Doctoral Dissertation

Increasing Controllability of Color in Projection-Based Appearance Control

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Increasing Controllability of Color in Projection-Based Appearance Control*

Ryo Akiyama

Abstract

Projectors can control colors of real objects by overlaying light projection. There are a lot of studies that employ a projector–camera system to control appearance of real objects. However, almost none of them is actually used as practical applications. One of the main reason is environmental light. The most of the studies assume dark environments, which are not favorable in many practical scenes, to guarantee enough controllability of appearance. The goal of this dissertation is to increase controllability of colors in all existing projection-based appearance control system. It is connected to broaden applicability of all projection-based appearance control studies. In particular, I focused on following two from the problems caused by environmental light: 1. conventional estimating method for original appearance does not work in a dynamic light environment, 2. presentable color range of projectors decrease because of environmentall light and original colors of the object.

Firstly, I established robust reflectance estimation method against dynamic environmental light. Real-time reflectance estimation method is already proposed, and it is required for present desiable appearance by projection. However, the method regards constant environmental light. In practical scene, environmental light changes frequently, the system needs re-calibration in every change of environmental light. This will be problem for actual applications. To solve this problem, I established robust reflectance estimation method. With proposed method, my system can present absolute colors by considering reflectance and

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environmental light. In addition, the system become calibration-less. Secondly, I designed a method for expanding controllable color range of projectors perceptually. Because of objects' colors and environmental light, controllable color range of projectors become narrower. In order to expand controllable color range of projectors without changing devices or environments, my idea is controlling projection based on human perceived colors by inducing one of the visual illusion, color constancy. With proposed method, my system can perceptually present colors which cannot be presented physically.

Keywords:

Projection, augmented reality, color, reflectance, visual illusion, color perception

光投影による見かけの制御における色彩の可制御性の向上*

秋山 諒

内容梗概

プロジェクタは実物体に光を重畳投影することによって色彩を制御することが可能である．プロジェクションマッピングのようにエンターテイメント目的に使用されるだけでなく，教育や医療などの現場でも利用されている．ただし，光投影による実物体の見かけを制御する研究の多くは環境光の少ない状況を前提としている．この前提を実世界で満たすのは困難な場合や好ましくない場合が多く，実応用までは至らないことが多いのが現状である．　本研究では，環境光により生じる多くの問題の中でも，環境光を考慮しなければ正確な色表現ができない点と，環境光によって表現可能な色範囲が狭まる点が重要な問題点であると考え，この二点の解決を試みる．この二点を解決することができれば，現在すでに提案されているあらゆる光投影による見かけの制御の研究の環境光に対する制限を緩和し，適用可能範囲を拡張することが可能となる．具体的には，ある程度明るい環境で有彩色の投影対象に対しても所望の投影像を表示することや，所望の環境光と物体色を同時に再現することなどが可能となる．上記の問題点の解決のために本研究では，大きく分けて以下の二つのことに取り組んだ．一つ目は環境光変化に頑健な反射率推定による正確な色表現，二つ目は人の知覚色に基づいた制御を行うことによるプロジェクタの表現可能色域の知覚的拡張である．　まず一つ目は，プロジェクションによる色彩制御のための環境光変化に頑健な反射率推定手法の確立である．実物体の反射率を実時間で推定し，その物体の色彩を制御する手法がすでに提案されているものの，その手法は時間的に一定な環境光を前提をしている．そのため環境光が変化すると所望の制御が行えなくなってしまう．実世界では環境光は頻繁に変化するため，実応用を考えると問題となる．そこで我々は，環境光変化に頑健な反射率推定手法を確立し，環境光が変化しても

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特定の見かけを保つことを可能とした．また，既存手法では環境光が変わる度に色校正を要していたが，それを不要なものとした．　二つ目に，プロジェクタの表現可能色域の知覚的拡張である．プロジェクタは環境光と実物体の色彩の影響によって，表現可能な色域が狭まってしまう．それに対する解決策としては，環境を暗くしたり，プロジェクタを高輝度にすることが考えられるが，実世界においてそれが常に可能であるわけではない．よって，現状のセットアップで表現できる色域を拡張することが求められる．そこで我々は，色恒常性という錯視をプロジェクションにより誘発することにより，プロジェクタの表現できる色域を知覚的に拡張する手法を提案した．これにより，従来の重畳投影では本来表現できなかった色を知覚的に表現することが可能となった..

キーワード

プロジェクション，拡張現実感，色，反射率，錯視，色知覚

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1. Introduction

Projectors can control intensity and color of each pixel in projection images. Although projectors are commonly used as display devices, many research works employ projectors as tools for controlling appearance of real-world objects. In this dissertation, I call this technology as projection-based appearance control. This technology is used not only projection mapping for entertainment, but also educational, medical, and other applications. This research field is treated as a type of augmented reality (AR) research. AR is the technology that visualizes computer-generated graphics onto the real world. Mainly, handheld devices (smartphone or tablet computers) or head-mounted displays are used for visualizing. Controlling object appearance or visualizing computer-generated graphics suited to real world with projection is specifically called spatial augmented reality (SAR) or projection-based augmented reality.

Many studies employ a projector–camera system to control appearance of real objects. However, almost none of them is actually used as a practical application. There are many problems to solve to archive a perfect projector–camera system that can be used anywhere and visualize anything. In this dissertation, I tried to solve one of the problems. It is the effect of environmental light. Most of SAR studies assume dark environments. The most significant advantage of projectors is that projectors can change any physical objects to displays by overlaying light projection. However, to guarantee enough controllability of projected appearance, I require to keep environments dark and select target surfaces as white as possible. These requirements are too strict about applying the projection-based systems in actual scenes. For example, there is much research that tries to create a future office [85]. With projection, all objects in the office, like walls or tables, become displays to support discussions. Although it sounds fascinating and useful, dark environments and white target objects are desirable for better experiences. Keeping environments dark isn't favorable not only in offices but also in many actual scenarios. People require environmental light for daily lives.

The goal of this dissertation is to increase controllability of colors in all existing projection-based appearance control system. As I mentioned above, a lot of projection-based appearance control studies assume dark environments. This is because environmental light affects the projected surfaces, and it limits the controllability of objects' colors. Among problems caused by environmental light, I focused on following two problems: 1. conventional estimating method for original appearance does not work in a dynamic light environment, 2. presentable color range of projectors decrease in a well-lit environment. By solving these problems, the applicability of all projection-based appearance control studies increase. The detailed information about the methods for solving the two problems is shown in the following sections.

First, estimation of original appearance in a dynamic light environment is explained here. Reflected light from objects is affected by objects' colors and environmental light. Thus, I require to consider them for presenting desirable colors. In particular, even when a projector projects desirable colors to an object, the light mixes with environmental light and modulates by reflectance of a surface of the object. Thus, it is required to have information about reflectance of objects and environmental light to calculate projection colors and present desirable colors. Conventional methods regard constant environmental light and only focusing on estimating reflectance of objects in real-time [11, 9, 27]. However, in realistic scenes, environmental light changes dynamically in many situations, even indoors. Additionally, there is a lot of commercial light equipment which can control illuminance and color of light [1]. Thus, the assumption of constant environmental light is not suitable for practical applications. To make appearance control enable to apply to realistic environments, I proposed a robust reflectance estimation method in a dynamic light environment. With this method, an appearance control system becomes robust against dynamic environmental light, and it also can produce absolute color presentation.

Secondly, the other aspect is a presentable range of colors. The presentable color range of projectors depends on reflectance of target objects and environmental light. It is difficult to present colors that are far from the original colors of the objects. For instance, when an original color of the object is red, it is difficult to change it to blue or green by light projection. This is because red surfaces mainly only reflect red light, and blue or green light hardly reflects on the red surface even if projectors projects bright illumination. In addition, projectors only can present pale colors when there is environmental light. Projectors only can add illumination to objects, and they have an upper limit of brightness. When there is environmental light, the mixture of projection and environmental light reflect on the surface of objects. Thus, colors of the incident light become pale compared to projected colors. In order to broaden the presentable color range physically, using brighter projectors or making the environment darker are straightforward solutions. However, bright projectors are still large and expensive, and it is often impossible or unfavorable to make the environment darker. Thus, it is expected to broaden the presentable color range of projectors without changing equipment or environments. my idea for solving this is controlling projection colors based on human perceived colors. The purpose of appearance control is showing to humans. Therefore, even if the presented colors are not correct physically, it is no problem if the colors are correct perceptually. For presenting colors perceptually, I proposed a method for inducing one of the visual illusion, color constancy, artificially. With this method, the perceptual presentable color range becomes broader compared to a physical one.

With a combination of these two technologies, projectors can be used in broader situations. This is because I can have information of reflectance of objects, environmental light, and a model for perceptually presenting the desirable color. By using this information, the system can effectively change appearance of physical objects to another appearance. For example, I can change anything to display. When I would like to use projectors as a display device, I need to prepare a white screen and a dark environment. Because of these characteristics, it is difficult to do other things in the same environment, and I have no choice but to see projected images only. However, with proposed technology here, I can obtain a desirable appearance of digital contents even if target objects have colors or there is some amount of environmental light. An advantage of projectors is that they can project illumination to any physical objects. Thus, I can design and create environments with displays anywhere. I showed an application that focuses on visualizes digital content. Some applications control appearance based on the original appearance of physical objects. For instance, projectors can simulate appearance with many different colors of objects and environmental light with proposed technology. Proposed method can change apparent colors of object and environmental light. Thus, I can simulate appearance of a specified colored object under specied colored environmental light. It is helpful for designing physical things such as clothes or posters. Moreover, the system can be used as an intelligent light source of daily lives for controlling both appearance of objects and environmental light. For example, I can change appearance of equipment or furniture based on my daily mood. Moreover, I can make appearance of printed paper of books easier to read or to distinguish multiple colors for color deciency people. As described, the usage of projectors becomes broader and more familiar things with technology in this dissertation.

This dissertation is organized as follows. First, I discuss related work of projection-based augmented reality research and show the position of this research among them in Chapter 2. I introduce a robust reflectance estimation technique for projection-based appearance control in Chapter 3. In this study, I proposed a robust reflectance estimation technique in dynamic light environments to present desirable colors by considering environmental light. In Chapter 4, I proposed a method for controlling the color of objects perceptually. With this method, I can present colors perceptually which cannot be presented physically. Finally, Chapter 5 summarizes this dissertation and future work.

2. Background and Related Work

The work in this dissertation is motivated by many previous works for controlling appearance of real objects by light projection. This chapter gives the overview of existing SAR studies and shows the positions of my works among them.

2.1 Radiometric Control of Projection

SAR research works can be roughly divided to two types. One is solving geometrical problems, and the other is solving problems of colors. By solving geometrical problems, projected images can be geometrically aligned to objects which have complex geometry. After Rasker et al. [87] proposed a method for projection to complex three-dimensional objects, a lot of technology is proposed in order to projects to more complex objects. There are studies which propose methods for projecting to dynamic rigid objects [64, 96, 17, 18, 57], dynamic non-rigid objects [41, 85, 97, 23]. Additionally, there are a lot of studies for geometrical calibration. Recently. semi or full automatic calibration methods [108, 20, 35, 104] are proposed to make the calibration of multi-projector system easier for applying to large scaled scenes. Secondly, solving problems of colors means that calculating suitable projection colors to obtain desirable colors of reflected light from the surface of projected objects. my works in this dissertation are all categorized in the latter. This section discusses radiometric control and compensation of projection. One big purpose of radiometric control is to obtain appearance of projected surface as if the images are projected on a white screen. The example is shown in Fig. 1. Firstly, I introduce radiometric control research from the basic ones. The basic radiometric compensation methods modeled the light modulation between a camera and a projector as a linear matrix multiplication [78, 109]. Chen et al. [30] improved this color-mixing matrix model and simplified computational steps. Radiometric compensation of projection are required when projectors are projecting onto dark or strongly saturated surfaces. In that case, it is required to avoid compensation errors that are occurred by the lack of color gamut or projector power. Several methods automatically adjust the target colors which are outside of the presentable range to avoid artifacts [68, 62]. There is an approach based on spectral measurements [69], and it is extended by applying 3D look-up

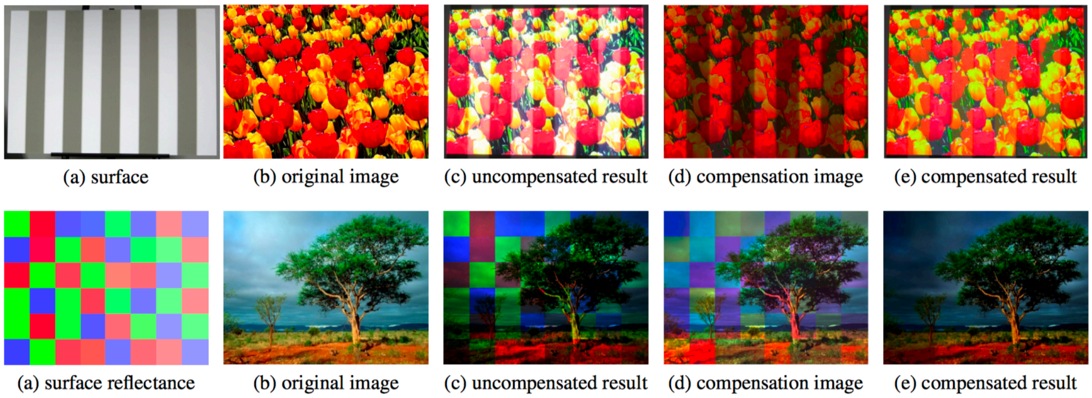


Figure 1. Controlled results by Glossberg et al.[43].

table (LUT) [67]. I require radiometric compensation for a accurate color reproduction as well [44, 46, 70]. There are not only algorithm for compensation itself but also methods for deciding placement of projectors. For implementing multi-projector system, Law et al. [61] proposed a method to automatically calculate an optimal projector placement to achieve the best compensation results. Other methods focused on optimal projector placement in terms of pixel coverage and intensity distribution [63].

The methods described above are only able to improve the image quality locally since the compensation is carried out independently for each pixel. However, these methods are not able to handle and neutralize any kind of global illumination effect. Even when using only Lambertian surfaces, diffuse inter-reflections will happen at any concavity. This unwanted scattering of light degrades the image quality by a reduction of contrast and might lead to undesired color-bleeding. Compensating the influence of such inter-reflections was initially presented by Bimber et al., where a global illumination calculation was carried out to estimate the amount of inter-reflections by subdividing the surface into patches [25]. Since the compensation depends on the projected image content, the method was optimized for real-time processing to enable the compensation within interactive applications, such as immersive virtual environments. Such inverse radiosity methods were then further refined by several groups [94, 93, 80]. Most of these methods were also able to compute a compensation image in real-time using

GPU-based parallel processing. A more recent study solved the same problem in real-time for multiple projectors in a dynamic environment [95]. Within a more general solution presented by Wetzstein and Bimber [103], inter-reflection artifacts were compensated by inverting the light transport matrix between a projector and camera. These are the algorithm for controlling intensity of projection to the specific area which have strong inter-reflection. In contrast, there is a study which uses UV-reactive photometric surface to achieve this issue. The UV-reactive photochromic surface material changes its color from white to black when it is strongly illuminated by UV light. Takeda et al. [99] used this as a projection surface, and control its reflectance partially by using UV LED arrays.

2.2 Closed-loop Radiometric Control

While the research summarized above are controlling appearance of real objects, they do not create closed-loop in their processes. Although it is possible to produce desirable appearance without creating closed-loop, the target appearance is required to be known in advance. Thus, in order to enhance or edit original properties of objects (e.g. colors, edges) interactively, the closed-loop process is needed. In contrast, appearance control require to create target appearance during the process, because the target appearance can only be created based on original appearance of the objects, which are unknown in advance. Amano et al. [11] proposed a method for controlling appearance with real-time reflectance estimation algorithm. The various results of the control are shown in Fig 2. Recently, there are several studies of appearance control with an optically-aligned projector–camera system. Optically aligning a projector and a camera is a non-trivial task and quite cumbersome since the alignment has to be managed in six degrees of freedom. To ease the registration, a simple, but efcient way to achieve a satisfactory optical calibration of the coaxial procams is given, where a spatial grid pattern is projected onto a differently shaped grid surface such that the alignment accuracy can be directly estimated by observing the camera while moving the latter [9]. The same principle of a coaxial procams is used to visually manipulate material appearance [8], microscopic specimens [27], and context aware illuminations [102]. The same idea was extended to multiple coaxial procams which were used to augment a 3D object [13].

Closed-loop radiometric control research I discussed above assume constant environmental light. In practical situation, environmental light is often dynamic even indoors. For example, environmental light of a room with windows changes because of sun light. There are commercial light equipment that can control intensity and colors of illumination. Thus, for practical application, closed-loop radiometric control require to be applied in dynamic light environments. Additionally, target objects of radiometric control are almost always non-white. Moreover, target objects of closed-loop radiometric control almost always have chromatic colors. Because of colors of objects and environmental light, presentable color range of projectors become narrower. Thus, radiometric control systems are almost always affected by the colors of objects and environmental light in practical scenes, and their presentable color range is often not enough to control appearance of the target objects freely.

