# SpaceRelighter

## – Recording and Reproducing Illumination in a Real Scene –

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**Abstract**

We introduce *SpaceRelighter* , a projector-based mixed reality system that records illumination in a real scene and reproduces it at a later time by projecting a light pattern onto the scene. Users can see a virtually illuminated real scene without having to wear special devices such as a head-mounted display. Because the virtual illumination and real scene are merged in a real 3-D environment and not on a 2-D display, users have a better sense of reality. We first explain the principle of estimating light patterns by photometric and geometric conversion. We then describe an extended method for reducing the problem of occlusion by using multiple cameras and multiple projectors. We constructed a prototype system including two cameras and two projectors to confirm that illumination can be reproduced using projectors.

# 1 Introduction

In a shared mixed reality environment, multiple users share a space in which real and virtual information is mixed. This provides a new style of collaboration. For this type of collaboration to be effective, mutual understanding through eye contact is very important, and the equipment providing virtual information should not hide the faces of users. Head-mounted displays (HMDs) are often used to realize mixed reality systems. However, HMDs hide the faces of users and therefore interfere with mutual understanding. To solve this problem, Takemura et al.[2] proposed a method for recovering eye contact among users by superimposing a facial image on the HMD. Using another approach, projector-based mixed reality systems have been proposed [3][4][5][6] in which virtual information is projected directly onto a real scene. Users do not have to wear special devices such as the HMD, and eye contact can be preserved.

We proposed a virtual photometric environment [7] as one application of projector-based mixed reality systems. It enables arbitrary control over lighting direction and the reflection properties of objects by projecting photometric patterns onto screen objects. To improve the sense of reality, the reflection properties of photometric patterns are acquired from real objects. The reproduction of reality in this way is an important factor in realizing an effective shared mixed reality environment.

In this paper, we introduce *SpaceRelighter* as another approach for improving the reproduction of reality. *SpaceRelighter* records the illumination in a real scene and then reproduces it by projecting a light pattern onto the scene. In other words, projectors mimic the real light sources. As a method for arbitrarily controlling the real lighting conditions of a scene, this technique is important not only for providing a mutual collaboration space among multiple users but also as a fundamental technique for projecting computer graphics onto real objects. This paper describes the principle on which the

*SpaceRelighter* is based and an extended method for reducing the occlusion problem through the use of multiple cameras and multiple projectors.

# 2 SpaceRelighter

## 2.1 Concept

The *SpaceRelighter* is a novel projector-based mixed reality system that can mimic arbitrary illuminations in a real scene. Once a view is recorded with cameras under various illumination conditions such as fluorescent lamps and spotlights, the same illumination can be reproduced using projectors even with the actual light sources removed, as illustrated in Fig. 1. For example, sunlight through a window can be recorded as the day proceeds from morning to night. Then, at any arbitrary recorded time, the illumination effect can be reproduced. This virtual illumination technique can be used for a variety of applications such as housing exhibitions.

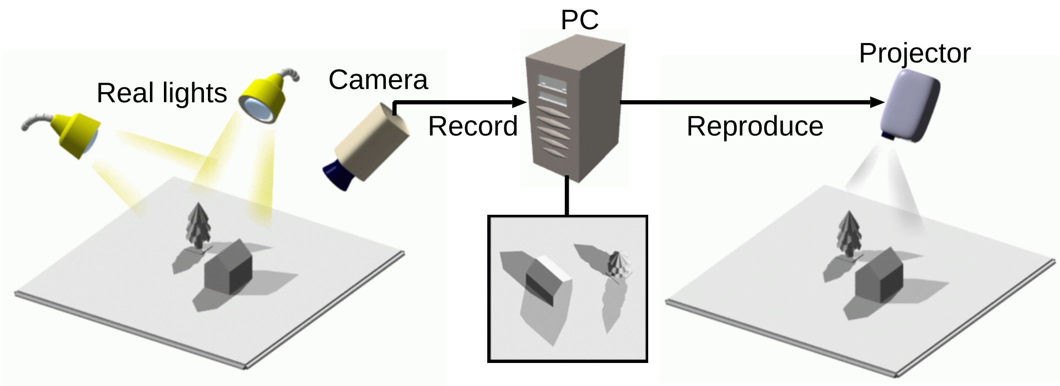



Figure 1: The concept of *SpaceRelighter* .

