors are oriented upwards, thereby ignoring the actual shape of the projection surface. This simplification introduced inconsistencies, such as reversed gradation, compression artifacts, and other distortions around areas of specular reflection. Despite these issues, identifying such inconsistencies is challenging, and they may have minimal impact on the perception of material properties. In this study, we clarified through a subjective evaluation experiment that even with such inaccuracies in reproducing reflected light, viewers do not perceive these errors in using Kimura et al.'s method.

Keywords

Light Field, SAR, BRDF

1. Introduction

In recent years, spatial augmented reality (SAR) technology, which adds information to buildings and objects through light projection, has been actively utilized in projection mapping. In SAR research, material appearance manipulation has been proposed to alter the perceived texture of objects in the real world, with applications in product design, art exhibitions in museums, and product displays.

Amano et al.[1] proposed a method for manipulating color and gloss, similar to structural colors, by using feedback system consisting of four sets of projector-camera pairs, Furthermore, reflection analysis-based viewpoint-dependent appearance manipulations that manipulate structural color[2], and anisotropic reflection property[3] are proposed. While these manipulations enable sophisticated perceptual BRDF alternation, they require both geometric and photometric calibration between multiple projectors and cameras, making it difficult to apply them to dynamic scenes.

To solve this problem, Kimura et al.[4] proposed a method for adding material appearance using light field projection, assuming a vertically upward normal vector. This method reproduces the material appearance represented by presenting color changes corresponding to viewpoint movement without geometric and photometric calibration, based on BRDF data.

However, when the target object is not a plane, the method fails to correctly present the direction of specular reflection or the order of colors around specular highlights. Nevertheless, viewers do not easily perceive these inaccuracies. This raises the question: do we accurately understand light reflection and the gradation of structural colors when judging material appearance? In this study, we aim to clarify how the incorrect color presentation caused by BRDF display on non-planar objects using Kimura et al.'s method affects the perception of BRDF-based material appearance.

2. BRDF manipulation by light field projection

As shown on the left of Fig. 1, when light from a light source vector $\boldsymbol{L}$ illuminates a point on the surface of an object whose reflective properties are represented by BRDF f, the colors observed from viewpoints $\boldsymbol{V}$ and $\boldsymbol{V'}$ can be expressed as $f(\theta_i, \theta_o)$ and $f(\theta_i, \theta'_o)$, respectively, using the incident and viewing angles.

In Kimura et al.'s method, as illustrated on the right of Fig. 1, the reflection of the object is assumed to be specular reflection, and by projecting $f(\theta_i, \theta_o)$ and $f(\theta_i, \theta'_o)$ from the specular reflection direction of the viewpoint, the BRDF is reproduced. However, to accurately reproduce BRDF, information about the shape and position of the target object is necessary, making it difficult to achieve dynamic BRDF presentation. Therefore, in Kimura et al.'s method, to provide versatility, they assume the shape is a plane and set the normal $\boldsymbol{n}$ to point

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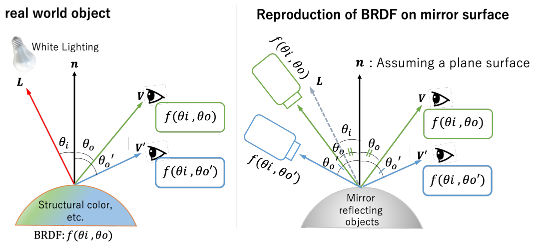


Figure 1: Reproducton of BRDF on specular reflective surface[4]

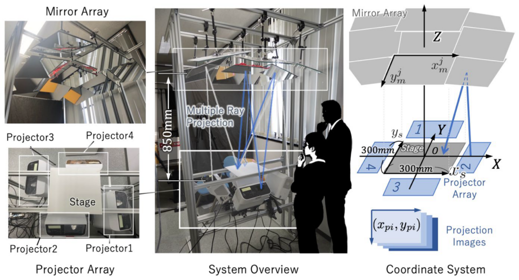


Figure 2: Light field projection system[5]

vertically upward.

In BRDF reproduction, by performing this projection in the assumed observation direction, the target BRDF can be presented. However, it is difficult to predetermine the viewing directions. Therefore, it is necessary to project light rays with high angular resolution to accommodate various viewpoints. To address this, Kimura et al. used the light field projection system developed by Amano and Kubo [5], as shown in Fig. 2. This system consists of four projectors (RICOH PJWX4125) and nine mirrors (300 mm × 300 mm), with a distance of 850 mm between the stage and the mirrors.

The stage, where the projection object is placed, measures 300mm square, and an average of 13 light rays are projected per 1mm square on the stage, thanks to the combination of projectors and mirrors. Since the light rays projected onto the stage can be geometrically determined based on which projector emits the light and which mirror reflects it to reach the stage, it is possible to present the target color from the specular reflection direction based on the BRDF.

Fig. 3 shows the results of BRDF reproduction using Kimura et al.'s method. Changes in the specular highlight positions and the gradation around the specular highlights can be observed with viewpoint changes, successfully reproducing the illumination distribution along to the BRDF model. Moreover, it can also be reproduced for various projection targets.

