International Conference on Artificial Reality and Telexistence
Eurographics Symposium on Virtual Environments (2017)
R. Lindeman, G. Bruder, and D. Iwai (Editors)

Viewpoint-Dependent Appearance-Manipulation with Multiple Projector-Camera Systems

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Figure 1: *Viewing-direction-dependent appearance-manipulation results. These pictures show the appearance at each viewpoint. Horizontally aligned four projector-camera unit pairs manipulate the appearance of the newspaper from each viewpoint. The two left-side units reduce the saturation, and the other two units enhance saturation with the appearance-manipulation technique. Because the news ink has gloss reflection, the projection from the other side cannot be influenced, and we can apply a different manipulation at each viewpoint.*

Abstract

This paper proposes a novel projection display technique that realizes viewing-direction-dependent appearance-manipulation. The proposed method employs a multiple projector-camera feedback system, and each projector-camera system simultaneously manipulates the apparent color or contrast from the different viewing directions. Since we assume the mirror reflection is a dominant component, we placed the camera on the counter side of the projector for the system. We confirmed that our multiple projector-camera system enables viewpoint-dependent appearance-manipulation on an anisotropic reflection surface by the experimental results. Interestingly, the application target is not limited to a metallic surface, and we have confirmed that it can be applied to matte paper media for glossy ink reflection.

CCS Concepts

•***Human-centered computing*** → *Mixed / augmented reality;* •***Computing methodologies*** → *Mixed / augmented reality;*

1. Introduction

The structural color has complicated reflections and interferences, and it shows different apparent colors from each viewing angle caused by optical interference. This is not only true for structural color objects, but our diverse surroundings also have complex bidirectional reflection-distribution functions (BRDF), which show viewpoint-dependent reflections. In this paper, we propose a cutting-edge projection display technique that enables diverse appearance-manipulation at each viewpoint to alter perceptual BRDF with a multiple projector-camera system (Figure 1).

In their pioneering work, the Shader Lamps [RWLB01] enabled mapping of a brick texture with shadow animations based on the movement of the sun onto a physical model of the Taj Mahal. A virtual photometric environment system [MNS04] enables control of the lighting directions and the reflection properties of objects. Recently, a novel real-time projection-mapping system, which allows multiple projections onto arbitrarily shaped surfaces, has been proposed. Resch et al. proposed a fast posture estimation method from the image feature of the projection surface and enabled fast-tracking for 3D projection mapping [RKK15]. Siegl enabled dynamic illumination correction for the freely moving objects without the markers on the objects [SCT*15].

The projection display technique is not limited to projection onto solid-color objects; it also enables appearance-manipulation by overlap-projection on textured surfaces. For example, projec-

DOI: 10.2312/egve.20171346

tion display enables the virtual restoration of oil paintings [YHS03] and of degenerated ancient clay vases [ALY08]. Additionally, it enables a high-dynamic-range display, which combines object albedo and an overlay projection [BI08]. Such high-dynamic-range display techniques have also been applied to improve the contrast of the texture of the objects which fabricated by a 3D printer [SIS11].

Both optical theory and perceptually based material appearance display [OOD10] and editing [LAS*11] techniques have been proposed. This projection based material perception manipulation was also accomplished as a successive process by projector-camera feedback [Ama13]. As for other perception manipulation techniques, the augmentation of physical avatars [BBG*13] can increase expressiveness. In addition, the perceptual approach of the Deformation Lamps can add an illusory deformation [KFSN16], and Swinging 3D Lamps create 3D optical illusions of motion parallax on 2D paintings [ONH17].

Until now, all projection display applications attempt to show textures on solid objects or manipulate appearances with overlay projections. However, those techniques assume a Lambert reflection on objects ’ surfaces. Therefore, viewing-direction-dependent appearance-manipulation is impossible.

The main contribution of this paper is a novel projection display technique that realizes direction-dependent appearance-manipulation using a multiple projector-camera feedback system. To the best of our knowledge, this is the first attempt to create a viewing-direction-dependent appearance-manipulation system using closed-loop feedback.