My studies in this dissertation is a step to enable closed-loop radiometric control to apply in practical applications. With conventional studies, it is difficult to control appearance of printed poster or advertisements in stations, amusement parks, and so on. In addition, it is also difficult to hold projection mapping events in well-lit indoors. I can solve these difficulties by my studies in this dissertation.

(a) Original Appearance (b) Saturation Enhencement (c) Color Removal
(d) Color Phase Control (e) Edge Enhance and Blur (f) Unique Brightness
(g) Contrast Boost (h) Posterization (i) Optical Hiding

Figure 2. Controlled results by the system of Amano et al.[11]

3. Robust Reflectance Estimation for Appearance Control with a Projector-Camera System in a Dynamic Light Environment

3.1 Introduction

Colors and textures are essential elements constituting the appearance of objects. Recently, projection mapping technologies have advanced to a point where projectors can control the colors and textures observed on the surfaces of physical objects. They are used for entertainment in amusement parks [73], museum events [22], gaming [51, 50], and educational [106], and medical applications [31].

Many studies have addressed projector–camera systems that are capable of interactively controlling a projection with the changes in the object onto which an image is being projected. For example, there are projection technologies that can project light onto a static object with a complex geometry [87], a face [23], and other deformable objects [41, 76]. Some of these interactive systems first capture the original colors and textures of the target objects and then artificially change their appearance by overlaying a projection. In the present study, I focus on an interactive projection system with a color-replacing function that I refer to as *Appearance Control* [11]. The system changes an object's appearance by considering its original reflectance properties. Even when the object moves or new objects appear, the system creates projection images for appearance control by estimating the reflectance of the target object(s). However, the system does not consider dynamically changing environmental light. When the environmental light changes, the system cannot correctly estimate the reflectance unless photometric calibration is performed again.

Although it is possible to re-calibrate the system whenever the environmental light changes, this is an impractical approach because the environmental light changes frequently. For example, environmental light continuously changes when there is a window, even indoors. There are also various types of light equipment that can control the color and illuminance. Moreover, it is almost impossible to create a portable appearance control system with current algorithms. In addition, this calibration is carried out by capturing images of red, green, and blue projections on a white plane. Clearly, it would be impractical to repeatedly prepare a white plane for calibration throughout the day. Therefore, appearance control can never be completely practical unless it can be applied under dynamically changing lighting conditions.

In the present study, I develop a means to estimate the reflectance robustly under dynamic environmental light for appearance control with a projector–camera system. The basic concept on which this study is based is shown in Fig. 3. With proposed method, a projector–camera system can estimate the original appearance of a painting regardless of the environmental light, while previous methods would be adversely affected by changes in light. I created this method by improving on the reflectance estimation method by Amano *et al.* [11]. Henceforth, in this paper, I will refer to the method devised by Amano *et al.* [11] as "the previous method." With my improvement, the appearance control system can be applied in both static and dynamically changing lighting conditions. As a results, the system is capable of the following:

- The appearance control system can be utilized even when both the reflectance and environmental light are dynamically changing.
- Colors can be presented exactly as desired when the color is inside the presentable range of a projector. The previous method could only present relative colors.
- The system can continue to operate as expected without additional calibration, even when the lighting conditions change.

I describe these contributions in greater detail in Section 3.5.

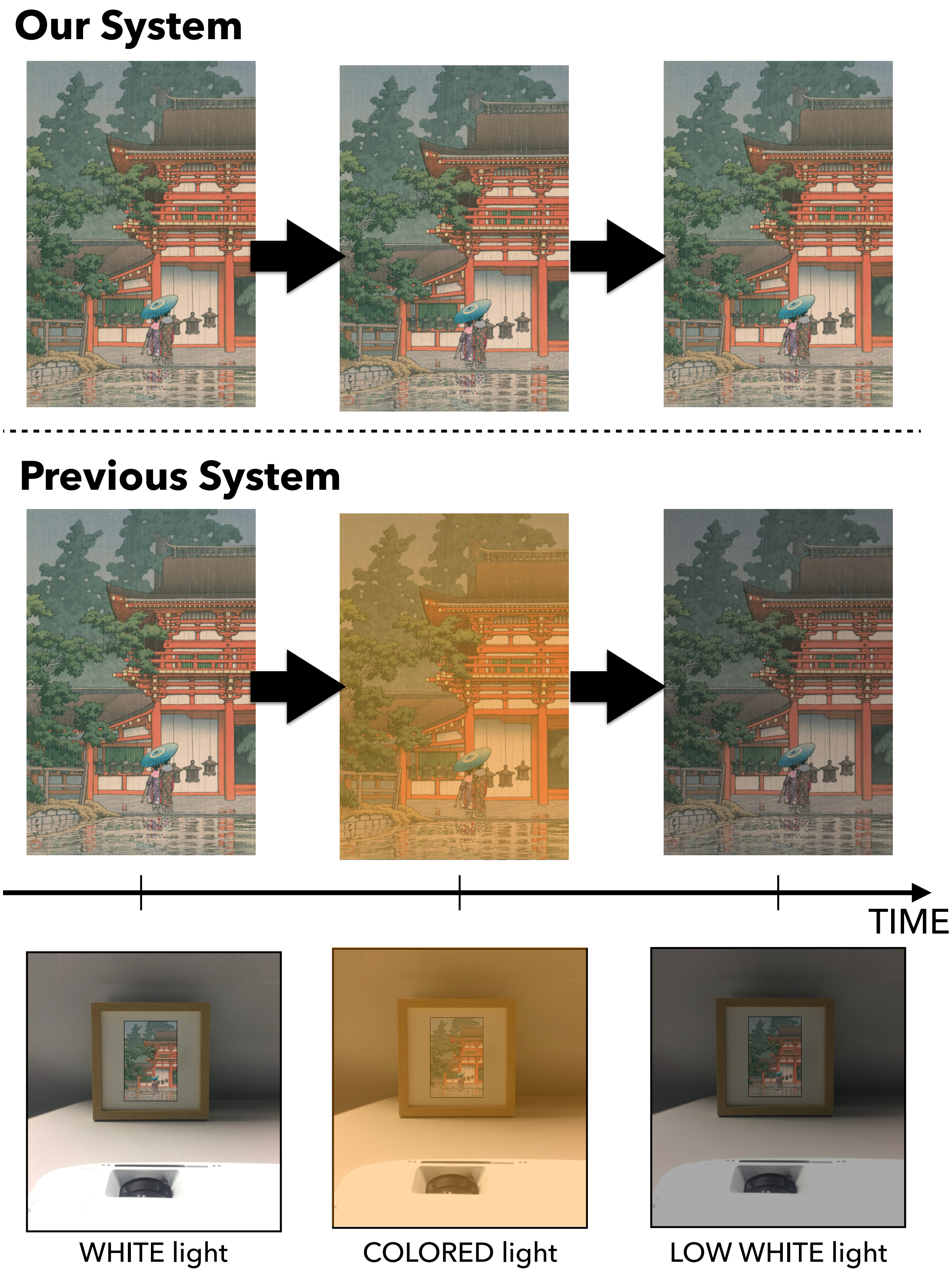


Figure 3. Estimated original appearance of painting, as determined by my system and the previous system under three lighting conditions: white light, colored light, low white light.

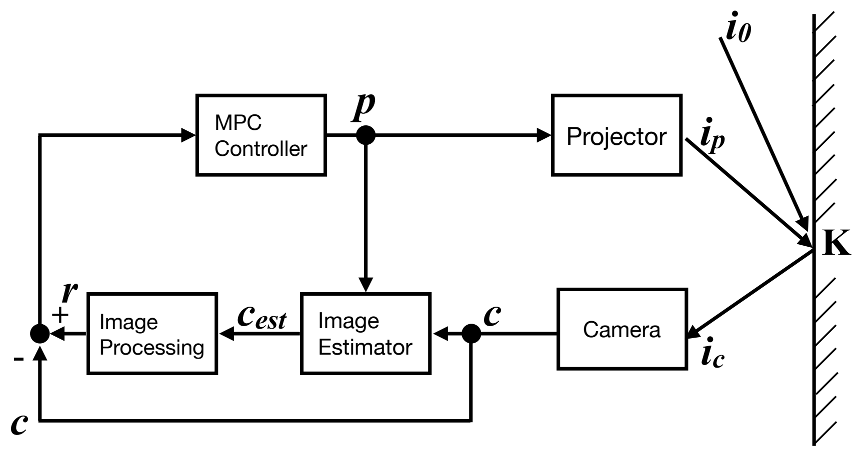


Figure 4. Appearance control method proposed by Amano et al.[11].

3.2 Related Work

Nayar *et al.* [78] and Grossberg *et al.* [43] designed methods of optical compensation for static situations. In these studies, a projection onto a colored surface appeared as if it were on a white screen. Grundhofer *et al.* [45] established a method to reproduce high-contrast images in a projected display by considering the properties of human vision. Brown *et al.* [29] created a model based on the characteristics of projectors and the object onto which an image was being projected to control the brightness of the display produced by a multiprojector system. These techniques require prior knowledge of the reflection characteristics of the target objects. In other words, users cannot move the target object, and the environmental light also needs to be constant.

By improving these techniques, Fujii *et al.* [40] designed another optical compensation method that can be applied when the target objects are moving. Tsukamoto *et al.* [101] designed an optical compensation system based on a multiprojector–camera system. They considered the calculation and communication cost and implemented a system to which more cameras or projectors can easily be added. Mihara *et al.* [71] designed a radiometric compensation technique that is effective for projecting light onto steep reflecting objects. These techniques can adjust the projection color even when the target objects and environmental light are dynamically changing. Pjanic *et al.* [83] created a system using a galvanoscopic laser projector (GLP) and normal video projector, in which the GLP was used to reproduce the colors that cannot be reproduced by the normal projector. The objective of all of these studies was to enable the reproduction of the original colors of digital content as they would appear when observed under white light. Therefore, these systems relied on target images and adjusted the colors of the reflected light to match those of the target images. The appearance control system reproduces target images using a feedback mechanism. This is the main difference between optical compensation techniques and appearance control techniques, including that devised in the present study.

In contrast to optical compensation, many studies have attempted to control the appearance of a target object by overlaying a projection based on the original appearance of the target object. The fundamental technology of appearance control is same as that of optical compensation. Appearance control technology also controls the light projected onto a real object at the pixel level. In the initial stages, projection technology must acquire the appearance of an object in advance and under white light. In other words, it can only be used in static situations [26, 14]. To introduce a feedback structure to appearance enhancement, Amano *et al.* [10] and Bimber *et al.* [27, 24] designed a real-time appearance control algorithm that does not require an object's original appearance to be precaptured. By adapting control theory, Amano *et al.* [11, 15] dynamically control the appearance control that employed a model predictive control (MPC) algorithm. Recently, some research has focused on the manipulation of material perception by light projection [100, 12]. In the present study, I devised a means of estimating the reflectance for appearance control.

In this paper, I propose a method for estimating the reflectance of a target object as required for appearance control with a projector–camera system. Previous studies that have addressed appearance control as a means of manipulating the colors of objects required knowledge of the reflectance of the object. Conventional methods can estimate the reflectance of dynamic objects in real time; however, they assume that the environmental light is constant. With proposed method, an appearance control system can be applied even when both the reflectance and environmental light are dynamically changing. my preliminary trials suggest that my idea has the potential to robustly estimate the reflectance in a dynamic light environment [7]. In this study, I appended a more generalized method to increase the number of potential applications. Furthermore, I conducted experiments to evaluate proposed method with a projector–camera system that I implemented.

The following table shows position of this study. I divided the radiometric control technology to two group depends on its contents. In addition, I also divide them by static / dynamic reflectance and environmental light. There is no appearance control research that can estimate dynamic reflectance in a dynamic environmental light.

Table 1. Position of my reflectance estimation study

	Technology	Reflectance	Environmental light
Nayer et al. [78]	Radiometric Compensation	Static	Static
Grossberg et al. [43]	Radiometric Compensation	Static	Static
Ashdown et al [19].	Radiometric Compensation	Static	Static
Brown et al. [29]	Radiometric Compensation	Static	Static
Fujii et al. [40]	Radiometric Compensation	Dynamic	Static
Tsukamoto et al. [101]	ORadiometric Compensation	Dynamic	Dynamic
Mihara et al. [71]	Radiometric Compensation	Dynamic	Dynamic
Bimber et al. [26]	Appearance Control	Static	Dynamic
Bimber et al. [24] [27]	Appearance Control	Dynamic	Static
Amano et al. [11]	Appearance Control	Dynamic	Static
Ours	Appearance Control	Dynamic	Dynamic

3.3 Robust Reflectance Estimation

In this section, I explain proposed method for estimating the reflectance using a projector–camera system. First, I discuss estimation under static environmental light conditions, as described by Amano *et al.* [11]. Second, I explain proposed method that can robustly estimate the reflectance under dynamic environmental light conditions. There are several ways to implement a projector–camera system that is capable of implementing proposed method. Herein, I explain my estimation method assuming the use of two cameras. Finally, I explain the control theory employed in my system to realize convergent projection.

3.3.1 Reflectance Estimation in a Static Light Environment

Amano *et al.* [11] estimated the reflectance of each pixel as well as the changes in the appearance of the objects' surfaces using a projector–camera system with a single projector and single camera, as shown in Fig. 4. The light $\boldsymbol{i_p} \in R^3$ from the projector and the constant environmental light $\boldsymbol{i_0} \in R^3$ are reflected by the surfaces, for which the reflectance is 3×3 diagonal matrix $\mathbf{K} \in R^{3\times3}$. The light captured by the camera $\boldsymbol{i_c} \in R^3$ consists of the reflected light of $\boldsymbol{i_p}$ and $\boldsymbol{i_0}$. This system regards $\boldsymbol{i_c}$ as the same as the light captured by a human eye. $\boldsymbol{i_c}$ is expressed as follows:

$$\boldsymbol{i_c} = \mathbf{K}(\boldsymbol{i_p} + \boldsymbol{i_0}) \tag{1}$$

An image $\boldsymbol{c}$ captured by the camera is represented by the following model;

$$\boldsymbol{c} = \mathbf{K}\{(\boldsymbol{c_{full}} - \boldsymbol{c_0}) \odot \boldsymbol{p} + \boldsymbol{c_0}\}, \tag{2}$$

where $\boldsymbol{p}$ is the projected image, $\mathbf{K}$ is the reflectance of each pixel, and $\boldsymbol{c_{full}}$ and $\boldsymbol{c_0}$ are the captured images with the maximum and minimum power projections, respectively. $\odot$ means the element-wise multiplication. In (2), the color space conversion process is omitted. When I display one color with a projector and capture the projection with a camera, the pixel values of the projection and captured images are usually different. This is because each device has its own color space. In order to treat these images with same equation, their color spaces must match. To achieve this, I utilize a color-conversion matrix to convert from one color space to another. In photometric calibration, a projector sequentially displays red, green, and blue images on a white plane, and a camera captures the projection. With three projection images and three captured images, the system can calculate the color-conversion matrix between the projector and the camera. I assume that the geometric and photometric calibration between a camera and

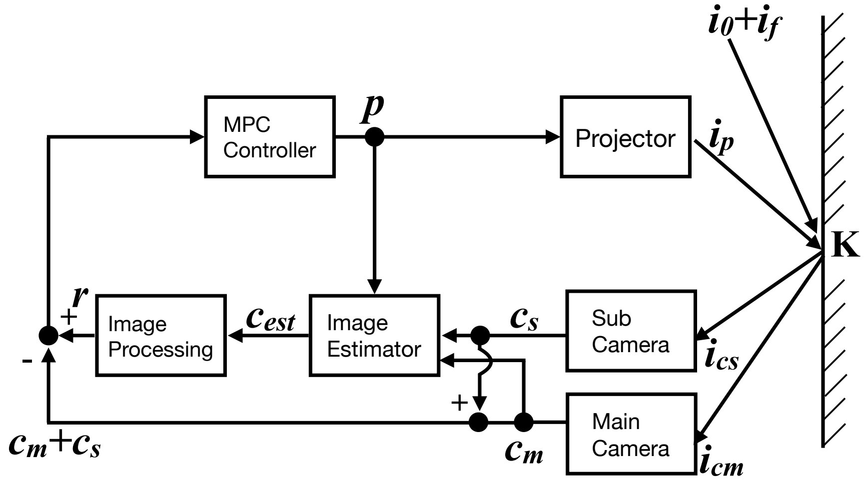


Figure 5. Appearance control method using two cameras.

a projector has already been completed. I do not attempt to incorporate geometrical and color conversion into the equations at this point. In (2), the only unknown parameter is $\mathbf{K}$. Therefore, $\mathbf{K}$ can be estimated as $\hat{\mathbf{K}}$ using

$$\hat{\mathbf{K}} = \mathrm{diag}\left[\boldsymbol{c}./\{(\boldsymbol{c_{full}} - \boldsymbol{c_0}) \odot \boldsymbol{p} + \boldsymbol{c_0}\}\right] \tag{3}$$

where ./ is the element-wise division.