## 2.2 Principle

*SpaceRelighter* consists of cameras and projectors. The cameras are used to record views under real illumination. The projectors are then used to project light patterns onto the scene at any later time. The projectors mimic the real illumination.

The key technology is image conversion. The recorded view must be appropriately converted to a projected light pattern so that the same view is observed from the camera. The image conversion is divided into a photometric process and a geometric process. Detailed algorithms are presented in the following two sections.

## 2.3 Photometric Conversion

The recorded view is first photometrically converted because the spectral distribution of the projector light and the spectral response of the camera are different. Figure 2 shows examples of the relationships between projected colors and observed colors. These relationships are nonlinear and depend on the characteristics of the individual equipment.

We must determine the colors to be projected so that the desired colors are observed by the camera. To find the correspondence of colors between camera and projector,

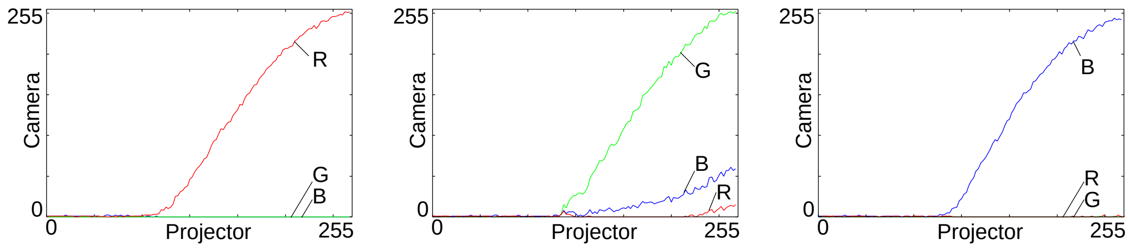



Figure 2: Relationships between projected colors and observed colors.

typical color patterns are projected onto a scene and the images are captured by the camera. Based on the results, we obtain an affine transformation matrix that converts projected colors to observed colors. The inverse of this matrix is used to determine the colors of the projected patterns.

While this photometric conversion method is simple and easy to implement, it is difficult to reproduce colors perfectly by simply projecting light patterns. To solve this problem, we apply a feedback iteration process [9]. If we let $\boldsymbol{I}_t$ be the projecting pattern at $t$ and $\boldsymbol{M}_t$ the captured image of the scene, the pattern that should be projected at $t+1$ can be calculated as

$$\boldsymbol{I}_{t+1} = \boldsymbol{I}_t + \alpha(\boldsymbol{R} - \boldsymbol{M}_t). \tag{1}$$

Here, $\boldsymbol{R}$ is the desired image (recored view). The coefficient $\alpha$ is a parameter controlling the feedback gain.

### 2.4 Geometric conversion

Next, the view is geometrically converted according to the 3-D shape of the scene, the position of the camera, and the position of the projector. For a geometric calibration, we employ the coded structured light method [8]. Several light patterns are projected onto the scene to reconstruct the 3-D shape. Coordinates of the 2-D camera are converted into coordinates of the 2-D projector based on the 3-D shape. The recorded view is divided into many small triangle facets. The vertex coordinates of these triangles are geometrically converted, and the texture of the triangle is mapped to the projection pattern. This process realizes a fully automated geometric conversion without special devices such as a 3-D digitizer.

## 3 Multiple cameras and projectors

### 3.1 Unrecordable and unprojectable region

If the 3-D shape of a scene is simple, a single camera and projector pair works well. However, more complex scenes require that we solve the occlusion problem. Some regions cannot be observed from a single camera. We call these regions *unrecordable*. On the other hand, some regions cannot be projected by a single projector. We call these regions *unprojectable*. Such blind regions can be easily detected. When no texture is mapped to the projecting pattern by geometric conversion, it means the region is unrecordable. If the difference is small when a white pattern and black pattern are projected, it means the region is unprojectable.