2. RelatedWork

Our research attempts to manipulate the perceptual BRDF from the context of a projection display. When we precisely manipulate light distribution on a surface, various apparent materials can be displayed. This manipulation has been practically realized via a horizontal parallax (e.g., auto-stereoscopic 3D display).

2.1. Auto-Stereoscopic 3D Display

The 3D display system can be achieved using a projector array of two vertically oriented lenticular lenses and a diffuse screen [MP04, YHLJ08]. The projection image first passes through a lenticular lens and focuses on the diffuse screen. Then, the second lenticular lens redistributes the image in a different angular direction. In recent years, Jones et al. [JUN*15] demonstrated a narrow horizontal blur auto-stereoscopic 3D display that employed 216 closely spaced projectors.

The auto-stereoscopic 3D display also can be rendered via front-projection [MP04]. Nagano et al. [NJL*13] proposed an auto-stereoscopic projection display that projects 72 overlay images onto a vertically oriented lenticular screen with its back painted black. The front projection not only can represent parallax, but it can also alter the surface light distribution and represent wing structural color reflections of a Morpho butterfly on the retroreflective surface [AM15].

2.2. Designed Mesostructure

The above-mentioned auto-stereoscopic 3D displays rely on the retro reflection property and require a lenticular screen or retro-reflective film. Otherwise, they require embedding microbeads densely in the coating. This method can be used for a display technique, but it is not a good solution for a perceptual alternation of the BRDF, even if we can add the retro reflection properties by the paint that contains microbeads.

Alternatively, the mesostructure design technique produces a dissimilar image using a different illumination direction [AM10]. In this technique, a discrete relief model contains many pyramid-shaped structures, and their reflection and shadow-casting properties produce the desired image via height-optimization of the pyramids. The mesostructure design is not impossible to apply to industrial solutions, but it requires a restricted illumination environment. For our solution, we designed an illumination pattern for the projection display technique.

2.3. Projector Camera Feedback

Radiometric compensation using closed-loop feedback was proposed in an earlier work [GPNB04]. This framework can easily compensate irradiance errors, and it shows the desired image correctly onto a textured screen. Unlike radiometric compensation, the appearance-manipulation technique enhances, changes, and replaces the apparent appearance based on the physical reflectance of the projection target [AKS*12]. In this method, the desired appearance is provided with a user-defined processing algorithm, and the system converges the projection patterns to alter the appearance to the desired.

When the projection target has a non-Lambertian reflection, such as specular and other structural reflections, the overlay projection from multiple light sources shows different appearances from each viewing direction. In this research, we focus on this optical property and enable a viewing-direction-dependent appearance-manipulation that uses a multiple projector-camera feedback system. The appearance-manipulation technique optimizes the projection pattern during the feedback process and enables successive manipulations of the perceptual BRDF.

3. Viewpoint-Dependent Appearance-Manipulation

Our goal is to alternate the object BRDF of our perception by using viewing-direction-dependent appearance-manipulation, as shown in Figure 1. This means that the user can perceive various BRDFs on the same object, and we can change the apparent BRDF instantaneously with illumination projection.

Alternation of apparent BRDF enables not only color manipulation but also manipulation of the perceptual surface normal and it provides us the realistic perception of metal reflection, clear glass refraction, complex anisotropic reflection and structural color materials (e.g. pearl color, iridescent color, and reflective rainbow) as shown in Figure 2. In addition, the perceptual BRDF manipulation can be an innovative projection technique that provides higher stage perceptual manipulations such as material density, roughness, and elasticity.

