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Successive Wide Viewing Angle Appearance Manipulation with Dual Projector Camera Systems

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Abstract

In this study, we investigated the use of successive omnidirectional appearance manipulation for the cooperative control of multiple projector camera systems. This type of system comprises several surrounding projector camera units, where each unit projects illumination independently onto a different aspect of a target object based on feedback from the projector cameras. Thus, the system can facilitate appearance manipulation from any viewpoint in the surrounding area. An advantage of this system is that it does not require information sharing or a geometrical model. However, this approach is problematic because the stability of the total control system cannot be guaranteed even if the feedback system of each projector camera is stable. Therefore, we simulated the feedback from the cooperative projector camera system to evaluate its stability. Based on hardware experiments, we confirmed the stability of omnidirectional appearance manipulation using two projector camera units in an interference condition. The results showed that the object's appearance could be manipulated throughout approximately 296 degrees of the total circumference of the target object.

Categories and Subject Descriptors (according to ACM CCS): H.5.1 [Information Interface and Presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities

1. Introduction

The projection display technique is a key method employed in spatial augmented reality [BR05], which allows various environments to be augmented directly onto real objects without the need for head-mounted displays or other mobile devices. Thus, users are not required to wear or hold any display devices. In addition, this approach can easily be applied to public viewing situations such as projection mapping because there is no requirement for individual processing that depends on the user's viewpoint.

The Shader Lamps [RWLB01] proposed by Raskar et al. is a well-known pioneering work in projection displays, which used multiple precisely aligned projectors and they represented brick texture and shadow animations based on the movement of the sun on a physical model of the Taj Mahal. A major problem when applying projection displays to 3D objects is that shadows are produced by self-occlusion of a complex shape or by the use of multiple target objects. This problem has been solved by using a modified feathering algorithm, which is an image-blending technique.

The application of projection display is not limited to a texture projection and it has been applied for a high quality synthesis of virtual reflectance on real objects [OOD10], an overlay projection on a degenerated ancient base for virtual restoration [ALY08], high dynamic range display by the overlay projection [SIS11] and other applications.

Unlike conventional projection displays, Amano et al. [AK08] proposed a successive appearance manipulation technique. This technique comprises a projector-camera feedback system and enhances an object's appearance by a projection. Furthermore, employment of a Model Predictive Control with a reflectance estimation enables desired manipulation where the appearance becomes the same as a reference image [AK10]. Its major advantage is that appearance manipulation using coaxial projector camera optics allows successive appearance manipulation of 3D object without object models, and it does not require projection registration on the target object [AKS*12]. Thus, we can use this technique when the desired appearance is obtained by modifying the original appearance. Hence, this appearance manip-

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ulation technique is similar to photo retouching in an actual environment and it is convenient for non-professional use.

In this study, we aimed to achieve omnidirectional appearance manipulation by extending the appearance manipulation technique to multiple independent working projector camera systems. First, we investigated the stability of the system based on control theory and we evaluated the capacity for successive omnidirectional appearance manipulation using multiple projector camera systems based on numeric simulations and hardware experiments.

2. Related Work

Most projection display techniques are based on physical models, where they estimate surface reflection from a premeasured shape using an appropriate Lambert reflection model. Therefore, they facilitate physically correct appearance editing. However, these approaches require a geometrical model that captures the shape and reflectance, as well as the precise projection registration under the correct ambient lighting environment. These requirements are not difficult to satisfy for fully designed booths such as those used in theme parks and museums, but they are not easy to meet in everyday environments. Thus, the image-based approach using a projector camera feedback system may be a good solution in these situations. Nayar et al. proposed a radiometric compensation method for a non-uniform textured screen with projector camera feedback [NPGB03]. Grossberg et al. considered ambient light in a photometric model and they demonstrated its ability to alternate the appearance of a 3D textured object [GPNB04]. A similar modeling approach was also proposed by Yoshida et al. for the projection-based virtual restoration of a damaged oil painting [TYS03]. In a later study, Fujii et al. [FGN05] applied this radiometric compensation technique to a dynamic scene with a coaxial device configuration.