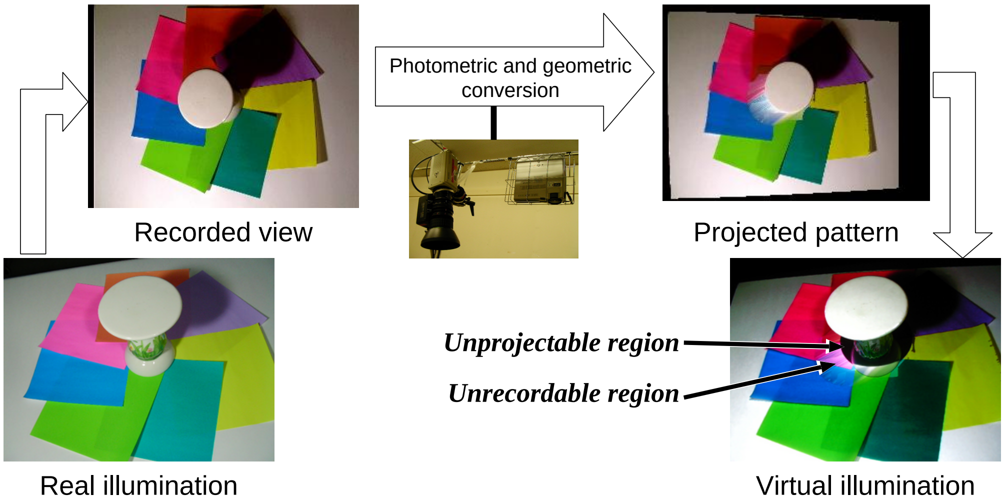



Figure 3: Unrecordable and unprojectable regions.

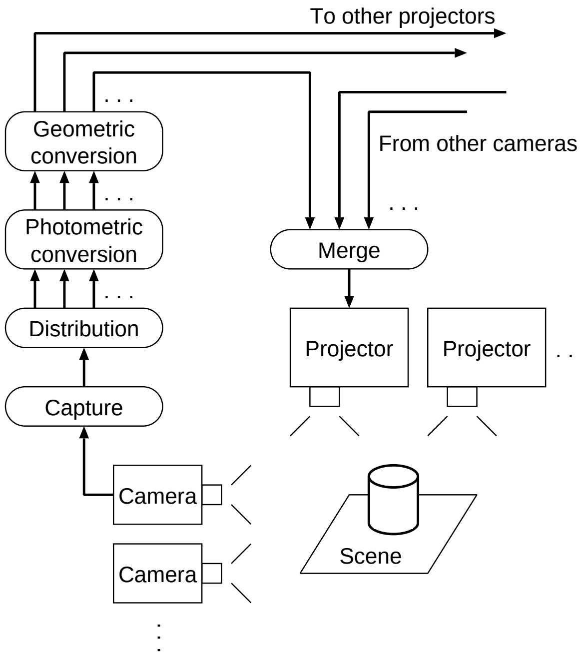



Figure 4: Multiple cameras and projectors.

These occlusion problems can be solved using multiple cameras and projectors. However, we must consider all camera and projector visibility combinations for every triangle facet, and calculating colors according to all visibility combinations becomes complex.

In our method, we divide the complex combination problem into two steps: view distribution and pattern merging. The process flow is illustrated in Fig. 4. The view recorded by a camera is distributed to all projectors according to the visibility of the projectors. Each projector receives projection patterns from all cameras and merges them according to the visibility of the cameras. This method, based on a visibility check, allows us to apply the *SpaceRelighter* to more complex scenes.