The original appearance of a target object $\boldsymbol{c_{est}}$, that is, the appearance under white light, can be estimated based on the reflectance $\hat{\mathbf{K}}$ and a white image $\boldsymbol{c_{white}} = (1, 1, 1)^T$. $\boldsymbol{c_{white}}$ needs to be inside of the camera dynamic range, and $\boldsymbol{c_{white}}$ is required to be reproduced by capturing white projection onto a white plane.

$$\boldsymbol{c_{est}} = \hat{\mathbf{K}}\boldsymbol{c_{white}} \tag{4}$$

After the original appearance $\boldsymbol{c_{est}}$ is estimated, a reference image $\boldsymbol{r}$ is created by adding some effects to $\boldsymbol{c_{est}}$. Then, the system calculates the difference between the reference image $\boldsymbol{r}$ and current appearance $\boldsymbol{c}$ in order to create a negative-feedback loop.

3.3.2 Reflectance Estimation in a Dynamic Light Environment

To estimate the reflectance in a dynamic light environment, it is necessary to simultaneously estimate both the reflectance and environmental light. My concept involves the creation of two different light conditions that alternate very quickly such that they are not be perceived by the human eye. Images of objects under each light condition are captured. The idea of embedding different images within consecutive projection frames has been proposed in many spatial augmented reality studies [32, 47, 86]. The light conditions $\boldsymbol{i_1}$ and $\boldsymbol{i_2}$ are respectively expressed as

$$\boldsymbol{i_1} = \mathbf{K}(\boldsymbol{i_{p1}} + \boldsymbol{i_0} + \boldsymbol{i_f}) \tag{5}$$

$$\boldsymbol{i_2} = \mathbf{K}(\boldsymbol{i_{p2}} + \boldsymbol{i_0} + \boldsymbol{i_f}) \tag{6}$$

where $\mathbf{K} \in R^{3\times3}$ is the reflectance of each pixel, $\boldsymbol{i_{p1}}, \boldsymbol{i_{p2}} \in R^3$ is the light from the projector, $\boldsymbol{i_0} \in R^3$ is the environmental light when the system is calibrated, and $\boldsymbol{i_f} \in R^3$ is the variation in the environmental light from $\boldsymbol{i_0}$. $\boldsymbol{i_p}, \boldsymbol{i_0}$, and $\boldsymbol{i_f}$ are reflected from the objects' surfaces, and the camera captures the reflected light. By switching $\boldsymbol{i_{p1}}$ and $\boldsymbol{i_{p2}}$ at a high speed, the human eye perceives the combination of $\boldsymbol{i_{p1}}$ and $\boldsymbol{i_{p2}}$ as the projected light. When two colors are switched faster than the critical flicker frequency (CFF), the human eye perceives the average color of the two [38, 107]. By creating two light conditions by switching the projection, I can capture two types of reflected light, which an observer cannot perceive.

I added a new parameter—"environmental light $\boldsymbol{f}$"—to (3) to represent the captured images of $\boldsymbol{i_1}$ and $\boldsymbol{i_2}$ on the basis of (5) and (6). In the following, I assume that the geometric relationship between the camera and the projector is already known and that the camera pixels correspond to the projector pixels on a one-to-one basis. In addition, if both $\boldsymbol{i_{p1}}$ and $\boldsymbol{i_{p2}}$ are chromatic, I must consider the mixture of the colors, which makes the problem complex. I set $\boldsymbol{i_{p2}} = (0,0,0)^T$ to avoid this complexity, such that I only have to consider the brightness. The captured images of $\boldsymbol{i_1}$ and $\boldsymbol{i_2}$ are expressed as

$$\boldsymbol{c_1} = \mathbf{K}\{(\boldsymbol{c_{full}} - \boldsymbol{c_0}) \odot \boldsymbol{p} + \boldsymbol{c_0} + \boldsymbol{f}\} \tag{7}$$

$$\boldsymbol{c_2} = \mathbf{K}(\boldsymbol{c_0} + \boldsymbol{f}) \tag{8}$$

where $\boldsymbol{c_1}$ and $\boldsymbol{c_2}$ are the captured images of $\boldsymbol{i_1}$ and $\boldsymbol{i_2}$, respectively. From (7) and (8), the reflectance $\mathbf{K}$ can be estimated by considering the change in the environmental light according to

$$\hat{\mathrm{K}} = \mathrm{diag}[(\boldsymbol{c_1} - \boldsymbol{c_2})./\{(\boldsymbol{c_{full}} - \boldsymbol{c_0}) \odot \boldsymbol{p}\}] \tag{9}$$

In addition, the environmental light $\hat{\boldsymbol{f}}$ can be also estimated simultaneously with the reflectance $\mathbf{K}$ from Eq. (7) and Eq. (8).

$$\hat{\boldsymbol{f}} = \hat{\mathrm{K}}^{-\mathbf{1}}\boldsymbol{c_2} - \boldsymbol{c_0}. \tag{10}$$

3.3.3 Separation of environmental light using two cameras

When the projector–camera system consists of a single camera and single projector, the reflectance can be estimated using (9). However, when the system incorporates two cameras, I must also consider their geometrical relationship and color spaces. In this section, I explain proposed method of reflectance estimation using two cameras that matches the geometric relationship and color spaces between two cameras. The light paths and processing flow are shown in Fig. 5.

First, I explain how I match the geometrical relationship between the devices. The viewpoints of the cameras cannot be the same unless the camera center corresponds to the projection center. Therefore, I need to convert the two different viewpoints to a single viewpoint. I refer to one camera as the "main camera" and the other as the "subcamera," and I convert the viewpoint of the subcamera to that of the main camera. The geometric relationships between each pixel of the "main camera and projector" and each pixel of the "subcamera and projector" are determined by gray code pattern projection [91]. Using these two relationships, the system can calculate the relationship between each pixel of the main camera and each pixel of the subcamera, while the viewpoint of the images can be converted from that of the subcamera to that of the main camera.

The system is also required to apply a color-conversion matrix to match the color spaces of the devices. Each device has its own color space, with captured or projected images being represented within that color space. To represent all of the images in the same color space, the color-conversion matrix must be applied to those images. I convert the color space of the subcamera to that of the main camera using the following equation:

$$\boldsymbol{c_s}' = \mathbf{M_{ms}} \boldsymbol{c_s}, \tag{11}$$

where $\boldsymbol{c_s}$ is the image captured by the subcamera, and $\boldsymbol{c_s}'$ is the image captured by the subcamera, which is converted to the color space of the main camera. The image captured by the subcamera $\boldsymbol{c_s}$ is converted to and represented in the color space of the main camera $\mathbf{M_{ms}} \boldsymbol{c_s}$. $\mathbf{M_{ms}}$ is the color-conversion matrix that converts the color space of the subcamera to that of the main camera. I already have the color-conversion matrix between the main camera and the projector and that between the subcamera and the projector, as determined by photometric calibration. With these two matrices, I can easily calculate a color-conversion matrix between the main camera and the subcamera. When considering the color conversion from the subcamera to the main camera, I can rewrite (7) and (8) as

$$\boldsymbol{c_m} = \mathbf{K}\{(\boldsymbol{c_{mfull}} - \boldsymbol{c_{m0}}) \odot \boldsymbol{p} + \boldsymbol{c_{m0}} + \boldsymbol{f}\}, \tag{12}$$

$$\mathbf{M_{ms}} \boldsymbol{c_s} = \mathbf{K}(\mathbf{M_{ms}} \boldsymbol{c_{s0}} + \mathbf{M_{ms}} \boldsymbol{f'}). \tag{13}$$

where $\boldsymbol{c_m}$ is the image captured by the main camera. $\boldsymbol{c_{mfull}}$ is the image captured by the main camera with maximum power projection. $\boldsymbol{c_{m0}}$ and $\boldsymbol{c_{s0}}$ are the images captured by the main camera and subcamera with minimum power projection, respectively. $\boldsymbol{f'}$ is the environmental light represented in the color space of the subcamera. I assure that $\boldsymbol{f} = \mathbf{M_{ms}} \boldsymbol{f'}$. All of the elements of (12) are represented in the color space of the main camera, while the elements in (13) are converted to the color space of the main camera through the application of the color-conversion matrix $\mathbf{M_{ms}}$. From (12) and (13), the reflectance $\mathbf{K}$ can be estimated as

$$\hat{\mathbf{K}} = \mathrm{diag}[(\boldsymbol{c_m} - \mathbf{M_{ms}} \boldsymbol{c_s})./\{(\boldsymbol{c_{mfull}} - \boldsymbol{c_{m0}}) \odot \boldsymbol{p}\}] \tag{14}$$

The environmental light $\boldsymbol{f}$ can also be estimated using Eq. (12) and Eq. (13), in the same way as when only one camera is being used.

$$\hat{\boldsymbol{f}} = \{(\boldsymbol{c_{mfull}} - \boldsymbol{c_{m0}}) \odot \boldsymbol{p}. \circ \mathbf{M_{ms}} \boldsymbol{c_s}\}./(\boldsymbol{c_m} - \mathbf{M_{ms}} \boldsymbol{c_s}) - \boldsymbol{c_{m0}} \tag{15}$$

Furthermore, if the sub camera is calibrated and I can assume that the color spaces of the main and sub cameras are identical, Eq. (14) and Eq. (15) become the same as Eq. (9) and Eq. (10), respectively.

3.3.4 Model Predictive Control

Model predictive control (MPC) is a process control theory that was developed in the late 1980s. Dynamic adaptation [40] can be regarded as an MPC method. However, it cannot be easily applied to appearance control because it was designed to adjust the brightness of a projection onto a surface. Amano *et al.* [11] designed an appearance control system that calculates the reference trajectory and modeling errors using a negative-feedback loop. By applying MPC, the quality and robustness of their system are improved. In the present study, I used the MPC algorithm devised by Amano *et al.* [11].

To apply the MPC algorithm, I used the following projector response model:

$$\boldsymbol{c_M}(t+1) = \hat{\mathbf{K}}\{(\boldsymbol{c_{full}} - \boldsymbol{c_0}) \odot \boldsymbol{p}(t+1) + \boldsymbol{c_0} + \boldsymbol{f}(t+1)\}, \tag{16}$$

where $\boldsymbol{p}(t)$ and $\boldsymbol{c}(t) \in ([0,1],[0,1],[0,1])$ are the normalized projection pattern and image captured at step t. I created the projection response model defined in (16) by adding environmental light $\boldsymbol{f}$ to the model developed by Amano *et al.* [11]. This model is used to determine the projection required to attain convergence. Thus, this model must contain the projection $\boldsymbol{p}$. In the MPC process, I only focus on the images captured by the main camera ($\boldsymbol{c_1}$ in Section 3.2 or $\boldsymbol{c_m}$ in Section 3.3), as indicated by $\boldsymbol{c_M}$. The image prediction $\boldsymbol{c_p}(t) \in R^3$ that contains the model error $\boldsymbol{e}(t) \in R^3$ is expressed as

$$\boldsymbol{c_p}(t+1) = \boldsymbol{c_M}(t+1) + \boldsymbol{e}(t) \tag{17}$$

where

$$\boldsymbol{e}(t) = \boldsymbol{c}(t) - \boldsymbol{c_M}(t) \tag{18}$$

and, the reference trajectory is

$$\boldsymbol{c_R}(t+1) = \alpha\boldsymbol{c}(t) + (1-\alpha)\boldsymbol{r}(t+1) \tag{19}$$

From Eq. (16), Eq. (19), and the control law $\boldsymbol{c_p}(t+1) = \boldsymbol{c_R}(t+1)$, I can acquire the manipulating value.

$$\begin{aligned}
&\boldsymbol{p}(t+1) \\
&= \hat{\mathbf{K}}(t)^{-1}(1-\alpha)\{\boldsymbol{r}(t+1) - \boldsymbol{r}(t)./(\boldsymbol{c}_{full} - \boldsymbol{c}_0) \\
&\quad + \hat{\mathbf{K}}(t)^{-1}\hat{\mathbf{K}}(t-1)\{\boldsymbol{c_0} + \boldsymbol{f}(t)\} - \boldsymbol{c_0} - \boldsymbol{f}(t+1) \\
&\approx \hat{\mathbf{K}}(t)^{-1}(1-\alpha)\{\boldsymbol{r}(t+1) - \boldsymbol{c}(t)\}./(\boldsymbol{c_{full}} - \boldsymbol{c_0}) + \boldsymbol{p}(t)
\end{aligned} \tag{20}$$

with an approximation of $\boldsymbol{f}(t) \approx \boldsymbol{f}(t+1)$. Although I added the environmental light $\boldsymbol{f}$, it is eliminated in (20). Therefore, the system can predict the projection $\boldsymbol{p}$ without any influence from the environmental light.

3.4 Evaluation

In this section, I explain experiments that I undertook to prove that my estimation method can robustly estimate the reflectance as the environmental light is changing. First, I explain how I implemented the system. Then, I explain the experiments that I used to evaluate proposed method.

3.4.1 Implementation

In this section, I explain how I implemented the projector–camera system which I used for my experiments. First, I explain the two ways in which cameras capture the images that are alternately projected from a high-speed projector. Second, I explain how I simulated the image captured by the human eye.

3.4.1.1 System Implementation

To apply my reflectance estimation method, it is necessary to capture two different images which are projected alternately by a high-speed projector. There are two ways in which this can be achieved: 1) using two cameras, a projector, and liquid-crystal shutter filters which are synchronized with the projector, 2) synchronizing a camera with the projector. I implemented both systems to confirm that they can both capture two projections separately. In this section, I explain how these systems were implemented.

First, I will explain how I implemented the projector–camera system with two cameras. The system consisted of two cameras, a 3D projector, and a liquid-crystal shutter filter. Figure 7 shows the system structure and light paths. Liquid-crystal shutter filters (LCSFs) are commonly used in 3D glasses, which allow us to watch 3D digital content. The LCSFs synchronize with a 3D projector, which projects two different images, alternately at 120 Hz. There are two types of LCSF, with each allowing only one image to pass, while blocking the other image.

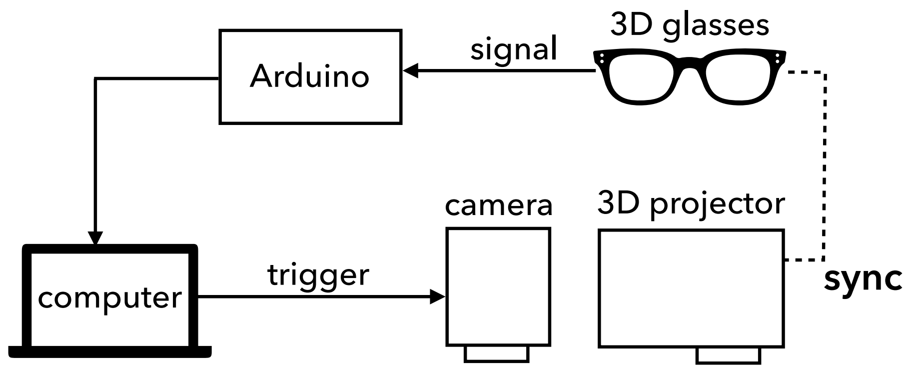


Figure 6. Synchronization process between a camera and a projector.

In my system, I attached the filters to the cameras to capture images under the two different lighting conditions. In particular, the 3D projector alternately projects images for appearance control and a black image (almost no projection), alternately. That LCSF, which cuts off the images for appearance control is attached to the sub camera. With this filter installed, the sub camera only captures the reflected environmental light. The other LCSF is attached to the main camera, which captures the reflected projected light. I will explain this in greater detail in the next section.