The projector camera feedback system facilitates radiometric compensation and appearance manipulation based on the original appearance. The superimposed dynamic range technique allows a highly dynamic range display and color compensation on printed media based on illumination projection [BI08]. Furthermore, the projector camera system enables appearance enhancement and successive appearance manipulation [AKS*12]. The coaxial projector camera system shown in Figure 1 is employed to achieve appearance manipulation and to implement appearance manipulation techniques, where this projector camera system allows successive manipulation without a model of the projection target. This type of coaxial projector camera system was originally introduced in [FGN05, ZN06]. Because the coaxial optical system determines the geometrical pixel relationships between a projector and an invariant camera, the implementation of appearance manipulation using these optics allows successive manipulation without a model of the target object.

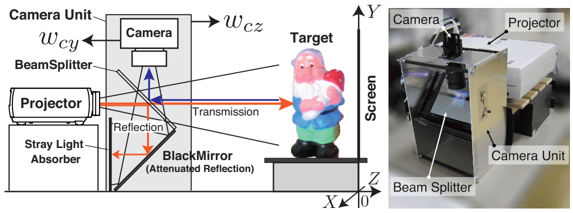

Figure 1: *Coaxial projector camera system [AKS*12]. The outgoing ray passes through the beam splitter and the incoming ray is reflected by the beam splitter. The major problem that affects the coaxial optics is stray light. Thus, the optics reduce stray light via black mirror reflection before absorbance using a black material.*

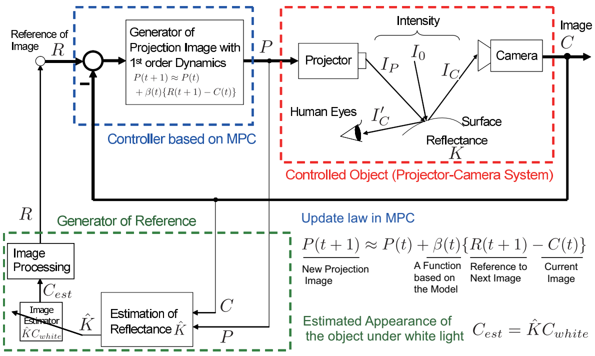

Figure 2: *Diagram showing the appearance control technique. The process is divided into three main parts: a controlled object, a controller that employs model predictive control, and a reference generator. The most important component is the reference generator, which allows adaptive scene appearance manipulation in a similar manner to photo retouching software.*

3. Analysis of the Stability of Appearance Manipulation

3.1. Single Projector Camera Model

The appearance manipulation process using a projector camera system proposed by Amano et al. [AK10] can be modeled as a feedback system, as shown in Figure 2. In this study, we consider the corresponding single pixel relationship between a projector and a camera using the model.

The appearance manipulation process comprises three main parts: a "controlled object," a "controller based on model predictive control," and a "reference generator," where each component can be described by transfer functions. However, the nonlinear property of the "estimation of reflectance" makes it difficult to perform an analytical evaluation of the stability of system. Thus, we consider a theoretical analysis based on a static image relative to R in the following subsection. In this simplified model, the appear-

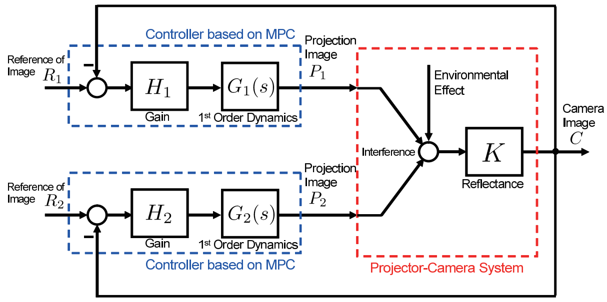

Figure 3: *Example of an interference situation based on projector camera feedback. The projection from one system can interfere with that from another system. The system cannot distinguish this interference from environmental illumination, which leads to control errors.*

ance manipulation process behaves in the same manner as radiometric compensation, as described by [GPNB04].

3.2. Cooperative Projector Camera Feedback

In this section, we model the interference situation where multiple projections overlap by using feedback components from a controlled object and two controllers, as shown in Figure 3. Each processing component for projector camera system i comprises the constant gain H_i and the open loop transfer functions $G_i(s)$ of the primary delay system, which are expressed by the Laplace variable s.

In this model, we assume that two projector camera systems project illumination onto the same point, which mixes with environmental illumination. Since we assume Lambert reflection, the reflection with a reflectance ratio K is observed by each system as the same brightness.