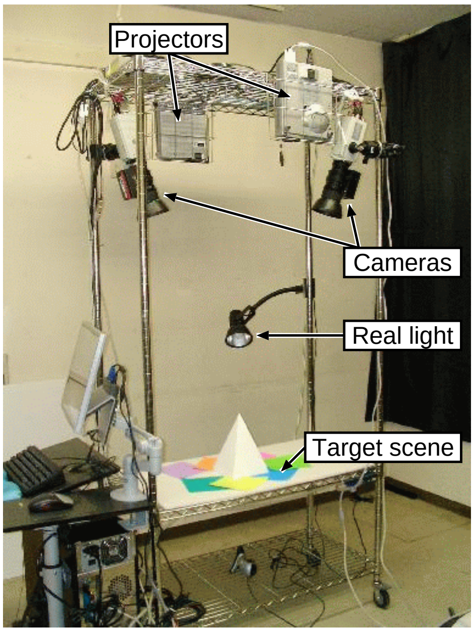



Figure 5: Prototype system of *SpaceRelighter* .

### 3.2 View distribution

The view recorded by the camera is distributed to all projectors. The visibility of each pixel in the recorded view can be evaluated in advance for each camera. In our method, the pixel color is fairly distributed to those projectors that can project the pixel. That is, if a pixel can be projected from $n$ projectors, then that pixel is distributed with $1/n$ times intensity.

### 3.3 Pattern merging

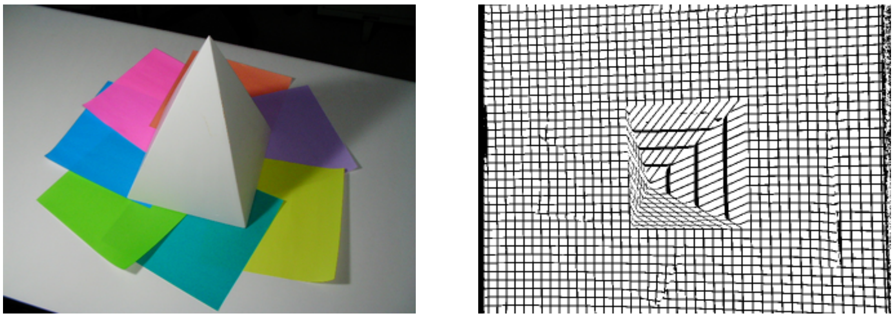
As described in the above section, projection patterns are transmitted from all cameras to each projector. Basically, a projection pattern is determined by averaging pixel intensities. However, it is difficult to perfectly model the photometric properties of the camera and the projector. Hence, transmitted colors may differ among camera, and a simple averaging causes misalignment.

In our method, one camera is selected as a primary camera. The colors of the other cameras are then compensated by an affine transformation to match the colors of the primary camera. The affine transformation matrix can be calculated from pixels in the recordable regions of all cameras.

## 4 Experimental results

### 4.1 Prototype system

We constructed a prototype system comprising one ordinary PC, two 3CCD cameras (SONY DXC-9000), and two DLP projectors (PLUS U4-136), as shown in Fig. 5. The PC is used to capture images from the cameras and to transmit XGA videos to the projectors.



(a) Simple scene without occlusion (b) Geometric relationship

Figure 6: Scene 1 ( Pyramid on color papers).

(a) Recorded view (b) Photometric conversion (c) Geometric conversion

Figure 7: Photometric and geometric conversion.

## 4.2 Simple scene without occlusion

We first confirmed the principles of the *SpaceRelighter* using a single camera and projector pair. Figure 6 (a) shows a simple scene without occlusion, and (b) shows the geometric relationship between the camera coordinate and the projector coordinate by grid. Because the camera and projector are installed just above the pyramid, there are no unrecordable regions and no unprojectable regions.

Figure 7 shows the results of photometric and geometric conversion. In this figure, (a) shows a recorded view under real illumination, and (b) and (c) show the results of photometric and geometric conversion, respectively. In the photometric conversion, brightness and color are compensated according to the properties of the equipment. In the geometric conversion, the viewpoint changed to the projector position.

Figure 8 shows the process of feedback iteration. The top row shows the projected patterns before geometric conversion, and the middle row shows the images captured by the camera. The bottom right image is the recorded view. Because the nonlinear relationship between projected colors and observed colors is not strictly considered, the illumination is not correctly reproduced at $t = 0$. However, the captured image becomes similar to the recorded view after feedback iteration. Figure 9 (a) and (b) show the recorded view and the reproduced view taken by another camera. It is difficult to distinguish between the two images except for cast shadow region. It is clear that the illuminations in a scene can be recorded and reproduced when the scene has no unrecordable and unprojectable regions. That is, we can say that the projector can mimic any real light source.