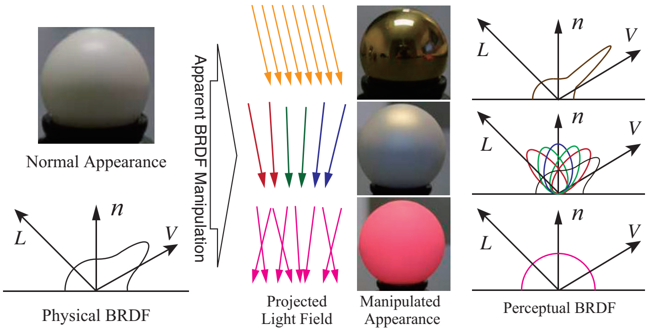


Figure 2: *The concept of apparent BRDF manipulation.*

Table 1: *Reflection mode. The reflection models can be represented by the following element arrangements. The reflection matrix* K *represents the contribution of the illumination from the projector to each camera. When the anti-diagonal element is dominant, it makes the feedback unstable and leads to vibration.*

Retro Reflection	Mirror Reflection	Lambert Reflection
Incident Light	Incident Light	Incident Light
$\begin{pmatrix} k_1 & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & k_2 & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & k_3 \end{pmatrix}$	$\begin{pmatrix} \mathbf{0} & \mathbf{0} & k_1 \\ \mathbf{0} & k_2 & \mathbf{0} \\ k_3 & \mathbf{0} & \mathbf{0} \end{pmatrix}$	$\begin{pmatrix} k_1 & k_2 & k_3 \\ k_1 & k_2 & k_3 \\ k_1 & k_2 & k_3 \end{pmatrix}$
Directly measurable	Immeasurable	Measurable

To achieve direction-dependent appearance-manipulation, we composed a multiple projector-camera feedback system, shown in Figure 3(a). This diagram shows the signal flow of the pixel values corresponding to the single point of the surface. The system consists of several projector-camera units, each consisting of a camera and a projector; they simultaneously perform appearance-manipulation [Ama13]. Because projections from some units can interfere with other units, stability should be discussed.

In the diagram, $i = 1,2,...,n$ are the indices of the unit; I_{pi} are projected illuminations of the color image $P'_i \in \mathcal{R}^3$; and $C'_i \in \mathcal{R}^3$ are buffered pixel values of the scene irradiance I_{ci}. These variables have three components of RGB value. The "Geometry Transform" picks up the corresponding pixel between P'_i and C'_i. Because "Color Comp." converts color space to match to the projection color space and "Gamma Comp." linearizes the response, we can write

$$\mathbf{C} = \mathrm{K}\mathbf{P}, \tag{1}$$

where

$$\mathrm{K} = \begin{pmatrix} k_{11} & k_{12} & \dots & k_{1n} \\ k_{21} & k_{22} & \dots & k_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ k_{n1} & k_{n2} & \dots & k_{nn} \end{pmatrix}, \tag{2}$$

where $\mathbf{C} = (C_1, C_2, \dots, C_n)^T \in \mathcal{R}^{3n}$ and $\mathbf{P} = (P_1, P_2, \dots, P_n)^T \in \mathcal{R}^{3n}$ are captured images and projection images, respectively. $\mathrm{K} \in \mathcal{R}^{3n \times 3n}$ describes a surface reflection property that is a rough sample of the BRDF. The $C_{est,i} \in \mathcal{R}^3$ is an estimated image when the $P_i \in \mathcal{R}^3$ is a white illumination. Let us assume that the each camera is placed near the projector in the same system in this section.

When we treat the surface as a retro reflection, the diagonal block matrices $k_{ij} \in \mathcal{R}^{3\times3}$ for $i = j, i = 1,2,\dots,n$ have a value, and the other off-diagonal block matrices $k_{ij} \in \mathcal{R}^{3\times3}$ for $i \neq j$ can be neglected, as shown in the Table 1. In this case, there is no interference among projector-camera units, and the appearance from each viewpoint can be manipulated correctly with the appearance-manipulation framework. Although the system contains complicated processing, we regard it as linear system. Thus, we can roughly model $\mathbf{C}$ at each step s with a Markov chain,

$$\mathbf{C}^{s+1} \leftarrow \mathrm{K}\mathcal{D}\mathbf{C}^{s} \tag{3}$$

where the block diagonal matrix $\mathcal{D}$ represents simplified processing in each feedback system.