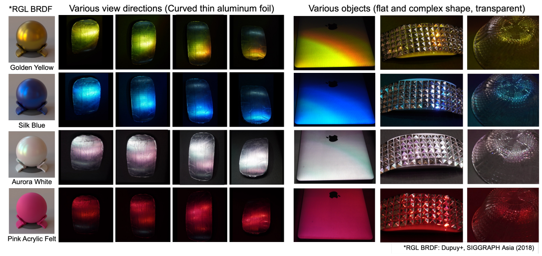


Figure 3: BRDF reproduction results[4]

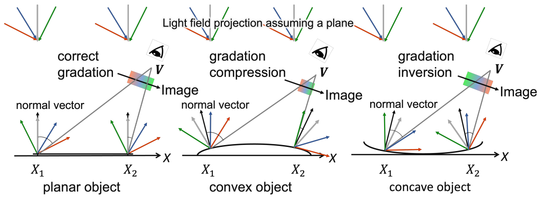


Figure 4: Gradation change due to shape

2.1. Problems due to changes in normal direction

One issue with Kimura et al.'s method is that it assumes a vertically upward normal vector, which leads to incorrect presentation of the color order around specular highlights when presenting BRDF textures on non-planar surfaces. For example, when projecting onto a convex object in Fig. 4, the reflection direction changes significantly from X_1 to X_2. Additionally, when projecting onto a concave object, the direction of reflection also changes. This results in compression or inversion of gradation around specular reflection on the image. Although this method cannot achieve precise reproduction of BRDF, the results from Kimura et al. suggest that viewers may not readily perceive these gradation inconsistencies. Therefore, we aim to investigate whether presenting BRDF textures on non-planar surfaces is perceived as having different material appearances.

3. Validation of BRDF reproduction using light field projection

3.1. Evaluation method

In this study, we evaluate whether participants accurately perceive precise color changes when perceiving material appearance using Kimura et al.'s method. Since material appearance is subjective, it is effective to compare results through visual experiments with participants.

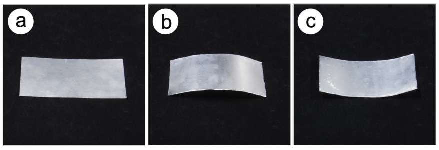


Figure 5: Projection targets: the shape is flat (a), convex (b) and concave (c)

For such evaluations, methods like Thurstone's paired comparison method[6] or the Semantic Differential (SD) method[7] could be considered. However, Thurstone's paired comparison method requires selecting one option over the other, leading to the issue that when all observers' evaluations are skewed, the differences between samples cannot be scaled on an interval scale. On the other hand, the SD method uses opposing adjective pairs, such as "bright-dark," to rate on a 5-point or 7-point scale. However, it is difficult to represent the material appearance evaluated in this study using such opposing adjective pairs. Therefore, in this study, we use Scheffe's paired comparison method[8]. However, since the evaluation targets cannot be compared simultaneously and the order of projection may influence the results, we adopt a modified version of Scheffe's paired comparison method(Ura's modification)[9] that accounts for the order of presentation.

Specifically, we projected the image onto the target shown Fig. 5 and evaluated whether participants perceived accurate color changes as follows:

1. For a planar object(Fig. 5(a)), convex object(Fig. 5(b)), and concave object(Fig. 5(c)), we will make projections that match the shape of each object: a projection aligned with the planar shape (hereafter referred to as "planar projection"), a projection aligned with the convex shape (hereafter referred to as "convex projection"), and a projection aligned with the concave shape (hereafter referred to as "concave projection").
2. We use the Scheffe's paired comparison method to survey participants on which specular highlight or gradation they consider correct.
3. If there is no significant difference between Kimura et al.'s planar projection and the optically correct projection that matches the shape of each target object, it will be concluded that the differences in specular highlights and gradation changes due to shape are not perceived.

3.2. Experimental procedure

The experimental procedure is outlined as follows.

1. The experimenter explains to the participants the direction of the light source and the shape of the projection target as set when creating the projected images, as shown in Fig. 6(a).
2. The experimenter presents an image rendered with RGL BRDF data[10], which represents the material appearance to be shown, as illustrated in Fig. 6(b), to the participants for 10 seconds.
3. Participants view the first projection through the viewing hole for 15 seconds, then view the second projection for 15 seconds, and answer a questionnaire.
4. Participants repeat step 3 for all combinations, totaling 6 sets.