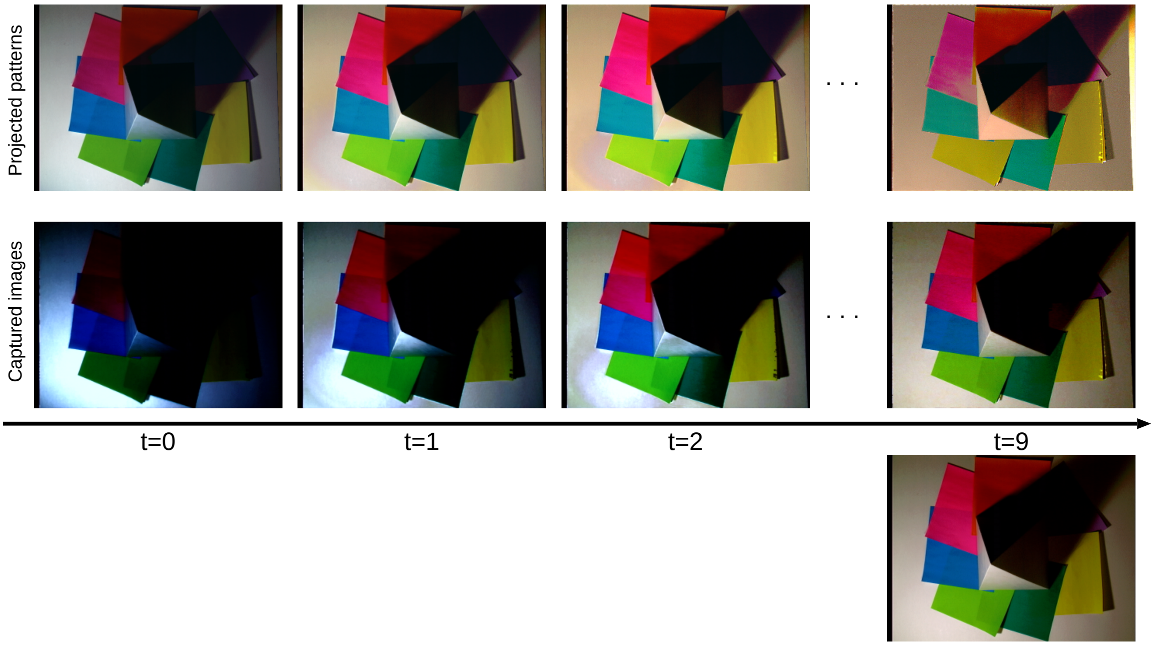
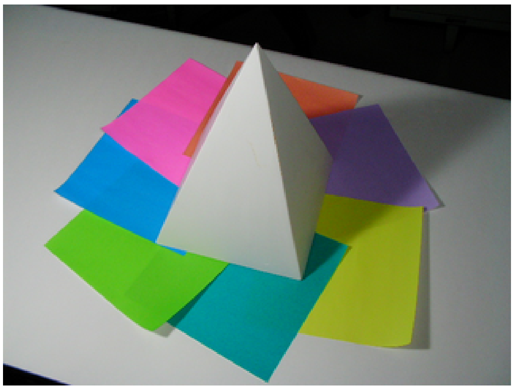
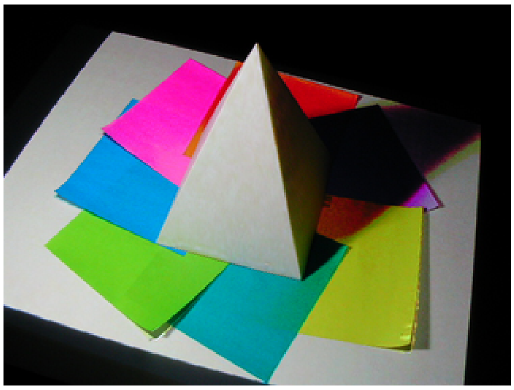



Figure 8: Feedback process.