In the case of mirror-reflection, anti-diagonal block matrices have value. Therefore, the block order of C_i in $\mathbf{C}^s$ is flipped in each processing step s, creating vibration. Additionally, the projected illumination I_{pi} is not measurable by the same system. Thus, it produces an incorrect image estimation $C_{est,i}$. To solve this problem, we correct the corresponding block in $\mathbf{C}^s$ using the permutation block matrix

$$\mathrm{T}_\pi = \begin{pmatrix} \mathbf{0} & \dots & \mathbf{0} & \mathrm{I} \\ \mathbf{0} & \dots & \mathrm{I} & \mathbf{0} \\ \vdots & \iddots & \vdots & \vdots \\ \mathrm{I} & \dots & \mathbf{0} & \mathbf{0} \end{pmatrix}, \tag{4}$$

where $\mathrm{I} \in \mathcal{R}^{3\times3}$ is an identity matrix, $\mathbf{0} \in \mathcal{R}^{3\times3}$ is a zero matrix.

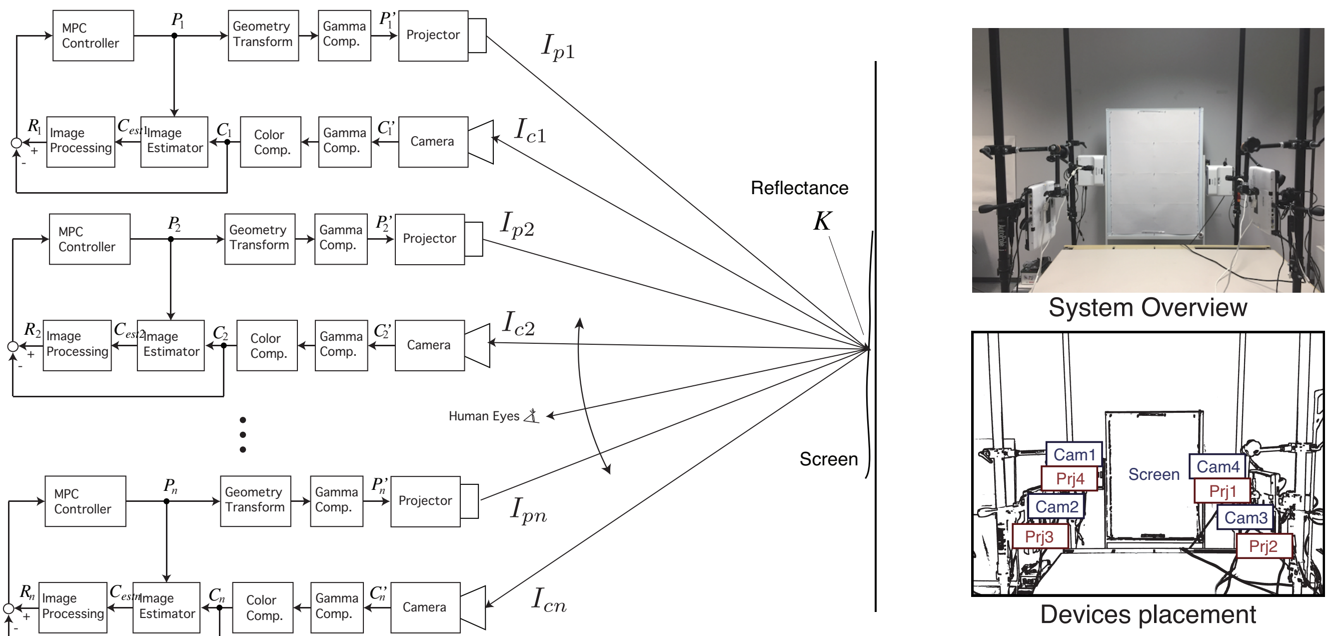
Accordingly, the Lambert reflection can be described by a matrix which has same block matrices in each column. In this case, the estimation C_{est} can be disturbed by radiances from the other system. This leads to an error with the chroma or illuminance in the manipulation result. However,

$$\mathrm{K}^n = (k_1 + k_2 + k_3)^n \mathrm{K}. \tag{5}$$

Thus, the response will now be stable. The behavior of such an interference situation is well-studied in [ASUK14], and confirms that the projection on a Lambertian surface can be balanced. However, viewing-direction-dependent appearance-manipulation is impossible because of the reflection property.