If we consider that two static images are given to each projector camera unit, we can describe the reference images as

$$R_i \propto \frac{1}{s},\ i = 1,2. \tag{1}$$

Thus, we may obtain the necessary and sufficient condition for stable appearance control where

$$\begin{aligned} &\frac{KG_i(s)}{1+KG_i(s)H_i}, \quad \frac{G_i(s)}{1+KG_i(s)H_i}, \\ &\frac{K}{1+KG_i(s)H_i}, \quad \frac{KG_i(s)H_i}{1+KG_i(s)H_i}, \qquad i = 1,2 \end{aligned} \tag{2}$$

are stable.

This suggests that we can stabilize the projector camera systems in an interference situation, even if each system works independently without sharing projection images when radiometric compensation is applied to the system.

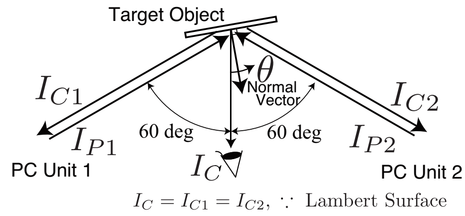

Figure 4: *Simulation setup. We placed two projector camera units on both sides of an observer. Each unit projected illumination I_P and observed the reflected illumination I_C. However, all of the reflected illumination should be equivalent because we assume Lambert reflection as the reflection property.*

4. Experimental Results

4.1. Numerical Simulation

We evaluated a cooperative projector camera feedback system that included reference generation based on a numerical simulation in terms of the system stability and irradiation deviation.

Figure 4 shows the setup of the numerical simulation. In this simulation, we assumed that the surface property was Lambert reflection and we expressed the direction of the normal vector as θ. $\mathbf{I}_{Pi}$ denotes the light projected from each projector camera unit, which were placed on both sides of the viewing angle at intervals of 60 degrees. Since we assumed Lambert reflection, the brightness $\mathbf{I}_{Ci}$ and $\mathbf{I}_C$ observed from each viewpoint were equivalent. However, in our simulation, the illuminance from each projector could be changed by θ due to the cosine law of the incident angle.

Figure 5 shows the responses of the projected light $I_{P1,j}$, $I_{P2,j}$ and observed brightness $I_{C,j}$ for each projector camera system. We designed a color projector camera model with three channels $j \in \{R,G,B\}$ and color saturation enhancement for reference generation as

$$R_j = gain\{(1-sat)\,\bar{C}_{est} + sat\ C_{est,j}\} \tag{3}$$

where $C_{est,j}$ is the estimated true appearance, which is the appearance under white light, $\bar{C}_{est}$ is the average of $C_{est,R}, C_{est,G}, C_{est,B}$, and *gain* and *sat* are the brightness gain and saturation, respectively. In our simulation, we set $\theta = -20$ deg., physical reflectance ratio $(k_R, k_G, k_B) = (0.5, 0.4, 0.6)$, $gain = 0.75$, $sat = 2.0$ for both projector camera systems. In this case, we can see that all $I_{P1,j}$, $I_{P2,j}$ converged without fluctuations or divergence. It was notable that both of the projection powers were balanced in the convergence result. However, the controlled result was overestimated because the projection from one system could interfere with that from the other system. This problem will be addressed in our future research.

We also evaluated the irradiance deviation for each θ (fig-

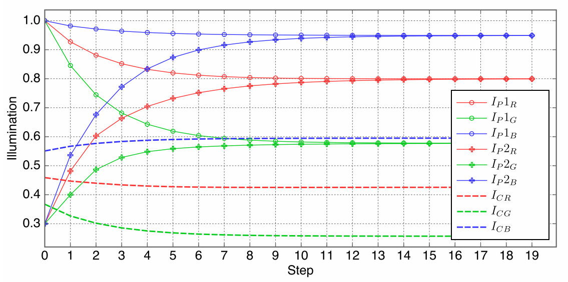

Figure 5: *Step response in the interference situation. It is notable that the independent projector camera systems were balanced, although each projection was initialized with different gray levels.*

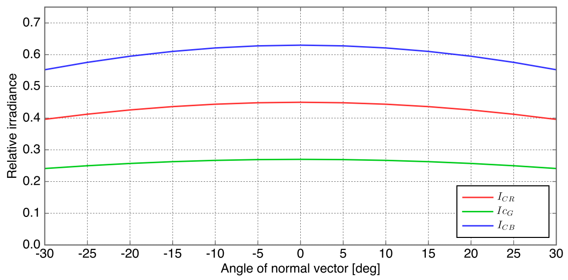

Figure 6: *Iluminance decline due to the surface normal direction. The surface normal direction affected the estimation of the reflectance and the brightness in marginal areas of the target object. It is similar to the attached shadow.*

ure 6). Unfortunately, the irradiance, which comprised both the projection and environmental illumination, changed with θ and the irradiance declined by 12.3% in the worst case at $-30 \leq \theta \leq 30$ degrees. However, this feature was very similar to the attached shadow and we do not expect that it would appear unusual.