(a) Under real lights



(b) Under virtual illumination

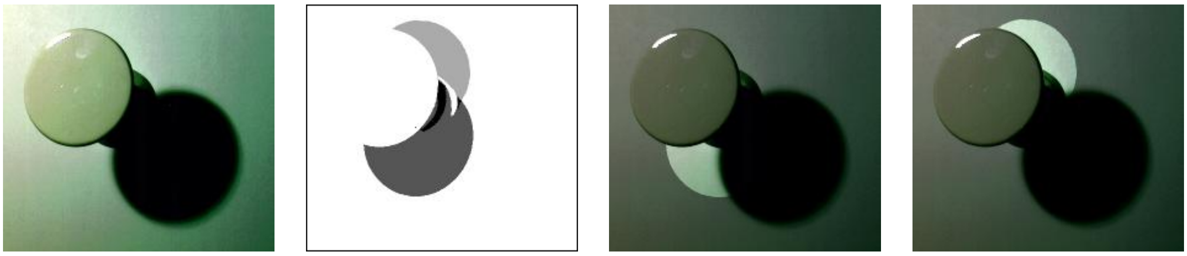
Figure 9: Comparison of the reproduced virtual view with the recorded real view.

## 4.3 Complex scene with occlusion

We next confirmed the ability to reduce the occlusion problem using two cameras and two projectors. In the target scene, a ceramic object is illuminated by a point light source as shown in Fig. 10. While the shape of the ceramic is not very complex, both unrecordable and unprojectable regions exist. Therefore, a single camera and projector pair cannot correctly record and reproduce the scene illumination.

Figure 11 shows the result of view distribution. In the figure, (a) is an image captured by the camera #1, and (b) illustrates the unprojectable regions of each projector. White in this figure indicates the region that is projectable by both projectors. Dark gray and bright gray indicate the regions that can be projected by only projector #1 and projector #2, respectively. Black indicates the region that is unprojectable by both projectors. Figure 11 (c) and (d) show the results of view distribution, indicat-

Figure 10: Scene 2 (ceramic object).



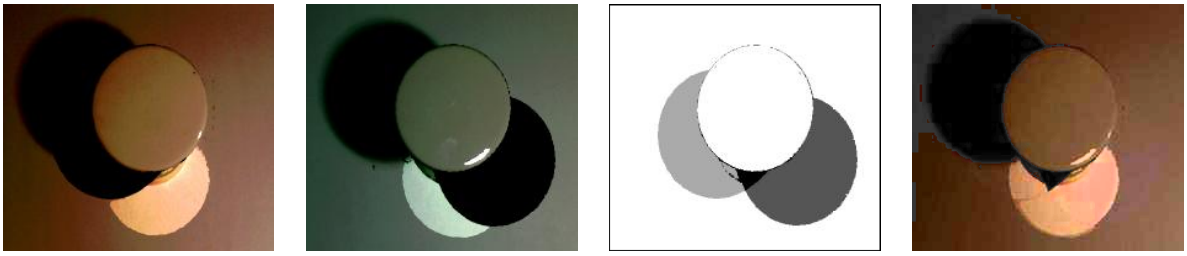
(a) (b) (c) (d)

Figure 11: Results of the view distribution: (a) recorded view; (b) unprojectable regions of each projector; (c) distributed view to projector #1; (d) distributed view to projector #2.

ing that the recorded view is appropriately distributed while taking into account the unprojectable regions of the projectors.

Figure 12 shows the results of the pattern merging. In the figure, (a) and (b) show the patterns transmitted to projector #1 from camera #1 and camera #2, respectively, and (c) shows the unrecordable regions of each camera in the same manner as Fig. 11 (b). Figure 12 (d) indicated that the patterns transmitted from two cameras are appropriately merged while taking into account the unrecordable regions of the cameras.