4. Experimental Results

We use two short-throw projectors (WXGA 2600lm for Prj2 and Prj3), two ultra-short-throw projectors (WXGA 3500lm for Prj1



(a) Block diagram

(b) A prototype system

Figure 3: *Our multiple projector-camera feedback system. (a) Block diagram: Each unit consists of a camera and a projector. These units simultaneously and independently perform appearance-manipulation. (b) Over view of a prototype system: The system consists of two short-throw projectors, two ultra-short-throw projectors, and four IEEE 1394b cameras. The manipulation target was stuck to the screen.*

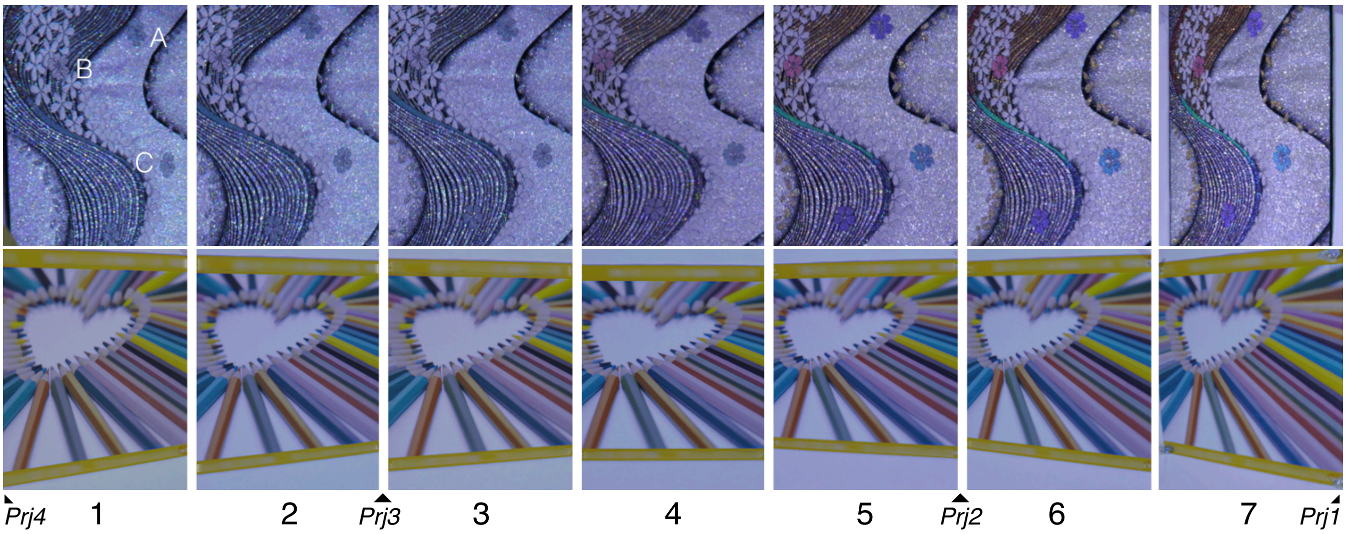


Figure 4: *Manipulation results of a textile (top) and a matte photo print (bottom). These graphics show the appearance captured by each viewing direction. Prj1, Prj2, Prj3, and Prj4 denote the relative locations of each projector. The numbers below are indices of the viewing direction corresponding to azimuth.*

and Prj4), and four IEEE 1394b cameras (1288x964, 30fps). The optimal arrangement of the projectors and the camera is preliminarily designed as shown in Figure 3(b). We assume the mirror reflection to be a dominant component (e.g., metallic object or a smooth surface object with a strong specular reflection) over a retro-reflection. Therefore, we connect the projector and the camera that is placed counter side (symmetrical position) to the same unit. These devices were driven by four quad-core PCs (two MacBook Pros and two Mac Pros).