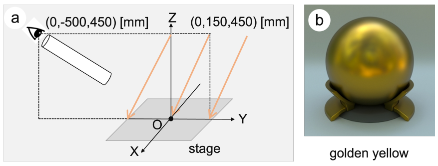


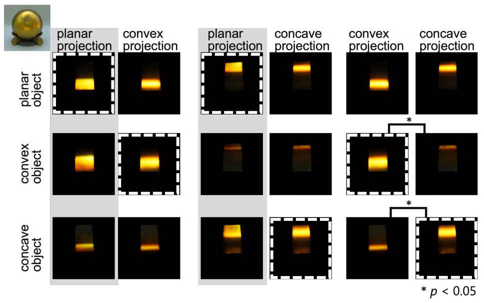
Figure 6: Information for subjects: (a) Participant's viewpoint and light source direction, (b) Presented material appearance[10]

The questionnaire asked, "When the parallel light source is hitting the projection target from the direction shown in Fig. 6(a), which gradation or specular highlight appears correct?" We asked participants to choose from the following options: "Projection 1 is correct," "Projection 1 is somewhat correct," "Cannot say," "Projection 2 is somewhat correct," or "Projection 2 is correct."

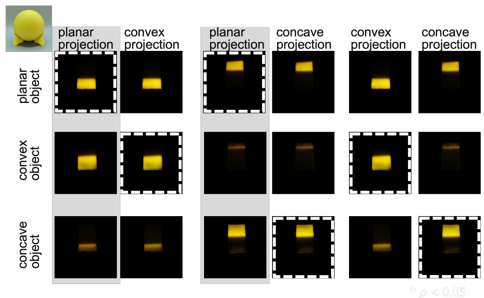
4. Experimental results

We conducted an evaluation experiment with eight participants in their 20s who had normal or corrected-to-normal vision and possessed basic knowledge of computer graphics concepts such as parallel light sources, gradation, and specular highlights. The results are shown in Fig. 7.

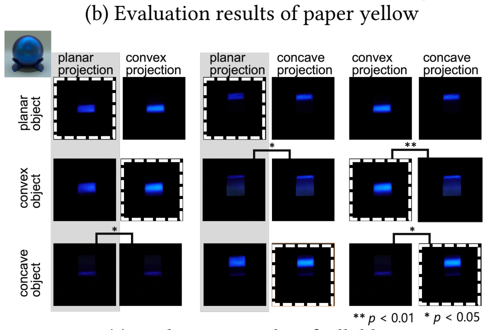
Fig. 7(a) showed significant differences when comparing the convex projection with the concave projection for both the convex and concave objects. No significant differences were found when comparing the other projections in Fig. 7(a). There were no significant differences in any of the combinations shown in Fig. 7(b). As shown in Fig. 7(c), significant differences were observed when comparing the planar projection with the concave projection and the convex projection with the concave projection for the convex object. Similarly, significant differences were found when comparing the planar projection with the convex projection and the convex projection with the concave projection for the concave object. No significant differences were found when comparing the other projections.



(a) Evaluation results of golden yellow



(b) Evaluation results of paper yellow



(c) Evaluation results of silk blue

Figure 7: Evaluation results

5. Discussion

In Fig. 7, the planar projection represents the method used by Kimura et al., and the area enclosed by the white dotted line indicates the optically correct projection for that shape. Since no significant differences were observed in any of the combinations comparing the planar projection with the optically correct projection, we confirmed that Kimura et al.'s method can also present the BRDF material appearance for non-planar objects.

In the combinations of projections where significant differences were observed in Fig. 7(a), both selected projections were optically correct. In Fig. 7(b), no significant differences were observed among all the projections. Many participants expressed the opinion that they "could not discern the differences in specular highlights and gradation." This may be due to the fact that "paper yellow" represents a BRDF data with a matte appearance, resulting in minimal changes across the projections, making it difficult to determine which was correct.

In Fig. 7(c), it is hypothesized that, when comparing the planar projection with the concave projection for the convex object, the planar projection was chosen because it exhibited a smaller change in the normal direction relative to the convex object. Furthermore, it was confirmed that the optically correct projection was selected when comparing the convex projection with the concave projection for the convex object. However, when comparing the planar projection with the convex projection for the concave object, the convex projection was selected instead of the planar projection, which also showed a smaller change in the normal direction. Participants commented, "The overall appearance was darker, and the convex projection felt more correct because it was brighter than the planar projection," which is believed to have led to this result for that reason. When comparing the convex projection with the concave projection for the concave object, the convex projection was selected instead of the optically correct concave projection. Participants noted that "the specular highlights were bright, making the concave projection feel similar to the convex projection," which is likely the factor contributing to this observed result.

In the projections assuming a vertically upward normal vector, significant differences could not be discerned compared to the correct combinations. Therefore, for projections onto curved surfaces within the curvature range of -0.111 to 0.111, we confirmed that the optical errors caused by Kimura et al.'s method are imperceptible, allowing for the effective presentation of BRDF material appearances.

6. Conclusion

In this paper, we demonstrated through subjective evaluation experiments that variations in specular highlights and gradation due to shape do not affect material perception when presenting color changes based on BRDF. We assessed whether observers could notice the incorrect presentation of specular reflection directions and the order of colors around specular highlights when performing projections assuming a planar shape, as proposed by Kimura et al., on convex and concave objects. The results indicated that even when projecting onto convex and concave objects, which have simple shape changes, participants could not perceive differences in specular highlights or gradation. This shows that it is possible to present BRDF material appearances using Kimura et al.'s method.

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