To evaluate the precision of reproduced illumination, we recorded images of the scene using an additional digital camera (SANYO DMX-C1) and compared the real view to the reproduced view. The additional camera is used only for verification, as it has a different spectral distribution response from the cameras used to record the illumination. Figure 13 shows the image captured by the camera installed close to the user's viewpoint. The left four images are the reproduced illumination at $t = 0, 2, 4, 6$, respectively, while the right image is the recorded view under real illumination. Although the boundaries of the unrecordable and unprojectable regions are clearly observed at $t = 0$, the error gradually decreases after several iterations of the feedback process. We can see that the projectors behave like real light sources.



(a) (b) (c) (d)

Figure 12: Result of the pattern merging: (a) pattern from camera #1; (b) pattern from camera #2; (c) unrecordable regions of each camera; (d) merged result.

t=0 t=2 t=4 t=6 Recorded view

Figure 13: Captured images of reproduced illumination using additional camera.

# 5 Conclusion

We introduced *SpaceRelighter* , a system for recording illumination and reproducing it by pattern projection. It is one application of projector-based mixed reality systems. In a target scene containing a simple shape without occlusions, we confirmed that the illumination was perfectly reproduced by projecting an appropriate photometric pattern onto the scene. To reduce the occlusion problem, we introduced a method of distributing captured images and a method of integrating projected patterns using multiple cameras and projectors. To evaluate the ability to solve the occlusion problem, we constructed a prototype system using two cameras and two projectors. While the occlusion problem remains partially unsolved, it should be solvable by using additional cameras and projectors.

Reproduced illumination cannot be distinguished from the real illumination of a scene as observed by the camera used to record the illumination. However, the color of the recorded view often differs if the scene is observed by another camera having a different spectral response. The recorded view depends on the characteristics of the camera in the current implementation. We need to investigate our algorithm further so that illumination is recorded as universal colors independent of the individual cameras. One of our future projects will be to solve the color constancy problem.

# Acknowledgement

This research was supported by the Ministry of Education, Science, Sports and Culture, Grant-in-Aid for Young Scientists (B), 14780290, 2002.

# References


[1] Y.Ohta and H.Tamura: “Mixed Reality: Merging Real and Virtual Worlds”, Ohmsha / Springer-Verlag, 1999.

[2] M. Takemura adn Y.Ohta, “Diminishing Head-Mounted Display for Shared Mixed Reality”, IEEE and ACM International Symposium on Mixed and Augmented Reality (ISMAR 2002), pp.149-156, 2002.

[3] J.Underkoffler, B.Ullmer, and H.Ishii, “Emancipated Pixels: Real-World Graphics In The Luminous Room”, Proc. SIGGRAPH’99, pp.385-392, 1999.

[4] R.Raskar, G.Welch, and W.C.Chen, ‘Table-Top Spatially-Augmented Reality: Bringing Physical Models to Life with Projected Imagery”, Proc. International Workshop on Augmented Reality’99(IWAR’99), pp.64-71, 1999.

[5] R.Raskar, G.Welch, K.Low and D.Bandyopadhyay, “Shader Lamps: Animating Real Objects With Image-Based Illumination”, Proc. Eurographics Rendering Workshop (ERGW2001), pp.89-102, 2001.

[6] S.Hiura, K.Tojo and S.Inokuchi, “3D Tele-Direction Interface Using Video Projector”, SIGGRAPH 2003 Sketches, 2003.

[7] Y.Mukaigawa, M.Nishiyama and T.Shakunaga, “Realization of Virtual Photometric Environment by Photometric Pattern Projection”, Proc. IEEE International Symposium on Computational Intelligence in Robotics and Automation (CIRA2003), pp.435-440, 2003.

[8] K.Sato and S.Inokuchi, “Range-Imaging System Utilizing Nematic Liquid Crystal Mask”, Proc. ICCV’87, pp.657-661, 1987.

[9] S.K.Nayar, H.Peri, M.D.Grossberg, and P.N.Belhumeur, “A Projection System with Radiometric Compensation for Screen Imperfections” Proc. ICCV Workshop on Projector-Camera Systems (PROCAMS), 2003.