To validate the stability of the system further, we performed more simulations with several parameters and other types of image processing. We confirmed that the system was stable when we selected appropriate parameters to stabilize the single projector camera system.

4.2. Hardware-based Experiments

In our experiments, we placed two projector camera units at the front left and right positions of the projection target, as shown in Figure 7. Since each unit is working without information sharing, precise alignment that means two projection center axes are in same horizontal plane or facing the target object is not needed. Overlapping projection using these two projectors covered approximately 296 degrees of the object's circumference. This was much wider than the coverage

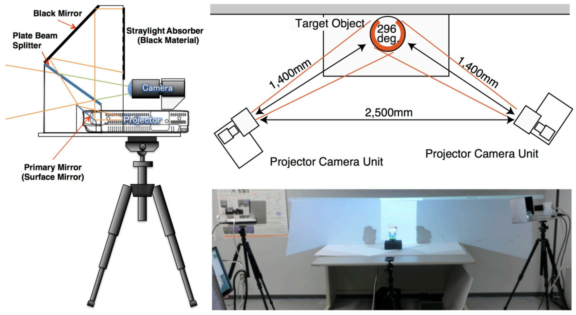

Figure 7: *Hardware settings. Left: Projector camera unit mounted on a tripod, which was used in our experiment. The projector camera unit comprised an IEEE1394 camera (960×720 image resolution), DLP projector (1024×768 image resolution), and a plate beam splitter with a stray light absorber. Right: Layout of the two projector camera units.*

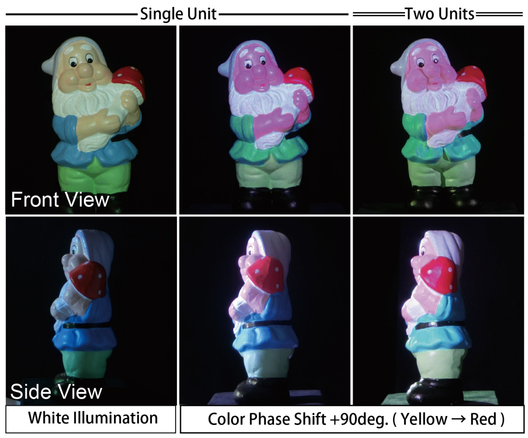

Figure 8: *Left: Appearance with white illumination projection from a single projector camera unit placed in front of the target object. Middle: Color phase manipulation results with the single projector camera unit. Right: Overlapping projection using two independent projector camera units to obtain an expanded manipulation area with stable control.*

of 170 degrees obtained using a single projector. Each projector camera unit was connected to a different processing computer (MacPro 6-core Intel Xeon 3.5 GHz and MacPro 4-core Intel Xeon 3.7 GHz) and the projector cameras operated independently based on feedback provided by the same programs.

Figure 8 shows the manipulation results obtained for a ceramic doll. In this experiment, we implemented color phase shift:

$$\mathbf{R} = gain\ \mathbf{U}\,\mathbf{T}\,\mathbf{U}^T\,\mathbf{C}_{est} \quad (4)$$

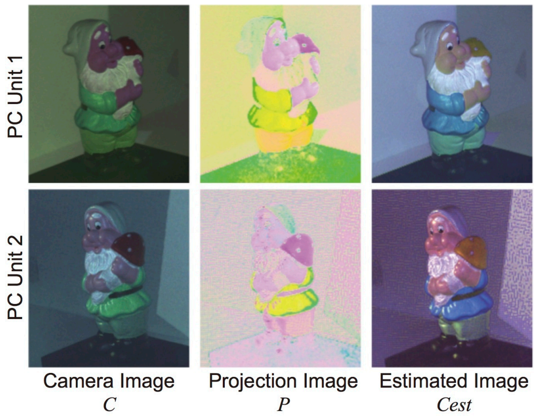

Figure 10: *Internal processes. The appearance with white light projection C_{est} was estimated from the captured image C and the projected image P. The individual feature of the projectors changed the estimated image color slightly.*

where $\mathbf{R} = (R_R, R_G, R_B)^T$, $\mathbf{C}_{est} = (C_{est,R}, C_{est,G}, C_{est,B})^T$ and