To synchronize the camera and a projector, I also used a 3D projector and LCSFs to obtain the timings at which the projection switches. This synchronization is illustrated in Fig. 6. The 3D projector and 3D glasses are synchronized, with the 3D glasses opening/closing under the command of signals received from the projector. Thus, I can acquire information on the projection timing by obtaining the signal from the 3D glasses. An Arduino microcomputer receives a signal from the 3D glasses, and then sends it to the computer over a USB connection. Then, the computer sends a trigger to the camera at the timing at which the projection switches. The 3D projection is switched at a frequency of 120 Hz. Thus, after obtaining several timings, the camera can capture both projections simply by maintaining the framerate at 120 Hz. In Fig. 9, captured images in each implementation are shown. With 120 Hz projector, I projected two kind of images alternately, and a camera (or two cameras) captured the projected images

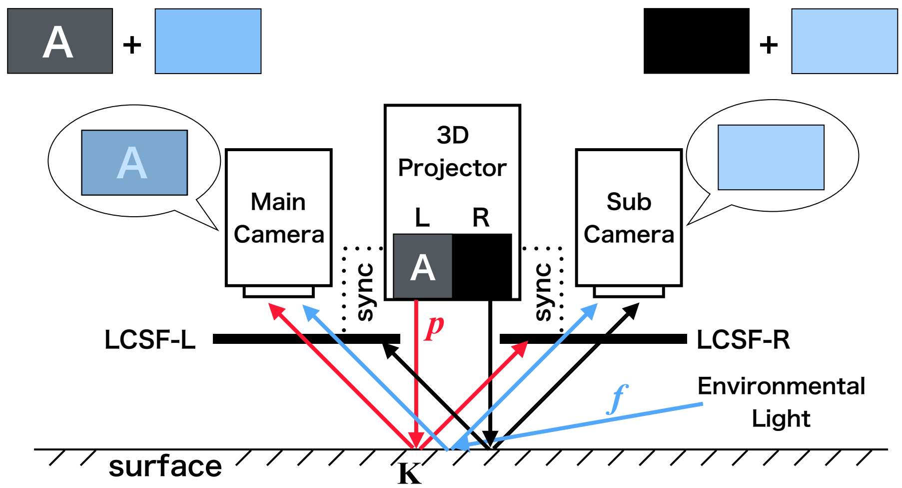
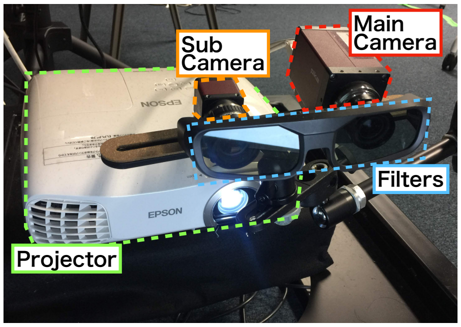


Figure 7. System structure and light from projector and environment.

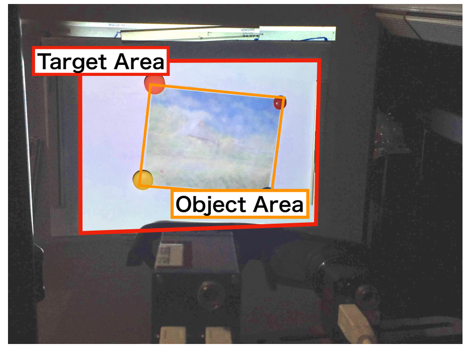
separately. I confirmed that both of implementation are effective for capturing projection separately. In my experiments, I used a projector–camera system which consists of two cameras and one projector. This is because it is required to consider about geometrical and color conversion between two cameras, which are needless in implementation of one camera and one projector. The conversion may occur errors to reflectance estimation. Thus, I select this implementation to make sure both of implementations are effective for reflectance estimation.

Figure 8 shows my system and a target area. The cameras are located close to the projector such that a large space can be used as the target area. I used the planar surface of a board placed in front of the system, with a sheet of white paper attached to it to act as the target area. I assumed that the target surface would have to be a Lambertian surface. Therefore, I used an inkjet printer to print a defined target object on the normal paper. I installed the projector parallel to the floor, while the board was perpendicular to the projector's optical axis.

The equipment was as follows: Allied Vision PIKE (main camera), Allied Vision Guppy PRO (sub camera), EPSON EH-TW5200 (3D projector), MacBook Pro (Intel Corei7 2.7GHz CPU computer). I used C++ with OpenCV and OpenGL libraries to implement the system. To confirm proposed method works even if the cameras are different, I used different two cameras for implementation.



(a)



(b)

Figure 8. System overview. (a) Projector and two cameras with filters. (b) Projected surface.

3.4.1.2 Effects of Filters on Captured Images

The images captured by the cameras with the LCSFs are darker than those captured without the LCSFs, because the filters open/close. I attached an LCSF to both the sub and main cameras. This was because I wanted to make the conditions under which the images were captured by the two cameras as similar as possible.

Amano et al. [11] assumed that the light being captured by a camera is the same as that captured by the human eye. However, I cannot make this assumption. Each camera in my system captures the light that has passed through an LCSF. Therefore, the light captured by the cameras is not that same as that captured by the human eye. The filters can modulate not only luminance but also color of the light. To match the conditions of light captured by the main camera and sub camera, I put the filter to both cameras. The light captured by the main camera, sub camera, and human eye is illustrated in Fig.10. I did, however, assume that the sum of the light captured by the main and sub cameras would be almost the same as that visible to the human eye. The image seen by a human $\boldsymbol{c_h}$ can be represented by following equation:

$$\hat{\boldsymbol{c_h}} = \frac{1}{2}(\boldsymbol{c_m} + \mathbf{M_{ms}}\boldsymbol{c_s}) \tag{21}$$

Therefore, I need to consider the brightness at any given instant. The images

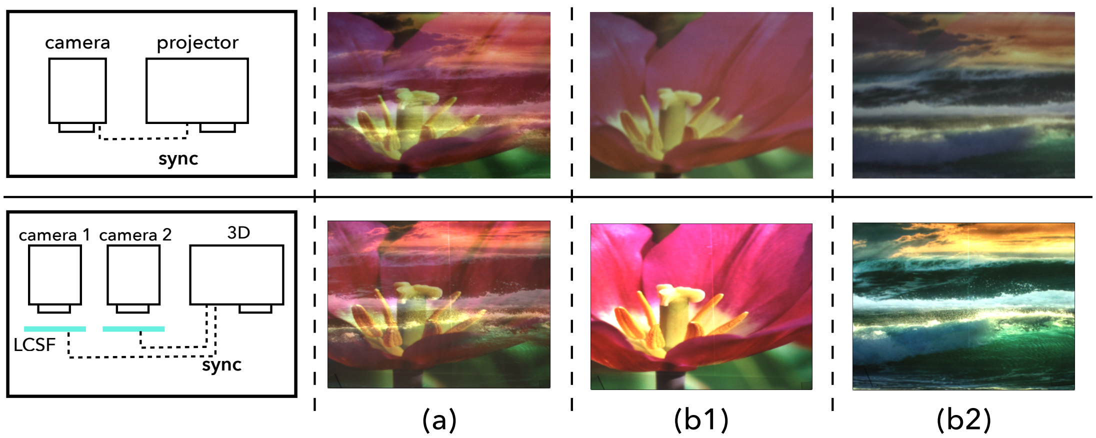


Figure 9. Captured photos by each implementation. Photos in first row are captured by the camera synchronized to the projector. Photos in second row are captured by the camera through LCSFs which synchronized to the projector. (a) Captured images in slow shutter speed. Two images are overlapped. (b1),(b2) Captured images at appropriate timing in high shutter speed. Two images are separated.

captured by the main and sub cameras are added together. This means that the result of adding the two images contains light from two units of time. Therefore, in the algorithm, I divided the sum by 2 to attain an amount $\hat{\boldsymbol{c_h}}$ that would be the same as that captured by the human eye. This estimation of $\boldsymbol{c_h}$ is also required for the implementation with one projector and one camera.

3.4.1.3 Controlling Environmental Light

To test the robustness of my system, I needed a means of controlling the environmental light striking the target surface. To achieve this, I added another projector to simulate the environmental light in the experiment. Using this extra projector, I could project light of various colors and brightnesses. In Experiment 1, I used the extra projector to control the brightness of the light, while in experiment 2, I used it to control the color saturation.

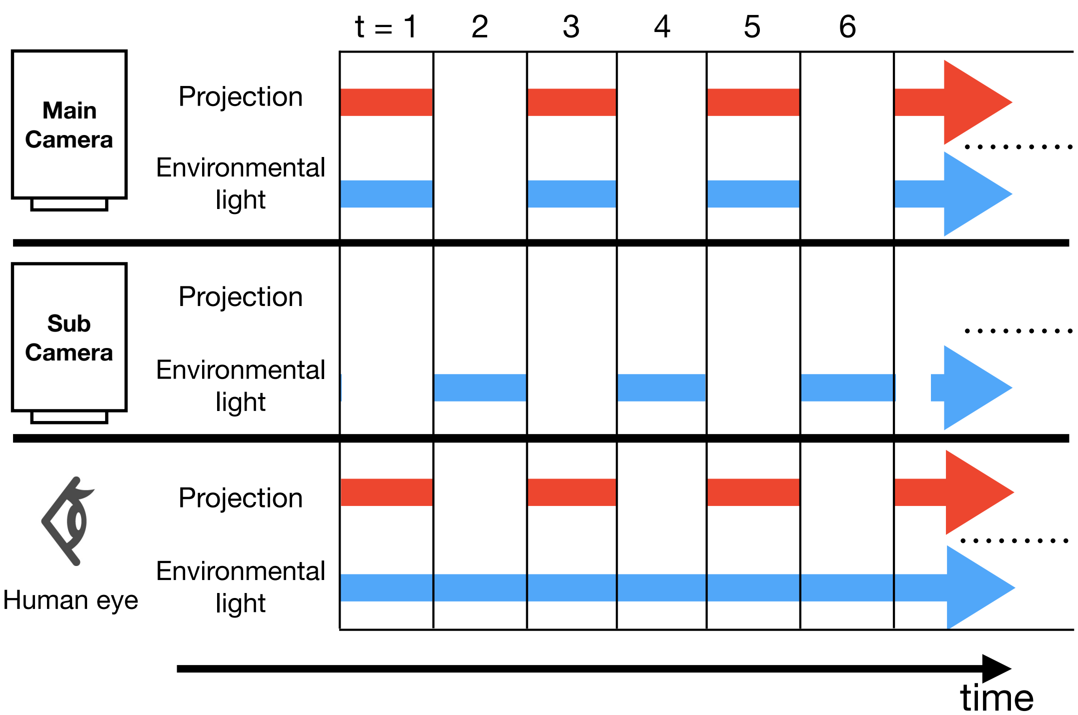


Figure 10. Capture of light by the main camera, sub camera, and the human eye.

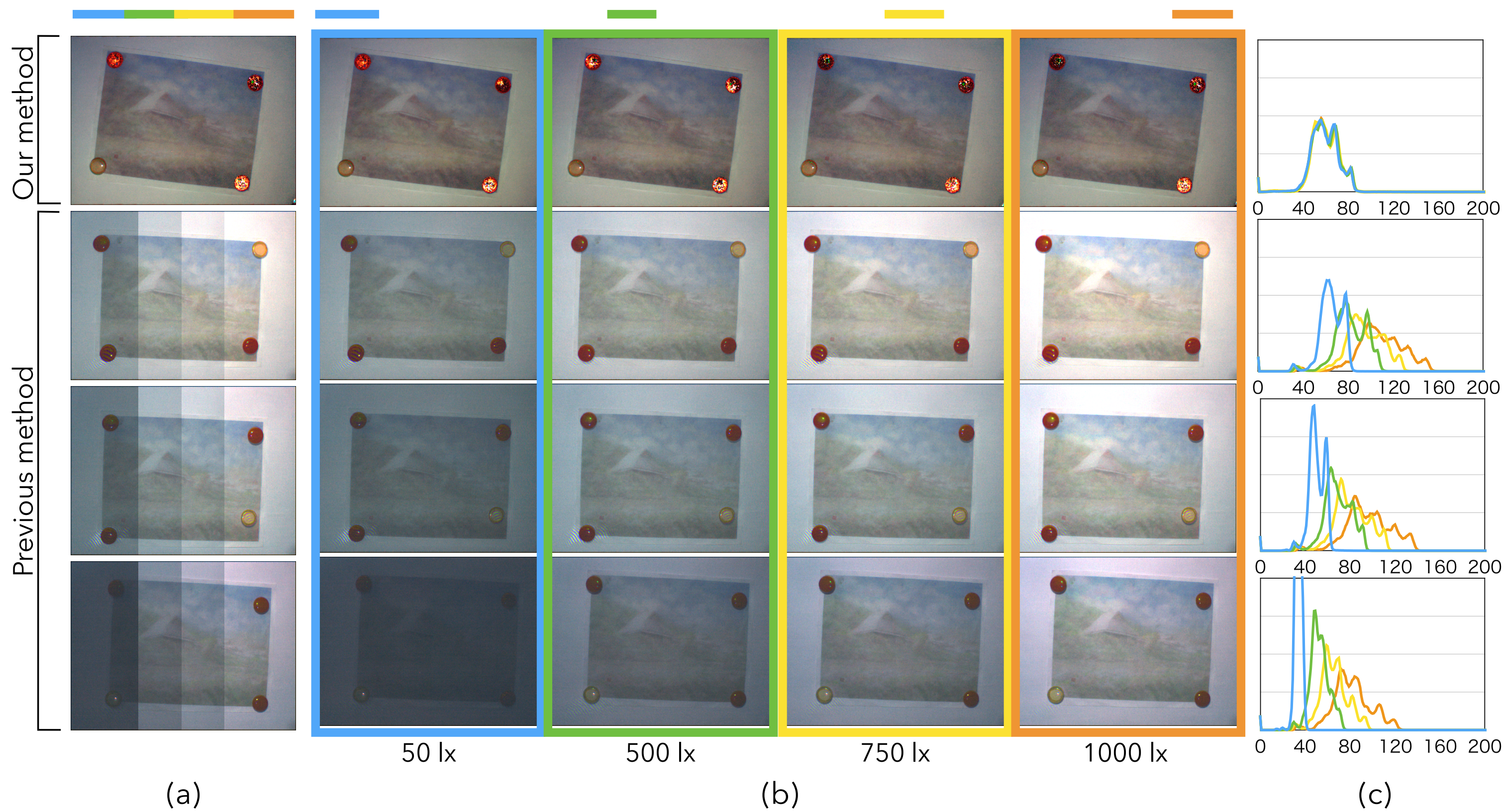


Figure 11. Results of experiment 1. (a) Combination of four slices from each estimated result. From left, estimated result at 50, 500, 750, and 1,000 lx, respectively. (b) Estimated original color under varying environmental light, (c) Brightness histograms for each image. Each color of the histogram corresponds to the color of the frame. The brightness values of these images are multiplied by 1.5.

3.4.2 Experiment 1: Brightness

The goal of this experiment was to confirm that proposed method can robustly estimate the reflectance when the brightness of the environmental light changes. In addition, I estimated the reflectance using the previous method, which does not take changes in the environmental light into account. This was done so that I could compare the results, which would confirm that proposed method produces superior results to those obtained with the previous method.

I measured the illuminance in my laboratory using a luminometer (Shinwa Rules, 78604 EYE HEALTH) at fixed intervals, and reproduced the illuminance by using a projector. The brightness of the environmental light in the morning, afternoon, and evening was 750, 1,000, and 500 lx, respectively. I tested whether proposed method and the previous method could estimate the reflectance under the simulated environmental light that was produced by the other projector. Prior to applying proposed method, I calibrated the system at 750 lx, which is the brightness of the environmental light in the morning. Prior to applying the previous method, I calibrated the previous system using white light with a brightness of 500, 750, and 1,000 lx. After the calibration, I adjusted the brightness of the environmental light to 50, 500, 750, and 1,000 lx. Both systems were able to estimate the reflectance under environmental light. I compared the estimated reflectance values obtained using proposed method and the previous method. In addition, I also created a brightness histogram for comparison.

Figure 11 (a), (b) shows images of the estimated original appearance under white light. Figure 11 (c) shows a histogram of the brightness. Each color in the histogram corresponds to each color of the frame surrounding the images. The images in the 1st row were evaluated using proposed method after it had been calibrated using 750-lx environmental light. The images in the 2nd, 3rd, and 4th rows were estimated using the previous method after it had been calibrated at 500, 750, and 1,000 lx, respectively. The results obtained with proposed method remain constant even as the brightness of the environmental light increases. However, with the previous method, as the brightness of the environmental light increases, so too do the results produced by the method. This can also be determined from the histograms. There are four histograms for the graphs shown in the 2nd, 3rd, and 4th rows, while there is only one histogram for the entire 1st row. Every histogram in the 2nd, 3rd, and 4th rows is different, because the results are affected by the amount of environmental light. However, when using proposed method, the histogram remains constant. Based on these results, I can say that proposed method can robustly estimate the reflectance despite changes in the brightness of the environmental light, unlike the previous method.

3.4.3 Experiment 2: Color Saturation

The goal of this experiment was to confirm that proposed method is capable of robustly estimating the reflectance when the color saturation of the environmental light changes. I also estimated the reflectance using the previous method, in the same way as in experiment 1.

In practice, the color of the environmental light is often orange, such as sunlight at dusk or the light from an incandescent lamp. Therefore, for this experiment, I chose to use an orange light to simulate the environmental light. After photometric calibration under white environmental light, I changed the color of the environmental light to orange with a hue of 36 $^\circ$, using another projector. I then compared estimated results obtained with proposed method and the previous method under a range of saturations of colored environmental light.