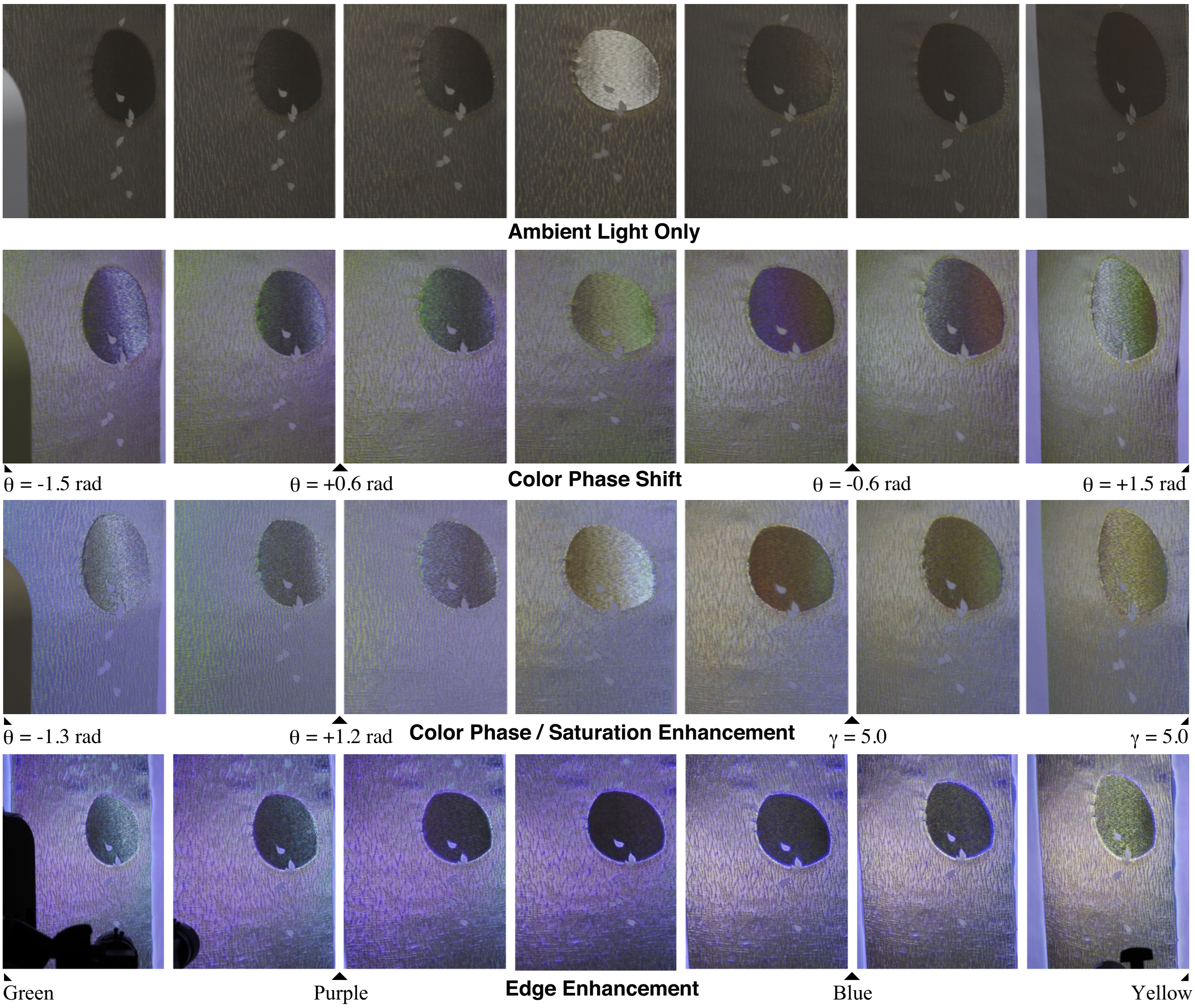


Figure 5: *Manipulation results of the moon textile. The drawing foil textile (made with gold and silver leaf strings) that depicts the moon with flower petals (top row). Inhomogeneous color phase-shift combination (second row), and the hybrid color phase-shift and saturation enhancement (third row) shows beautiful chroma-transition along the viewing direction, similar to the structural color. The edge enhancement by different color from each viewpoint (bottom).*