$$\mathbf{U} = \begin{bmatrix} \frac{\sqrt{3}}{3} & \frac{\sqrt{3}}{3} & \frac{\sqrt{3}}{3} \\ \frac{\sqrt{6}}{3} & -\frac{\sqrt{6}}{6} & -\frac{\sqrt{6}}{6} \\ 0 & \frac{\sqrt{2}}{2} & -\frac{\sqrt{2}}{2} \end{bmatrix}, \mathbf{T} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi & \cos\phi \end{bmatrix},$$

as the reference generation algorithm and we used the same processing parameters. The original texture color was replaced completely by the color phase shift algorithm ($\phi = 90$ degree) in both settings (single projection and dual projection). When we used two projector camera units, the projections were merged appropriately and they covered most of the visible regions. The projector camera feedback processing speed reached 25 fps. Clearly, we could also apply other processing methods to the system in addition to color phase shift, as shown in Figure 9.

Figure 10 shows the final images for a captured image C, a projected image P, and the estimated appearance C_{est} with each projector camera unit. These images confirm that the two projected images were balanced. The results were similar to the simulation, thereby confirming that the cooperative projection system operated successfully. The target object has isotropic surface reflection properties, which means that its appearance should be invariant in different viewing direction. However, the individual features of the projectors changed the hue of these images slightly because the color calibration procedure performed for the projector camera system relied on color reproducibility in the projected illumination. This problem can be solved by precise hardware color calibration for the projected light, although this is not possible with consumer products due to their inflexible hardware color adjustment function.

5. Discussion and Future Work

An additional projector camera unit could be placed at the rear of the target object to facilitate better omnidirectional appearance manipulation. However, the construction of a system with fewer projector camera units is preferable to reduce the hardware costs. In our experiment, most of the projected light rays did not contribute to appearance manipulation due to the wide angle of projection, as shown in Figure 7. Thus, the use of reflected projection via a mirror might be a good solution, as shown on the left side of Figure 11.

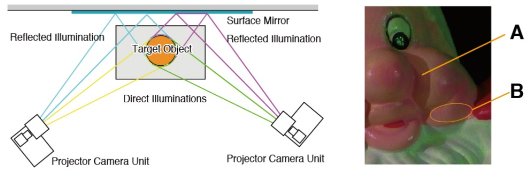

Figure 11: *Left: A wall-mounted mirror reflects stray projection light and omnidirectional appearance manipulation is achieved without additional projector camera units. Right: The errors in reflectance estimation caused by the cast shadows and different normal directions are major issues that need to be addressed in our future research.*

Since it is equivalent to the situation that placed another object on mirror reflection position, it is clearly controllable. However, a problem with these optics is the compensation of brightness differences between the front and rear views. This occurs because the length of the illumination path with mirror reflection is longer than the direct projection, which affects the reflectance estimation as the density of the projection light flux depends on the inverse-square law.

Another problem is the irradiance discontinuity caused by the shadow of the projection image, which is indicated as region A on the right-hand side of Figure 11. This occurs because only one projection image can reach the target object, which means that there is a difference in the estimated reflectance in the shadow region and other regions. Even if both projections are achieved, a deviation in irradiance can be caused by the normal direction, as shown in region B, which was suggested by the numerical simulation.

These problems appear to be different but they have the same common cause: the overestimation of reflectance. In our future research, we will attempt to find a solution to these problems based on the interesting feature that the projection powers can be balanced between different projector camera systems using cooperative projector camera feedback.

6. Conclusion

In this study, we investigated the stability of cooperative control for independent projector camera systems. Using numerical simulations and hardware-based experiments, we confirmed the stability of the appearance manipulation obtained with two projector camera units when interference occurred. This cooperative appearance manipulation approach using

Figure 9: *Appearance manipulation results. The top row and bottom row show front and side views, respectively, of the appearance manipulation results obtained using two projector camera units. From left to right, each column shows: the appearance under white illumination, color saturation enhancement, color removal, color phase shift with $\phi = -90$ degrees and $\phi = 90$ degrees, and optical hiding.*

three or more projector camera units is theoretically stable; thus, we consider that omnidirectional appearance manipulation may be possible. However, there is a major problem due to the reflectance overestimation caused by the illumination projected from other units. We assume that the systems work independently, which means that this is an ill-posed problem, but we consider that the balanced projection powers among different system may allow the solution of this problem.

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