Figure 12 shows the results of this experiment. The upper images (i_{a1} to i_{a4}) were obtained using proposed method, while the lower images (i_{b1} to i_{b4}) were estimated using the previous method. i_{a1} and i_{b1} were estimated under 0% color saturation, i_{a2} and i_{b2} under 20%, i_{a3} and i_{b3} under 60%, and i_{a4} and i_{b4} under 100%. Although the results obtained with the previous method assumed an orange color as the color saturation increased, the results obtained with proposed method remained constant.

I converted the color space of all the estimated results from RGB to Lab and calculated the mean value of a* and b* for each image. Using these values, I calculated the distance for each image on the a*b* plane. In particular, I calculated the distance between the image estimated using proposed method under calibrated light (i_{a1}) and the other images that were estimated using proposed method under colored environmental light. The same calculation was also applied to those images estimated by the previous method. Figure 13 is a graph of the calculated distances. Although the values obtained with the previous method are larger when the color saturation is higher, the value obtained with proposed method remains constant at around 1. This result proves that, relative to the previous method, proposed method can estimate the reflectance robustly when the color saturation of the environmental light changes.

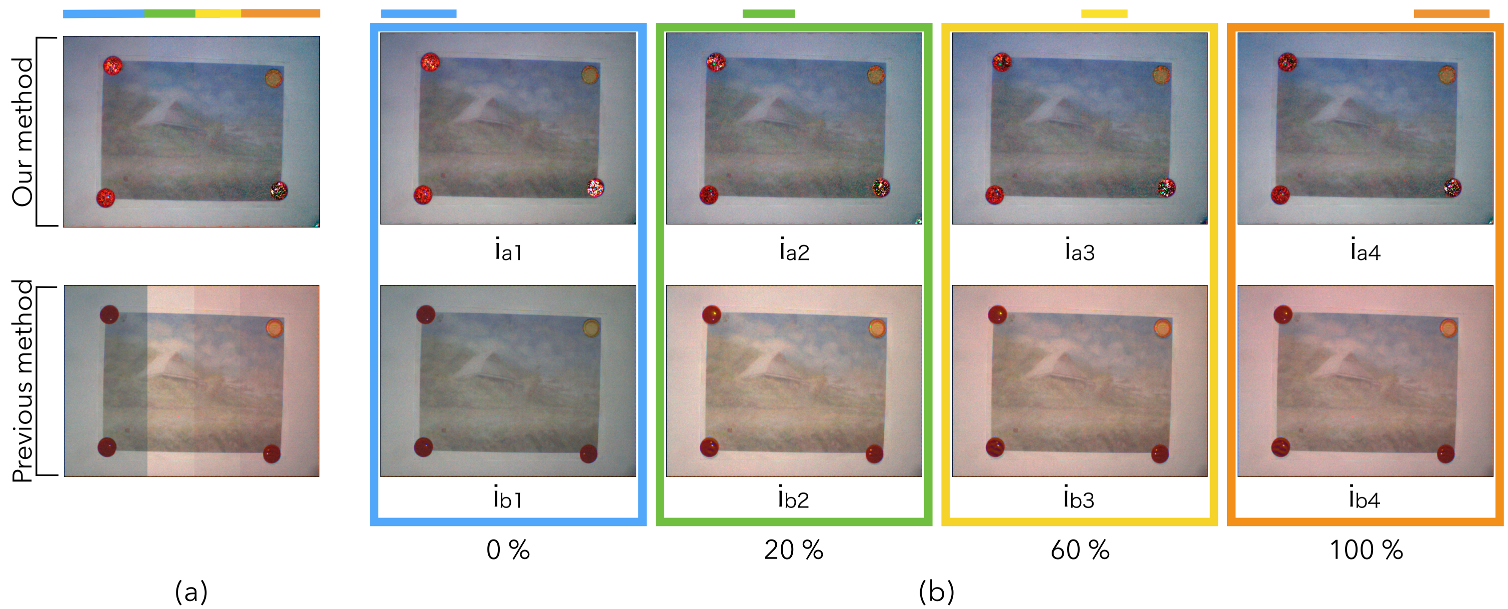


Figure 12. Results of experiment 2. (a) Combination of four slices from each estimated result. From left, estimated result under environmental light of 0, 20, 60, 100 percent color saturation, respectively. (b) Estimation results of original appearance under orange colored environmental light.i_{a1} to i_{a4} are estimated by proposed method, and i_{b1} to i_{b4} are estimated by previous method. The brightness values of these images are multiplied by 1.5.

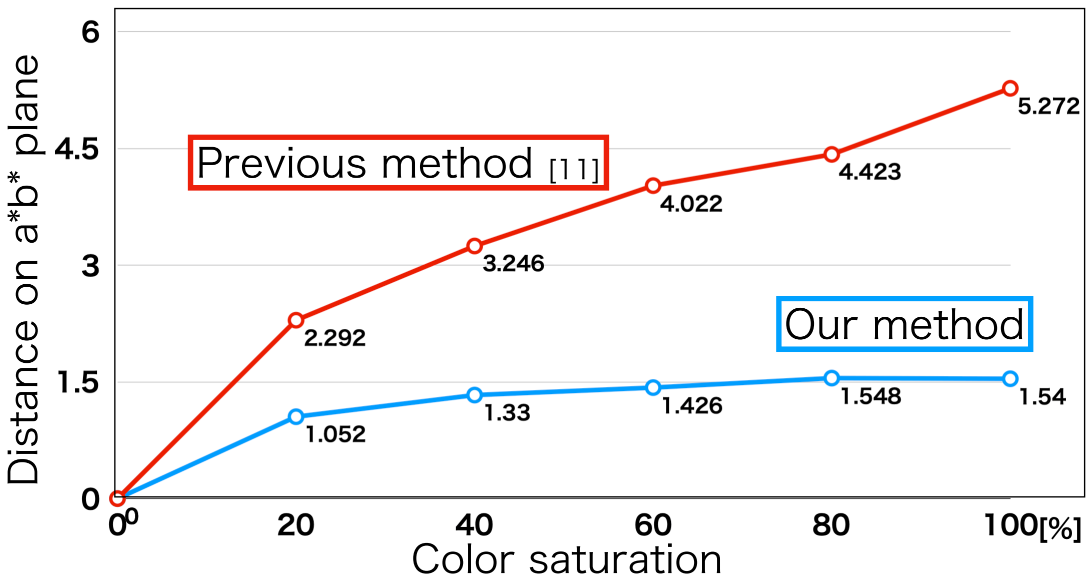


Figure 13. Distance between mean value of estimated result obtained under calibrated light and result obtained under colored light on a*b* plane. The red line indicates those results obtained with the previous method[11] while the blue line shows the results obtained with proposed method.

3.4.4 Experiment 3: Reflectance Estimation under Complex Environmental Light Pattern

The goal of this experiment was to confirm that proposed method can robustly estimate the reflectance of various objects under a range of environmental light levels, while comparing it with the previous method. I prepared three objects as targets, and four images with different levels of environmental light which are shown in Fig. 14. I estimated the reflectance for every combination using both my newly developed method and the previous method. The estimated results are shown in Fig. 15. I calculated the difference between corresponding pixel values of the estimated images and captured images under white illumination, and I created box plots in RGB individually. I performed an one-sided T-test between the data for each box plot (99 percent confidence interval). The results of the T-test are shown in Fig. 15.

Figure 14. Target objects and environmental light patterns used in Experiment 3. (a) images of three objects which captured under white illumination , (b) four environmental light patterns.

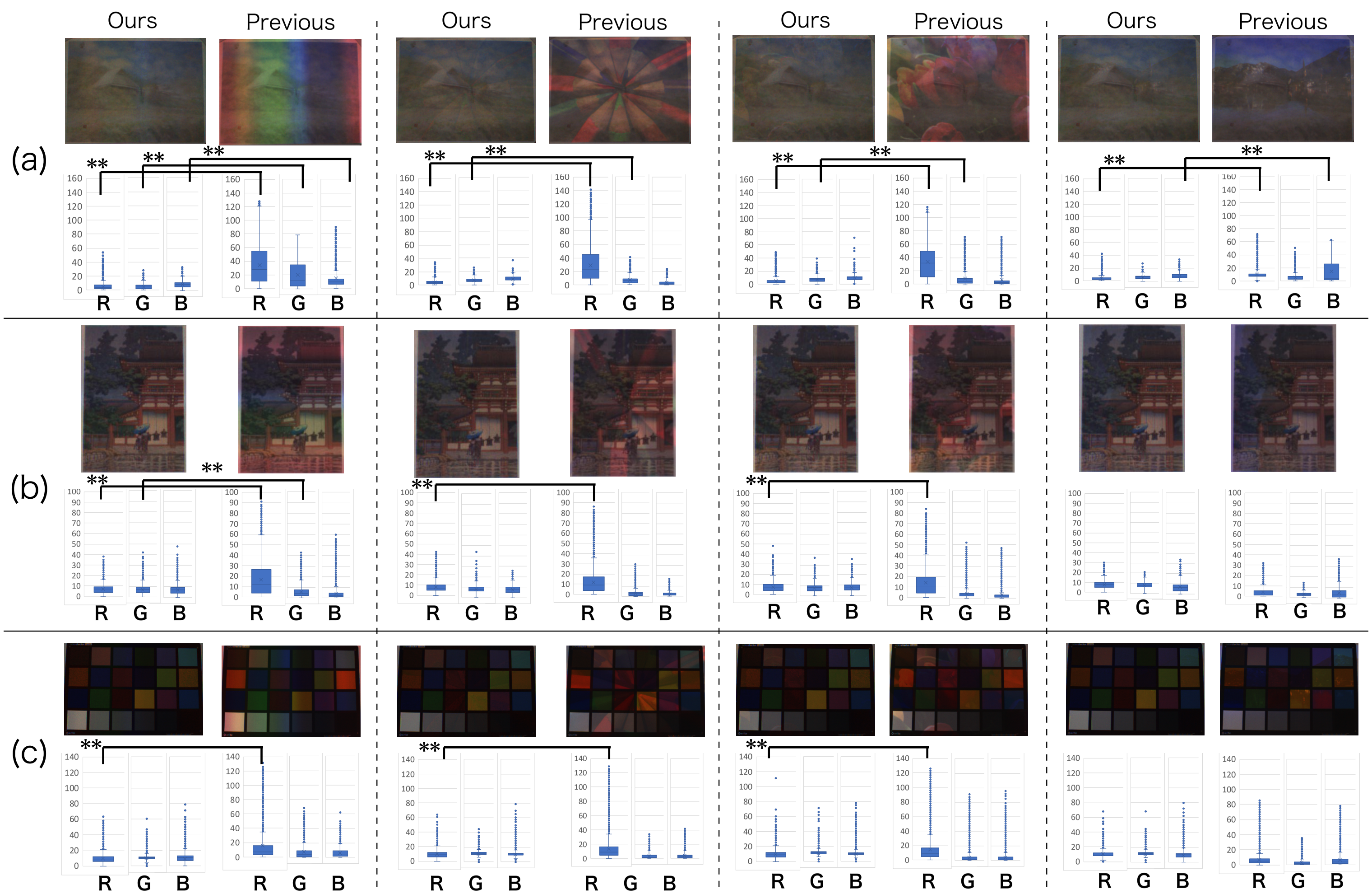


Figure 15. Results of experiment 3. (a), (b), and (c) are estimated results of different objects. Left Images in each pair are estimated results by proposed method, and right images are estimated results by previous method.

3.4.5 Experiment 4: Accuracy of Controlled Results

In this section, I compare the reference images and controlled results obtained with the system to determine whether my system can accurately change the appearance of an object from the original appearance to the target appearance. I used same objects as those used in Experiment 3, but presented them in monochrome. The reference images and controlled-appearance images are shown in Fig.16. I created a heat map of the difference images for each RGB pair to better visualize the results. In addition, I calculated the mean squared error (MSE) of each difference image. For (a) and (b), the two images are almost completely the same. This can be determined both visually and from the very low MSE values for every channels. However, for (c), some areas in the controlled-appearance image retain their colors slightly. In the heat map for the Blue channel of (c), the MSE value was the highest for this experiment in at least four areas.

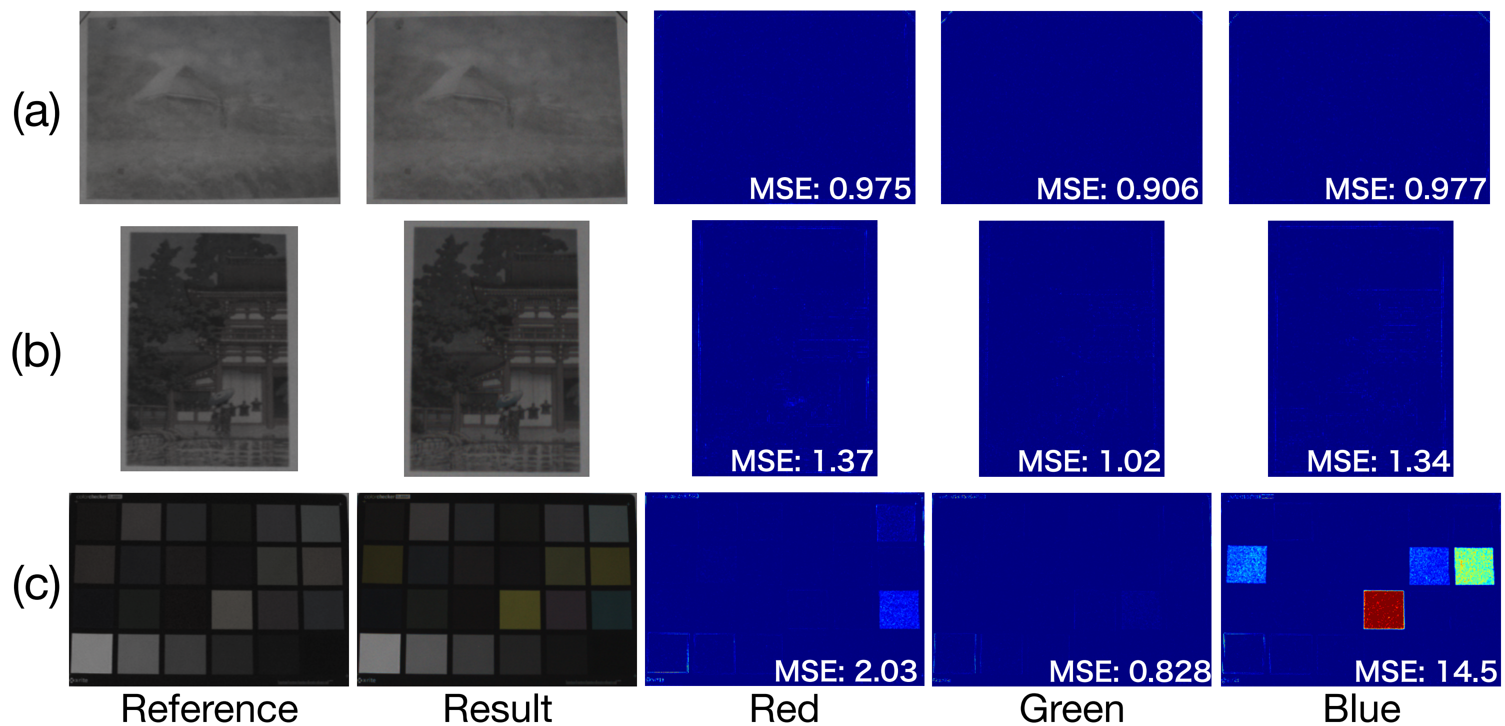


Figure 16. Reference images and controlled results. Difference between each pair of refernce image and controlled result image are visualized as heat map. They are divided to RGB channels.

3.4.6 Experiment 5: Controlled Results

In this section, I present the controlled appearance produced by my projector–camera system. I used two kinds of projectors, one being a 3LCD projector (EPSON EH-TW5200), and the other a 1-chip DLP projector (BENQ TH671ST). To confirm that proposed method does not depend on the type of projectors, I used two type of projectors. 3LCD and 1-chip DLP are both widely used in many consumer projectors. The controlled results for four effects are shown in Fig. 17 and Fig. 18. The four effects are 1) color saturation enhancement, 2) color phase shift (two direction), 3) monochrome effect, 4) texture reduction. These effects are designed by Amano et al. [11]. Equations for creating reference images are shown below. For color saturation enhancement, the equation is

$$\boldsymbol{r} = gain * (1+s)\boldsymbol{c_{est}} - s\boldsymbol{c_{mono}} \tag{22}$$

where s is a parameter for strength of the effect and its range is $s > 0$, and $\boldsymbol{c_{mono}} = (|\boldsymbol{c_{est}}|, |\boldsymbol{c_{est}}|, |\boldsymbol{c_{est}}|)^T$ is a monochrome image of estimated image $\boldsymbol{c_{est}}$. Monochrome effect is controlling colors to the opposite direction of the color saturation enhancement. The equation is

$$\boldsymbol{r} = gain * (1-s)\boldsymbol{c_{est}} + s\boldsymbol{c_{mono}} \tag{23}$$

where range is $0 < s \leq 1$.