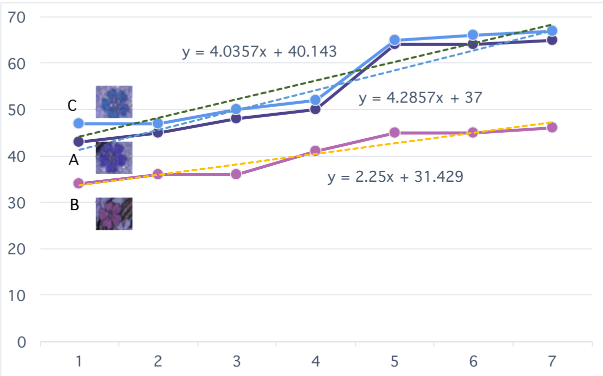
Figure 4 shows manipulation results of a drawing foil textile (top) and a matte photo print (bottom). Because the textile is made with sliced gold leaves, silver leaves, and silky strings, it has a metallic reflection. For this experiment, we applied a grayscale conversion

$$R = \beta C_m + (1-\beta) C_{est}, \tag{6}$$

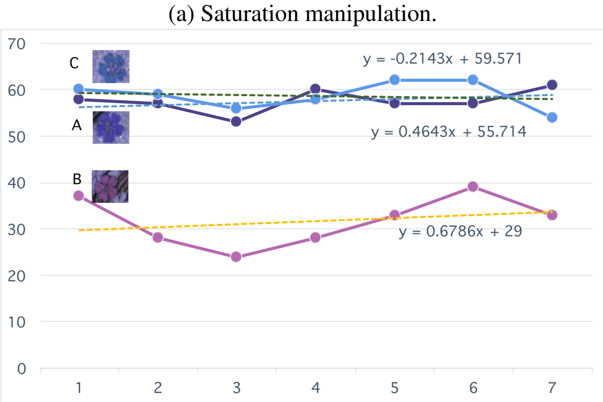
where $R \in \mathcal{R}^3$ and $C_{est} \in \mathcal{R}^3$ are color vectors of the reference image under a white illumination. $C_m \in \mathcal{R}^3$ is a grayscale image value of C_{est}. In order to reduce saturation, we set the monochrome parameter $\beta = 0.95$ as the reference generator for unit1 (Cam1 and Prj1) and unit2 (Cam2 and Prj2). Alternatively, we applied saturation enhancement

$$R = \gamma(C_{est} - C_m) + C_m, \tag{7}$$

with saturation parameter $\gamma = 2.5$ for unit3 (Cam3 and Prj3) and unit4 (Cam4 and Prj4). This effect is comparable to grayscale conversion with $\beta = -1.5$. Because the textile contains a metallic reflection, we can see that the saturation changes with the changing viewpoint. In contrast, the significant saturation difference cannot



(a) Saturation manipulation.



(b) White illumination-projection.

Figure 6: *Saturation of the flower parts measured by each viewing position (horizontal axis). The saturation increases with the changing viewing direction by our method.*

be confirmed in the matte photo print (Figure 4 bottom) because all incoming light rays are uniformly mixed.

For the evaluation, we checked the saturation of the flowers shown in Figure 4 from each viewing direction. Figure 6(a) shows the saturation in a hue, the saturation and luminance of the color space when we applied grayscale conversion by the unit1 and the unit2, and the saturation enhancement by unit3 and unit4. The graph shows the saturation (vertical axis, saturation [%]) measured from each viewing position (horizontal axis). Accordingly, we can see the saturation increase with the changing viewing direction. In contrast, the saturation does not change when we project white illuminations from all projectors, as in Figure 6(b). However, when the matte paper media has specular reflection in the ink, we can apply appearance-manipulation differently at each viewing direction, as shown in Figure 1.