For color phase shift, the equation is

$$\boldsymbol{r} = gain * \mathbf{U}\mathbf{T_R}\mathbf{U^T}\boldsymbol{c_{est}}. \tag{24}$$

The range of the parameter s is $0 < s \leq 1$. $\mathbf{U}$ is a matrix for RGB to Lab color space conversion and $\mathbf{T_R}$ a matrix for rotation.

$$\mathbf{U} = \begin{bmatrix} \frac{\sqrt{3}}{3} & \frac{\sqrt{3}}{3} & \frac{\sqrt{3}}{3} \\ \frac{\sqrt{6}}{3} & -\frac{\sqrt{6}}{6} & -\frac{\sqrt{6}}{6} \\ 0 & \frac{\sqrt{2}}{2} & -\frac{\sqrt{2}}{2} \end{bmatrix} \tag{25}$$

$$\mathbf{T_R} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos s & -\sin s \\ 0 & \sin s & \cos s \end{bmatrix} \tag{26}$$

For texture reduction, the equation is

$$\boldsymbol{r} = gain * \boldsymbol{e} \tag{27}$$

where $\boldsymbol{e}$ is an unit vector. Other effects here creates reference images based on estimated image $\boldsymbol{c_{est}}$. In contrast, the target appearance of texture reduction effect is always uniformed white image, and it is not affected by objects.

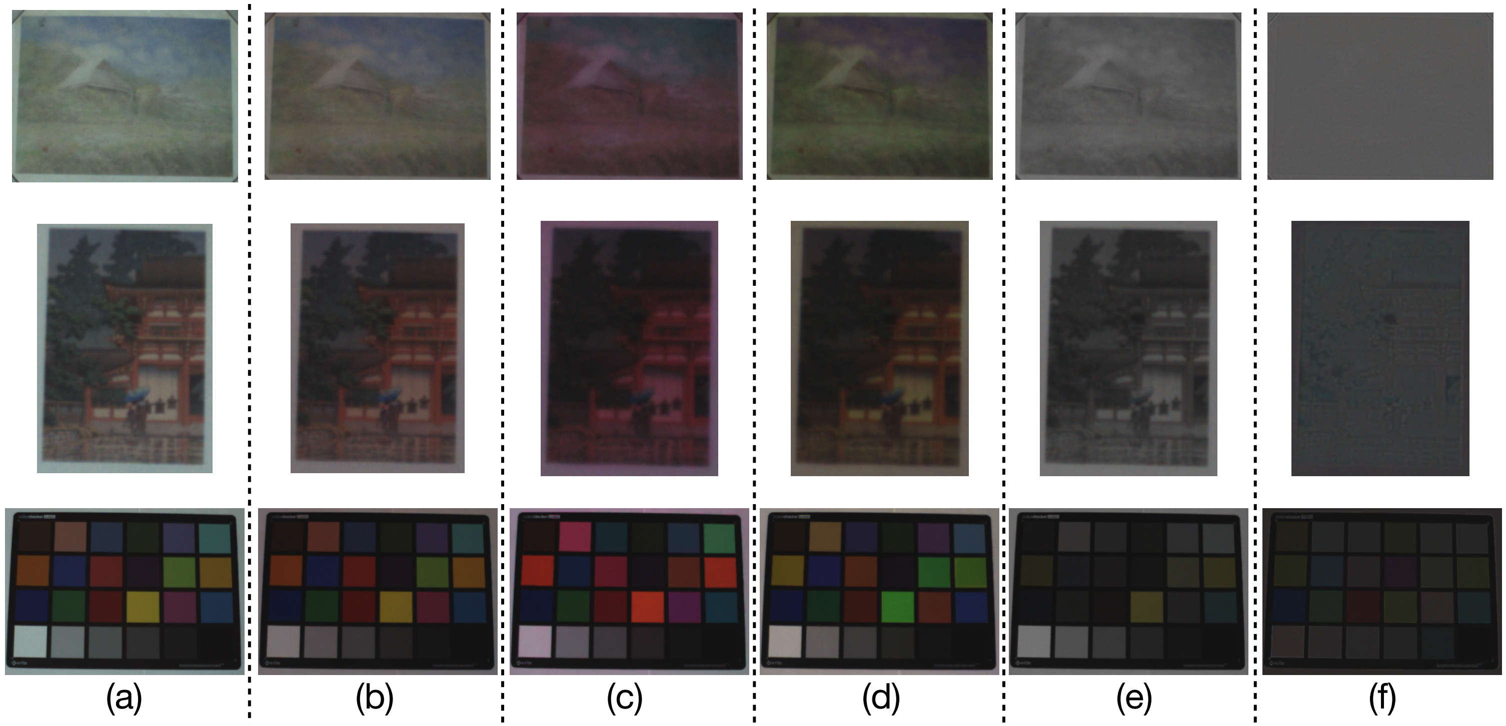


Figure 17. Controlled appearance with the system using a 3LCD projector. (a) original appearance, (b) color saturation enhancement, (c) color phase shift +, (d) color phase shift −, (e) monochrome effect, (f) texture reduction. The brightness values of images (b) - (f) are multiplied by 2.0.

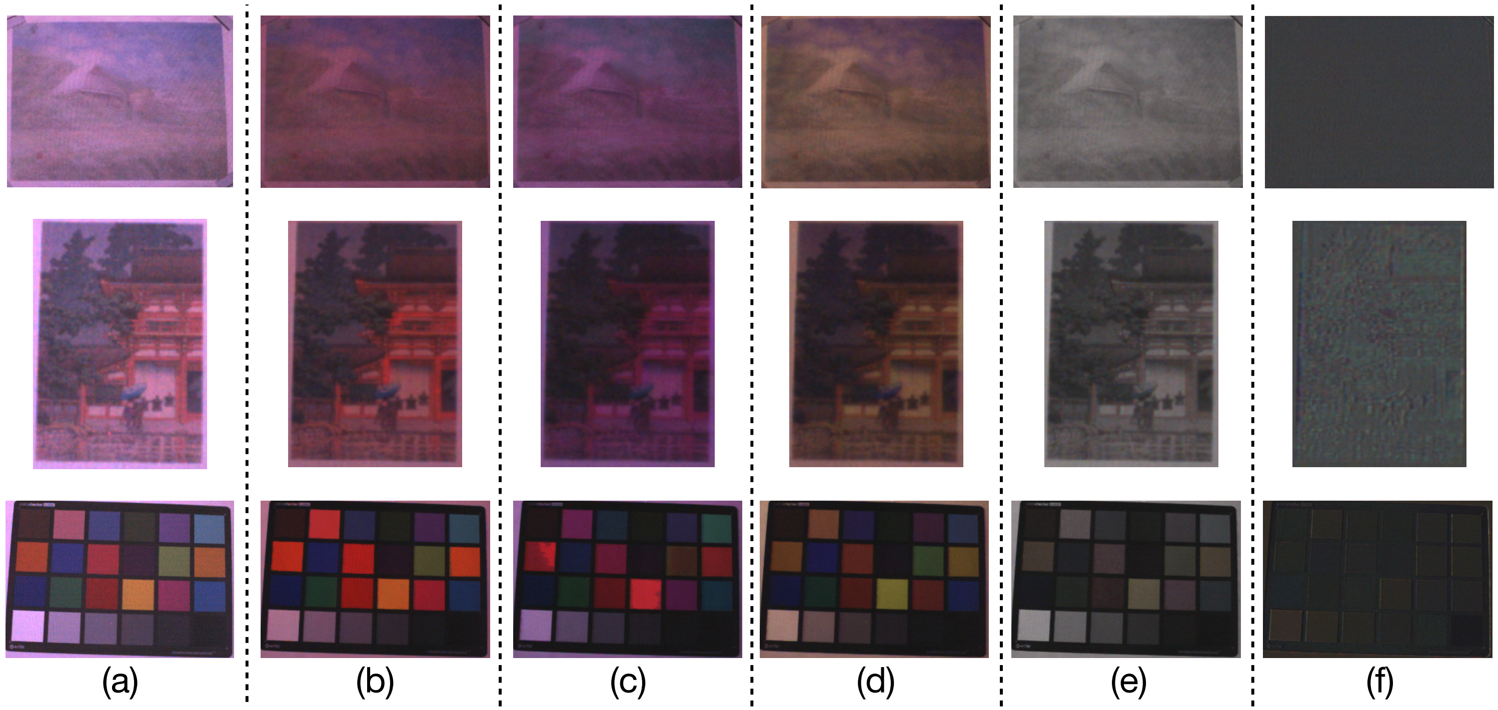


Figure 18. Controlled appearance with the system using a DLP projector. (a) original appearance, (b) color saturation enhancement, (c) color phase shift +, (d) color phase shift −, (e) monochrome effect, (f) texture reduction. The brightness values of images (b) - (f) are multiplied by 2.0.

I also tested the control of the appearance of objects which have specular reflection characteristics. I scanned an X-rite color checker and printed the captured images on two kinds of glossy papers (FUJIFILM Photo paper WPA420PRM, FUJIFILM Photo paper Ultra Gloss WPA412PRO). The estimated results are shown in Fig. 19. Although the positions of the camera and projector play a significant role, the system can estimate their reflectance. The cameras were not placed in a position which can capture the specular component of the projected light. Thus, the system can estimate the reflectance. However, when I illuminated the surface with a flashlight, a black spot and bright spot appear on the estimated images. These are caused by the specular components of the light from the flashlight. The positions on the objects where specular components appear differ depending on the camera positions. Given that I used two cameras, two spots appear on the images.

3.5 Discussion

The results of experiment 1 imply that my system is capable of robustly estimating the reflectance even when the brightness of the environmental light changes from 50 to 1,000 lx. The recommended illuminance for the likes of a drafting space in an office or an operating room in a hospital is usually no more than 1,000 lx [72]. Therefore, when my system is applied indoors, it operates as expected. Outdoors, however, the illuminance often reaches 100,000 lx at noon. Under this type of illumination, I would not expect my system to be capable of estimating the reflectance. This is because the camera cannot capture the light coming from the projector in such a bright environment. In this situation, the human eye also cannot see the projection light under strong sunlight because projection is very dark compared to the sunlight. Thus, even if my system were able to estimate the reflectance, it would not be possible to project images that would be visible when using a projector. Once the illuminance falls below 1,000 lx at dusk, however, my system can be applied outdoors. Therefore, I believe that my system's acceptable illuminance range is broad enough for application to typical situations.

Given the results of experiment 2, I can conclude that my system can be used under colored environmental light. The color of indoor light is not always white.

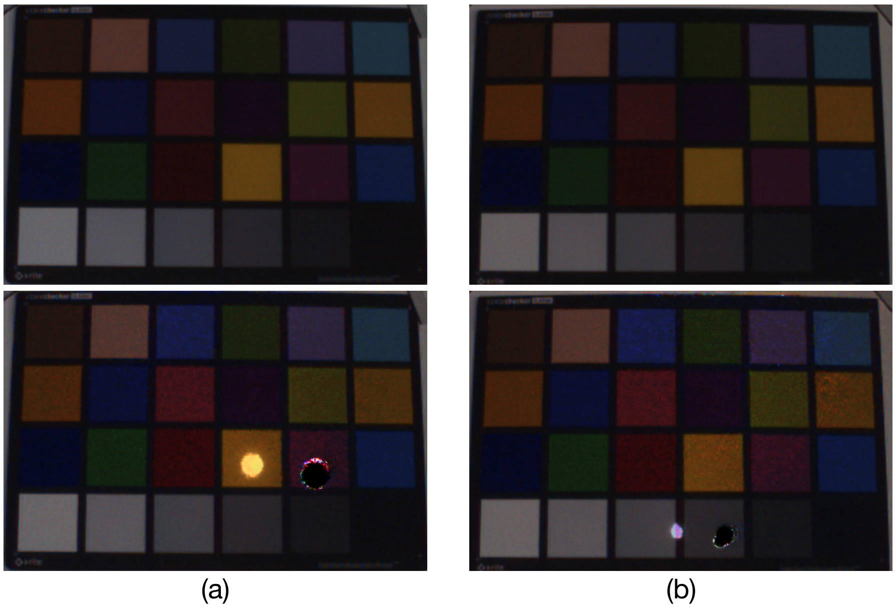


Figure 19. Estimated results of printed glossy papers.(a) estimated results of glossy paper (FUJIFILM Photo paper WPA420PRM), (b) estimated results of ultra glossy paper (FUJIFILM Photo paper Ultra Gloss WPA412PRO). Upper results are estimated in white indirect illumination, and lower results are estimated results of the object with direct illumination.

For example, incandescent lamps often give off an orange hue. In addition, it is very easy to acquire equipment that can be used to control the color of indoor lights. Generally, the color saturation of indoor light is not so high. Even when the color saturation is high, I would not expect it to exceed the 100. In addition, in experiment 2, I only performed a test under orange environmental light, but my system could theoretically be applied under any color of environmental light. Therefore, I feel that the acceptable color range of my system is also broad enough to allow its practical use.

Based on the results of Experiment 3, I can state that proposed method can robustly estimate reflectance even when the environmental light has complex brightness, color, and texture patterns. However, if I focus on each channel of the results, the previous method incurred smaller errors in some cases. For example, in the first result on the right in Fig. 15 (a), the environmental light pattern is mostly blue. Therefore, the results obtained with the previous method have larger errors than those incurred by proposed method for the B channel. However, for the G channel, the results obtained with the previous method have smaller errors than those obtained with my new method. I believe that proposed method incurs a greater continuous error than the previous method. The calculations required by proposed method are more complex than those of the previous method, and I also use two cameras, both of which incur errors. In addition, in the box plots shown in Fig. 15 (c), the results obtained with the two methods appear very similar. I believe that this is a result of the color checker having very deep colors, such that its surface does not reflect environmental light patterns strongly. In this case, the estimated results are not so greatly affected by the environmental light patterns. However, when I visually compare the results obtained with the two methods, I can easily identify some edge patterns and uneven brightness or color areas in the results obtained with the previous method. This effect is barely visible in my box plots, which is a major improvement over the previous method.

Based on the results of Experiment 4, I can conclude that my system can accurately control the appearance of objects relative to reference images. In Fig. (a), (b), the MSE values for every result are very low. However, in Fig. 16 (c), there are some areas which have errors. I believe that this is caused by the specifications of the projector. In the heat map for the blue channel shown in (c), the original colors of the areas with the larger errors are deep yellow and orange. The projector must project a strong blue illumination onto these areas to make them monochrome. However, in this experimental set-up, the projector cannot produce a sufficiently bright blue illumination. Thus, I believe that my estimation and control processes are not the source of the errors. Rather, the errors are incurred by the lack of projector power.

In Experiment 5, I demonstrated the possibility of controlling the appearance of three objects with two projectors, namely, a 3LCD and 1-chip DLP. I think proposed method can be applied irrespective of the type of projectors. 1-chip DLP projectors temporally switch RGB channels. The switching speed is so high that humans perceive mixture color of RGB channels. However, when shutter speed of cameras is high, the cameras may not capture fully mixed projection. To avoid this problem, I set shutter speed of the cameras longer in my implementation. This solution is only possible with the implementation with two cameras. The system with directly synchronized projector–camera system cannot freely set shutter speed. In addition, the controlled and estimated results for printed papers with strong specular reflection characteristics are also shown. These results show that my system can estimate the reflectance and control the appearance of objects having specular reflection. However, there are some limitations. First, the positions of the cameras and the projector are limited. If the camera captures the specular reflection of the projection, the system cannot estimate the reflectance of that area. Additionally, the system cannot estimate the reflectance or control the appearance when the projected area is lit by direct illumination. In this case, the position and direction of the direct illumination also plays a significant role, but when the cameras capture the specular reflection, the system loses control of that area. In my experimental setup, I used two cameras, such that the positions of the specular reflection in the projected area differed between them. This is because there are two points (black and white) in the estimated results shown in Fig. 19. Although this is one of the limitations of proposed method, the information may be useful for other purposes, such as light source position estimation. By using the positions of the specular reflection on the projected surface and the camera positions, I can estimate the position of the source of the direct illumination.