Figure 5 demonstrates other manipulation results. The top row shows pictures of the drawing foil textile images (made with gold and silver leaf strings) depicting a moon with flower petals under an ambient light environment. The second row shows the results of color phase shift-manipulation

$$R = U^T T_R U C_{est}, \quad (8)$$

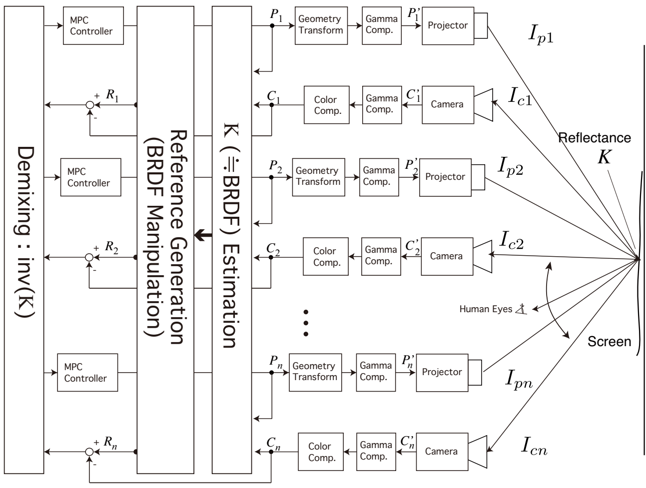


Figure 7: *The concept of the light-field feedback system.*

where

$$U = \begin{pmatrix} 0.577 & 0.577 & 0.577 \\ 0.816 & -0.408 & -0.408 \\ 0 & 0.707 & -0.707 \end{pmatrix}, T_R = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{pmatrix} \quad (9)$$

with $\theta_i = \{-1.5, +0.6, -0.6, +1.5\}$ [rad] for each unit. We can see chroma transition along the viewing directions similar to the structural colors at the moon region. The third row shows hybrid manipulation results of the color phases and saturation enhancements. We applied a color phase shift of $\theta_i = \{-1.3, +1.2\}$ [rad] for unit1 and unit2, and saturation enhancement with $\gamma = 5.0$ for the rest of the units. Because the different weaving patterns depict the moon and the background, the textile comprises the different reflections of the normal clusters at each small region. Therefore, we see the different transitions of the moon and the background. The bottom row shows the edge enhancement result which enhanced by the different color from each viewpoint. It reveals object's bump with colorful flame corresponding to surface normal. Our method provides a multiple-degree of freedom appearance-manipulation along the viewing direction, and it enables the sophisticated alternation of the perception of materials.

5. Discussion and Future Work

When reflections create interference among units, unit-projections can be disturbed, impacting manipulation performance. We have no solution for the scattered reflection problem. However, if the surface has an anisotropic reflection and we can estimate its reflection K, the manipulation quality can be improved by demixing the illumination from the captured image. Additionally, we can extend our system to the light-field feedback system as shown in Figure 7, which enables manipulation of our perceptual BRDF. For this feedback system, we require successive K estimations, BRDF manipulation algorithms, and the geometrical calibration among multiple projectors and cameras. In future work, we will study these technical issues and attempt to achieve a perceptual BRDF manipulation.

6. Conclusion

Our multiple projector-camera systems enable viewpoint-dependent appearance-manipulation on a surface with anisotropic reflection. To the best of our knowledge, this is the first effort to realize a viewing-direction-dependent manipulation of an object ' s appearance. Interestingly, the application target is not limited to metallic surfaces; we can also apply it to matte paper media when the ink has a glossy reflection. We believe the viewpoint-dependent appearance-manipulation technique can be a good solution for manipulation of our material perception of the real world without wearing any devices.

7. Acknowledgment

This work was supported by JSPS KAKENHI Grant Number 17H01781 and MEXT KAKENHI Grant Number 16H01674D02.

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