Proposed method create two kinds of light conditions for estimating both reflectance and environmental light. In other words, when the projector–camera system cannot create two different light conditions, the estimation fails. In particular, the system estimates them by (7) and (8). The difference between (7) and (8) is $\boldsymbol{p}$. When $\boldsymbol{p} = 0$, (7) and (8) become completely the same. In the situation, the system cannot separate reflectance and environmental light. Thus, the system cannot estimate both of them when $\boldsymbol{p} = 0$. This situation can happen when appearance of the object is already same with target appearance. Although previous method assumes constant environmental light, previous method can estimate reflectance even when $\boldsymbol{p} = 0$ with (4). Estimated result is used for creating a projection image of next period. Unstable estimated results are connected to unstable projection. Projection of previous system is stable even when $\boldsymbol{p} = 0$ because previous system can estimate reflectance. In contrast, estimated reflectance of proposed method become unstable. In 9, the system calculate $\boldsymbol{c_1} - \boldsymbol{c_2}$ whose result is theoretically zero. Additionally, the calculated result is divided by $\boldsymbol{p}$ which is zero. Calculated results of division of two elements which are both about zero are unstable. Therefore, when projection is zero, it is difficult for proposed method to estimate reflectance and environmental light. I have two solutions for solving this limitation. First one is creating a hybrid system with previous and proposed method. By switching two estimating methods by the value of $\boldsymbol{p}$, the projection hardly become unstable, and the system can estimate both reflectance and environmental light when $\boldsymbol{p}$ is not zero. Second one is not estimating reflectance in pixel but in area. Currently, the system estimates reflectance of each pixel in captured images. However, there are few objects whose color changes in every pixel when the distance between the system and objects is in few meters. In this situation, I can assume that the system can separate few regions with same colors. In actual scene, it is very rare case when a whole projection image become zero. Even if only reflectance of few pixels can be estimated, the system can know the reflectance of the area which the estimated pixels belong to. I showed two solutions above, however, main purpose of appearance control is to control colors of real objects, such as changing color shift or color saturation which are shown in 17 and Fig. 18. When Iwould like to change appearance from original one to another one, projection hardly become zero. Thus, proposed method is better when the purpose is to control colors of real objects.

I implemented two projector–camera system which are shown in Fig. 9. There are advantage and disadvantage in both systems. First, I discuss advantage and disadvantage of the projector–camera system which synchronizes directly. The system consists of one camera and one projector. It is easier to calibrate geometrically and chromatically. This is because each optical device, such as cameras and projectors, have each color space and each geometrical condition. When the number of devices becomes bigger, it takes time and effort to compensate the difference among them. This is also connected to implementation of an optically aligned projector–camera system. It is difficult to implement it with multiple cameras. A disadvantage of this system is difficulty of implementing synchronization between a camera and a projector. Framerate of the camera needs to be at least same with that of the projector. In addition, projection images and captured images are needed to be pairs. With implementation with two cameras, each camera captures each image. However, with one camera, the camera needs to capture separately and determine that each captured image is with or without projection. Even if the camera can capture projection separately, estimation fails when the determination fails. This camera captures images with high framerate, and captured images may influenced by illumination with temporal flickering. A lot of light equipment, such as LEDs and fluorescent lamps, flickers in high frequency. Framerate of my eyes or normal cameras is low enough, and they cannot perceive or capture flickering. However, the system have high framerate camera which may capture images of bright moment and dark moment caused by the flickering. In that case, this issue is needed to be solved by including statistical process to the estimation process. In implementation with two cameras, LCSFs are synchronize with a projector, and the cameras do not. Thus, I can set framerate of the cameras slower and exposure time longer in order to capture temporally uniformly. With this flexibility of framerate and exposure time, the system can be applied to high dynamic range scenes. I can set gain of the cameras individually, and the dynamic range of the system become larger compared to that of each camera.

3.5.1 Contribution

The contributions of this work are 1) robust reflectance estimation despite dynamic changes in the environmental light, 2) absolute color reproduction, 3) calibration-less operation. In this section, I explain these contributions in greater detail.

My first contribution is robust reflectance estimation despite dynamic changes in the environmental light. proposed method can estimate the reflectance of target objects even when both the reflectance and environmental light are changing dynamically. For example, if I attach the system to a moving object, they would both be dynamic. Projectors are becoming smaller, and many research efforts have considered the attachment of a projector to a user's body[98] or a vehicle such as a bicycle[33]. In addition, given its robust ability to estimate the reflectance, proposed method can overcome the effects of variations in the environmental light. Of course, it can not only handle changes in the overall

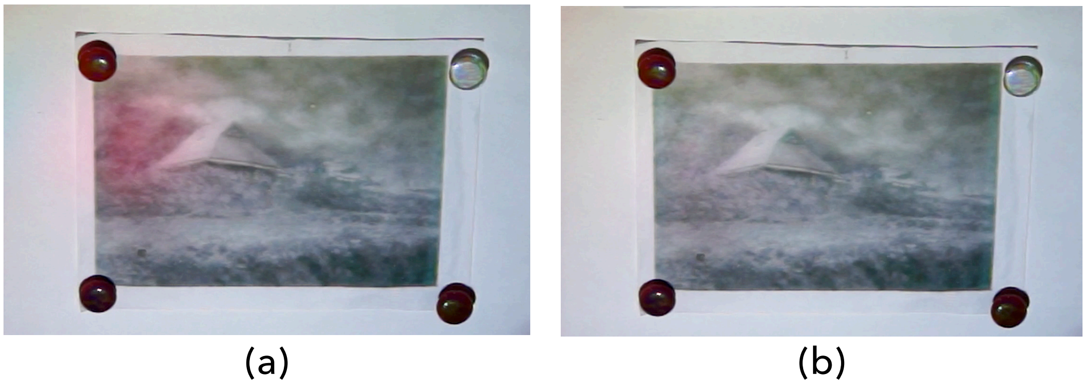


Figure 20. Appearance control with the canceling of additional light. my system can make the colored area appear monochromatic. (a) Instant at which a red spotlight is shone on the object surface, (b) after the system compensates to eliminate the red light.

environmental light of a room, but also handle spatial changes in the environmental light, as would occur with spotlights. In Fig. 20, the system eliminates the effect of the red spotlight, maintaining the monochrome appearance of the painting. It is also possible to change the color of spotted light while colors of objects are controlled differently. I think I can create new user experience by my system. Additionally, when the projected area is large, the environmental light is not always spatially uniform because of the layout of the lighting equipment or the presence of a highly directional light source. Even in this situation, proposed method can handle the variations in the environmental light, such that the projected area appears as if it is under uniform environmental light.

Second, proposed method can reproduce absolute color. The human eye captures light that is reflected from objects and thus perceives colors. Thus, colors are determined by the reflectance and the incident light. Even if a projector projects a given quality of light onto the same object, the reflected light will vary depending on the environmental light. Therefore, I need to know both the reflectance and level of the environmental light to reproduce absolute colors. My system estimates both the reflectance and the environmental light. The incident light consists of both environmental and projected light. Using this information, desired colors can be reproduced without special lighting. This would be useful for the designing tasks or the simulation of some appearance. For example, when I need to design a poster, I can try other colors after printing. Additionally, my system can simulate appearance under various colors of environmental light irrespective of the lighting conditions there.

Finally, proposed method allows an appearance control system to be operated without additional need for photometric calibration if it completed once. The appearance control system based on the previous method requires that photometric calibration be performed whenever there is a change in the environmental light. This is because the previous method focused only on short-term use and assumed that the environmental light would be constant. With proposed method, the appearance control system can be used over the long term without any additional calibration. Given the above, I believe that the appearance control system could be used as an intelligent light source that would be capable of supporting human vision. Applications could include changing the color of letters that are difficult to read or making the colors of a faded photo vivid. When used as an intelligent light source, I would expect users to keep the system turned on, in which case re-calibration would be troublesome. Therefore, given that proposed method allows an appearance control system to operate without the need for calibration, it would make a major contribution to using the system as an intelligent light source.

3.5.2 Limitation

My experiments revealed limitations in the new system. First, when the colors of objects are dark or deep, the system sometimes cannot accurately control their appearance. This is a function of the color of the surface and the environmental light [5]. When the surface color is very dark, the light emitted by the projector is barely reflected by the surface. Thus, very powerful projection is required to give the appearance of many colors. However, with proposed method, the full power of the projector cannot be used because of the switching projection. The maximum brightness of the projector is thus halved. Because of this limitation, there are difference between a reference image and a controlled result shown in Fig. 16 (c). Therefore, fewer colors can be presented physically relative to projectors which do not switch the projection on and off. However, the purpose of appearance control is showing controlled results to humans. In other words, even if some colors cannot be presented physically, there is no problems if they can be presented perceptually. The study for perceptually broadening presentable color range of projectors also has been done, and it is explained in Chapter 4.

Second, when I wanted to apply compensation for a colored spotlight, I found that my system is basically capable of doing so. However, the spotlight only became dimmer, with the color still visible in some parts of the target object. I believe that this is a function of the color space conversion between the main and sub cameras. The system multiplies every pixel of the images captured by the sub camera by matrix $\mathbf{M_{ms}}$. Thus, color space conversion is applied equally even if the cameras fail to capture the scene uniformly, as in the case of vignetting.

In my implementation, the projector switches on/off at 120 Hz. The difference in the brightness between these two projected images is very large. This may lead to flicker perception for some observers. I prepared two projector–camera systems to examine the issue of flicker perception. One system switched the projection on/off at 120 Hz, while the other system did not. I placed the same printed objects in front of each system, and used the system to control the appearance of the objects. I showed these controlled-appearance objects to participants and asked them to inform us if they felt that there was any difference between them. I performed this experiment using four participants, all of whom noted a slight flickering. I conjuncture there two reasons to induce this flickering perception in my experimental set-up. First reason is that the projection to the white surface switches to bright white and black. As shown in Fig. 8 (b), I take broader target area compared to the object area. In my algorithm, the system does not track the object, while it focuses on controlling colors of each pixel. The target area except the object area is illuminated by white light if the surface is white. I regard that a color of background is white, and, in my algorithm, non-target region will be illuminated by white light. The brightness amplitude between the two brightness values of the flickering area is one of the reasons for occurring flickering perception [56][79]. The difference in the brightness between two projection images of the area becomes larger than that of the object area. In addition, the larger the size of the white projection area, the more flicker perception is induced [81].

I conjuncture that this unnecessary white illumination lead flicker perception. Though it is a subjective evaluation by us, I felt flicker perception is reduced by limiting the projection area. Thus, I think I can reduce flicker perception by tracking objects and limiting projection region. It is also possible to solve this problem by projecting in high enough framerate which humans cannot perceive flicker. Davis et al. [34] found that humans perceive flicker even at a frequency of 500 Hz if projection images include high frequency spatial edges, while ours onle have 120 Hz. I conjuncture this lead the flickering perception. There are studies which employs high-speed projector–camera system [49][74]. They succeed to prevent flicker perception with high-speed systems. Thus, by employing a projection system whose framerate is higher than 500 Hz, I may prevent flicker perception.

Implemented system can be applied scenes with dynamic reflectance and environmental light. However, I can perceive delay of the projection. In particular, when I move object, the projection also move and chase the object. The speed of it is not so fast, and I can easily recognize. For wider range of application, this may be problem. I think there are two ways to solve this. One is simply using more high speed devices and more powerful computer. There are research that employ 1000Hz projector for displaying images in constant position on moving object [77, 76]. It is difficult for humans to perceive its delay. The other is put prediction process to estimation algorithm. If the system can predict the position of the object in next frame based on its movement, the delay decreases. By these delay reduction, the range of application can become wider.

3.6 Conclusion and future work

In the present study, I devised a method for robustly estimating an object's reflectance despite dynamic changes in the environmental light, as a basic technology for application to appearance control using a projector–camera system. Any such system requires the simultaneous estimation of both the reflectance and environmental light level. My concept is based on the creation of two different light conditions, capturing images of the same scene under the two conditions. To evaluate my proposed method, it was implemented with a 120-Hz frame rate projector, two cameras, and liquid-crystal shutter filters. The results of experiments confirmed that my system can robustly estimate when the brightness and color of the environmental light changes. I believe that the results of these experiments show that the system's resilience to brightness and color saturation are sufficient to allow its incorporation into indoor applications. The contributions of this study are 1) broadening the lighting conditions in which appearance control can be applied, 2) enabling the absolute presentation of colors, 3) allowing appearance control to be implemented without the need for calibration. I also identified some limitations in my system. In situations in which the reflectance is very low, the reflectance estimation become unstable. In addition, my system can weaken the effect of environmental light, while it is difficult to cancel the environmental light completely.

In my future work, I intend to apply the system to 3D objects. My system projects a gray code pattern onto a planar surface and makes a look-up table of each pixel for the cameras and projector to enable geometrical calibration. Therefore, it should be possible to apply this system to a 3D object, applying this calibration, by projecting a gray code pattern directly onto the 3D object. However, when the 3D object moves, even at the pixel level, the relationship between the pixels is lost, such that the currently implemented system will lose control as a result of the parallax effect between the cameras and projector. This problem can be overcome by creating a projector–camera system in which the optical axis of the projector and camera are the same [9]. With a coaxial projector–camera system, the camera can ignore any specular reflection except in the center area. The projector projects light radially, and the camera is at an optically identical position to that of the projector. Thus, even if a target object has specular reflection characteristics, the specular reflection component is not returned to the camera, except for that surface normal toward to projection center. This means that proposed method can be partially applied to a non-Lambertian surface with a coaxial projector–camera system. By this solution, proposed method can control appearance of a planar non-Lambertian surface. However, it depends on the shape of the target object. When the target object is three dimensional object such as a concave surface, specular reflection component returns to the camera even when a coaxial projector–camera system is used. I expect that my system with coaxial implementation provides much wider range of applications.

4. Perceptual Appearance Control by Projection-Induced Illusion

4.1 Introduction

Object properties such as reflectance, texture, and material significantly affect an object's appearance. Projection mapping is a technology that controls reflected light from the object to visually modify these properties. Projectors control appearance of real-world objects by adding illumination onto them, and they have upper limit in brightness. Because of these feature and spectral reflectance of the projected object, only limited colors can be presented by projectors. Projectors project light to a surface, and mixed light of both projected light and environmental light reflects on the surface. Environmental light become an offset of projection, and it decease contrast of projection. Thus, presentable color range depends on reflectance of a projected surface and environmental light. Figure 21 shows how presentable color range becomes narrower by reflectance and environmental light. In Fig. 21-(a), ideal environment for projectors is shown. When there is no environmental light and the surface color is white, projected light completely reflects on the surface. When the projector projects blue, reflected light will be same blue color. In this situation, the performance of projectors is fully drawn out. By contrast, when the surface is not white (Fig. 21-(b)), the surface has prejudiced spectral reflectance. Depending on the spectral reflectance, light which has specified wavelength hardly reflect. In addition, when there is environmental light (Fig. 21-(c)), environmental light become offset and the contrast of the projection decreases. In these situation, the performance of projectors cannot be fully drawn out and presentable color range becomes narrower. When the surface is red, the surface has spectral reflectance which reflects only red light strongly. Thus, even when the projector projects strong blue light, bright blue color cannot be presented unless the projector is much brighter than environmental light. In addition, when there is white environmental light in that environment, reflected light will be a mixture of white environmental light and blue projected light. Thus, only a pale color can be presented. In practical situations, there is almost no completely dark environments anywhere. Additionally, a projected surface often has chromatic color in projection-based application. Therefore, presentable color range of projectors almost always gets narrower because of these factors.

Although presentable colors of projectors are limited, these colors are physical quantity and they are not always the same with human perceived color. Human perceives color as a relative value which is affected by surrounding elements. For example, in Fig. 22, human perceives the colors of A to D as relatively constant colors no matter whether environmental light is orange or cyan. However, actual colors alter by the environmental light, and there are large differences between actual colors and human perceived colors. For example, the color of A on the left image and B on the right image look similar to the colors of the squares under the each image, respectively. Although these two colors look different perceptually, they are completely same color physically. This is an effect of color constancy, one of the visual illusions. Main purpose of a lot of projection based research is showing projection images to humans. In other words, even if presented colors are physically not correct, there is no problem if the colors are perceptually correct. My idea is creating differences between physical and perceptual colors intentionally by inducing color constancy in order to broaden the presentable color range of projectors perceptually.

In this chapter, I explained an algorithm which I proposed to determine projection color for perceptually presenting desirable color which cannot be presented by naïve light projection. For inducing color constancy, I require to change colors of both target area and surrounding area. my algorithm calculates suitable projection colors to both areas to present a desirable color. In addition, I conducted a user study to confirm my algorithm can 1) induce color constancy, 2) broaden presentable color range of projectors, 3) shift perceptual color to desirable directions.

4.2 Related work

proposed method controls colors of real-world objects with light projection. This technique can be categorized as spatial augmented reality (SAR). SAR is one of the augmented reality technique which visualizes virtual information in the real world, and viewers can observe the information without any tablet PC or head-mounted display [28]. Rasker et al. [87] proposed "Shader Lamps" which

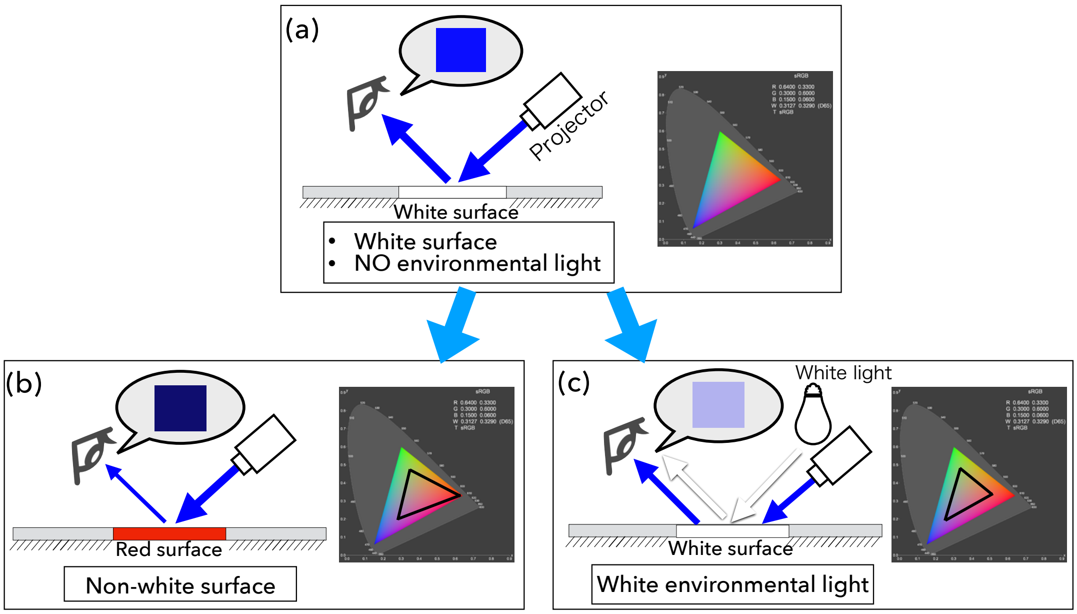


Figure 21. Presentable color ranges of projectors which depend on a surface color and environmental light.

can change appearance of objects of complex geometry by projecting images with keeping them geometrically undistorted. After this research, many research has been done for solving geometrical problem for doing projection mapping onto various objects, such as moving rigid objects [89][52], deformable objects [40][76], faces [23].

A lot of research is also focusing on reproducing desirable color appearance, which is also aim of this study. Nayer et al. [78] proposed radiometric compensation technique using a color-mixing matrix between a camera and a projector. Grossberg et al. [43] proposed an off-line calibration method for on-line compensation. Brown et al. [29] proposed a model-based method for controlling the brightness of a display produced by a multi-projector system. Although these works only can be applied for static situations, methods which can be applied for dynamic situation appear afterward. The method of Fujii et al. [40] can compensate projected appearance in dynamic environments with feedback algorithm. Amano et al. [11][15] proposed an algorithm which estimates reflectance of a real object and controls appearance of the object in real time by creating a feed-

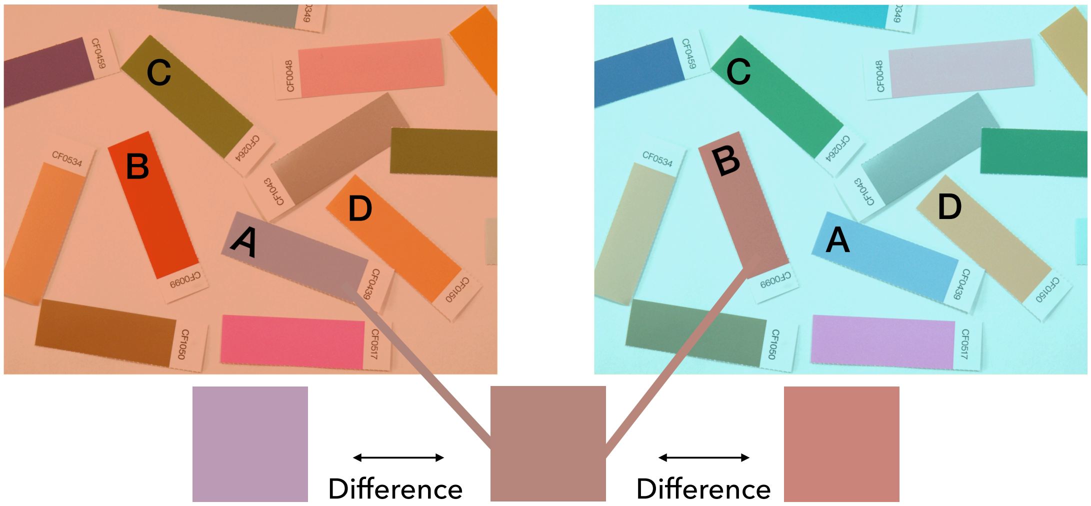


Figure 22. Examples of color constancy

back structure. These studies are physically-based, and perceived appearance by human is not considered.

My study reproduces colors based on human perceived colors. In the SAR field, color perception is considered in several color compensation techniques. Grundhofer et al. [45] established a method to reproduce perceptually high-contrast images in a projected display. Ashdown et al. [19] proposed a method that produces a perceptually wider dynamic range for photometric compensation. Madi et al. [66] created a model of color constancy for reproducing appearance of an object under different lighting conditions. Pjanic et al. [84] proposed a perception-based compensation technique for implementing a seamless multi-projection system by employing RLab, one of color perception models. All of previous technique here take human perceived colors into consideration. However, most of studies are focusing on reproducing perceptually correct colors. It is different from my main goal, broadening presentable color range of projectors. Some research is especially focusing on inducing visual illusion. Kawabe et al. proposed a method to give dynamic expression to static objects by projecting dynamic grayscaled images [55], and Fukiage et al. [42] created a perceptual model in order to figure out suitable motion size which humans perceive as natural motion. Kawabe et al. also proposed a method to give perceptual depth or transparency to letters or drawings on papers by visualizing virtual shadow [54]. The research described herein uses visual illusions that artificially create an expression that is difficult to create physically.

In this study, I induce a visual illusion of color by light projection to broaden presentable color range of projectors. Some research above take color perception into consideration, and some induce visual illusion. Unlike these research, I induce visual illusion of color for controlling object colors perceptually. My preliminary trials suggest that my idea has potential to extending presentable color range of projectors [5][6]. In this chapter, I explain a novel algorithm for calculating suitable projection colors to present desirable colors perceptually with inducing a visual illusion.

Many physical limitations of projectors cannot be overcome physically by algorithms alone. Modications and research on the hardware side exist for overcoming them. Conventional projection devices and their optical system are generally designed to maximize the projected image quality for a flat, non-textured, and perfectly Lambertian surface. The software based solutions described in Section 2.1 and 2.2 have been proposed to improve the visual quality when projecting onto imperfect surfaces, but algorithmically this is only possible up to a limited extent. Current three color channel, i.e., RGB, projectors can only reproduce limited color spaces. Improving the color gamut has been an active research topic in projection display design over decades. Pioneering multi-primary designs increase the number of color primaries either using grating (7 primaries) [3] or color lters [4] (6 primaries) for a larger color gamut. Recently, Various adaptive color primaries have been investigated such as LEDs [53], a pair of prism and DMD [90], a pair of diffraction grating and attenuating mask [75], and a programmable spectral light source [48]. In contrast to approach from hardware side, there are several studies to handling colors which cannot be presented physically. When projecting onto dark or strongly saturated surface pigments, it is desirable to avoid visually disturbing compensation errors resulting from the limited color gamut of the projector. Several methods automatically adjust the target colors which are outside of the presentable range to avoid artifacts [68, 62]. There is an approach based on spectral measurements in combination with HDR imaging to generate more accurate projection based augmentations [69], and it is extended

Table 2. Position of my perceptual appearance control study

	Purpose	Approach	Method
Ajito et al. [3, 4]	Expand gamut	Hardware	Physically
Kauver et al. [53]	Expand gamut	Hardware	Physically
Rice et al [90]	Expand gamut	Hardware	Physically
Mohan et al. [75]	Expand gamut	Hardware	Physically
Menk et al. [68]	Avoid artifacts	Software	Physically
Law et al. [62]	Avoid artifacts	Software	Perceptually
Menk et al. [71][67]	HDR reproduction	Software	Physically
Ours	Expand gamut	Software	Perceptually

by applying 3D look-up table (LUT) [67].

4.3 Projection Technique for Controlling Object Colors Perceptually

In this section, I explain how to control colors of objects perceptually by inducing color constancy. This section consists of two parts, 1) the method for inducing color constancy, 2) the method for calculating suitable projection color. In this paper, I call proposed method as Projection-Induced Illusion (PII).

4.3.1 Model for Inducing Color Constancy

Perceived colors of objects remains relatively constant under varying uniformed illumination conditions due to effects of color constancy [59]. Human vision system estimates colors of illumination and negates the effect of the colored illumination to perceive original color of objects. In other words, if I can create a misunderstanding about illumination color to observers, I can induce color constancy and control perceived color of objects. I explain how to create this misunderstanding of illumination color for controlling object color with using a projector here.

Figure 23 shows the concept of my technique. I illustrate the case of changing object color from red to skyblue by light projection. I regard the object's surface is Lambertian surface, and I only focus on diffuse reflection. I classify the object

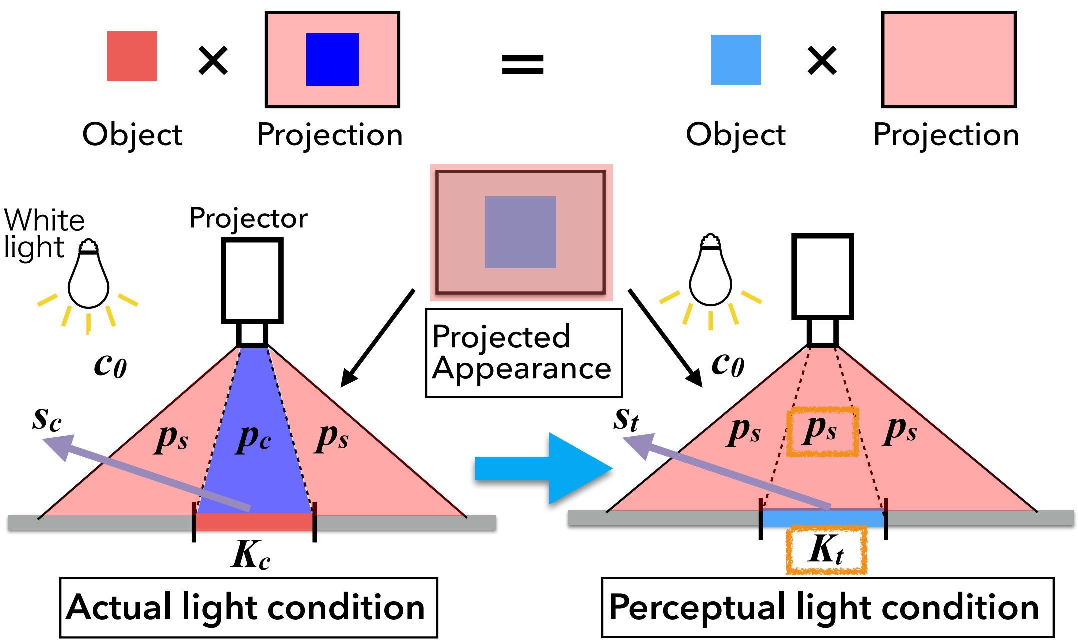


Figure 23. Idea for inducing color constancy.

into two areas, central area and surrounding area. The central area is red region and the surrounding area is gray area in the left figure in Fig. 23. The central area has reflectance $\mathbf{K_c} = \mathrm{diag}(k_{c,r}, k_{c,g}, k_{c,b})$, and environmental light $\boldsymbol{c_0} = (l_r, l_g, l_b)^{\mathrm{T}}$ and projection to central area $\boldsymbol{p_c} = (p_{c,r}, p_{c,g}, p_{c,b})^{\mathrm{T}}$ are reflected on the surface. Reflected light from the central area $\boldsymbol{s_c}$ is expressed by the equation below.

$$\boldsymbol{s_c} = \mathbf{K_c}(\boldsymbol{p_c} + \boldsymbol{c_0}) \tag{28}$$

Our eyes capture this reflected light to sense color of the central area. I call the physical color that is determined by wavelength of light as actual color. I regard a physically controllable range of projection $\boldsymbol{p_c}$ in each RGB channel is 0 to p_{max}. A physically controllable range of the reflected light $\boldsymbol{s_c}$ is determined by this range of $\boldsymbol{p_c}$. When the target color is inside this range, the projector can present the target color by $\boldsymbol{s_c}$ physically as an actual color. When the target is outside of the range, it is impossible to present it physically in the condition. In this case, I try to shift from the actual color to the target color perceptually by projection $\boldsymbol{p_s}$ to the surrounding area for inducing color constancy. Iintroduce the target color that has reflectance $\mathbf{K_t} = \mathrm{diag}(k_{t,r}, k_{t,g}, k_{t,b})$. In Fig. 23, this target color is skyblue. When this skyblue object is under uniformed colored illumination, like right figure in Fig. 23, I perceive the object color as skyblue relatively because of the color constancy effect. When the projection $\boldsymbol{p_s}$ and the environmental $\boldsymbol{c_0}$ are projected to the area that has reflectance $\mathbf{K_t}$, the reflected light $\boldsymbol{s_t}$ can be obtained by an equation below.

$$\boldsymbol{s_t} = \mathbf{K_t}(\boldsymbol{p_s} + \boldsymbol{c_0}) \tag{29}$$

When these reflected light $\boldsymbol{s_c}$ and $\boldsymbol{s_t}$ are completely same, I can reproduce light condition on the right of Fig. 23 by projecting $\boldsymbol{p_c}$ and $\boldsymbol{p_s}$ like the figure on the left of Fig. 23. By reproducing this perceptual light condition, observers perceive that the object with the target color $\mathbf{K_t}$ is under uniformed colored light $\boldsymbol{p_s}$. To obtain the projection $\boldsymbol{p_c}$ and $\boldsymbol{p_s}$ which can present target color, I need to solve cost function below.

$$\boldsymbol{p_c}, \boldsymbol{p_s} = \underset{\boldsymbol{p_c}, \boldsymbol{p_s}}{\arg\min} |\mathbf{K_c}(\boldsymbol{p_c} + \boldsymbol{l}) - \mathbf{K_t}(\boldsymbol{p_s} + \boldsymbol{l})| \tag{30}$$

When the result of eq. (30) is zero, humans understand that single colored uniformed illumination $\boldsymbol{p_s}$ is projected, and original color of the object is $\mathbf{K_t}$. However, with only this cost function, I cannot obtain suitable projection colors $\boldsymbol{p_c}$ and $\boldsymbol{p_s}$. I explain how to determine suitable projection colors in next section.

4.3.2 Calculating Suitable Projection Color

With proposed method, I require to project colored illumination to surrounding areas even when I do not want to change the colors of the areas. Thus, I define a suitable projection color of $\boldsymbol{p_s}$ as a color which is the closest to achromatic.

In this algorithm, I focus on reproducing target reflectance. In other words, I do not care about brightness of the target color, and I focus on hue and color saturation in HSV color space. When projectors can physically present the target color without proposed method, there is $\boldsymbol{p_c}$ which satisfy following eq. (31).

$$\mathbf{K_c}(\boldsymbol{p_c} + \boldsymbol{c_0}) = \operatorname{diag} \mathbf{K_t} \tag{31}$$

The left-hand side of eq. (31) is RGB values of reflected light from a projected surface, and the right-hand side is diagonal elements of the target reflectance.

When the target reflectance $\mathbf{K_t}$ cannot be presented by naïve projection,

$$\frac{k_{c,r}}{k_{t,r}}(p_{c,r}+l_r)=\frac{k_{c,g}}{k_{t,g}}(p_{c,g}+l_g)=\frac{k_{c,b}}{k_{t,b}}(p_{c,b}+l_b) \tag{32}$$

As a next step, I substitute maximum power projection value p_{max} for $p_{c,r}, p_{c,g}$ or $p_{c,b}$ which have the minimum value in $\frac{k_{c,r}}{k_{t,r}}$, $\frac{k_{c,g}}{k_{t,g}}$, and $\frac{k_{c,b}}{k_{t,b}}$. By doing this step, I can set one out of three values, $p_{c,r}, p_{c,g}, p_{c,b}$. With determined values, the system can calculate the other two values with eq. (32). When all the values are inside of a projector's presentable range $0 \leq p_{c,i} \leq p_{max}$ $(i \in \{r, g, b\})$, the target color can be presented physically by projecting obtained projection color $\boldsymbol{p_c}$. However, sometimes these values have negative, which is impossible to project by a projector. In these cases, I calculate projection color for surrounding area $\boldsymbol{p_s}$ for presenting the target color perceptually.

As I explained before, when residual of the cost function eq. (30) is zero, color constancy will be induced. I will calculate $\boldsymbol{p_s}$ which make the residual zero based on calculated $\boldsymbol{p_c}$ here. First, I substitute zero for $p_{c,r}, p_{c,g}, p_{c,b}$ which have a negative value. With this process, I can obtain all the values of $\boldsymbol{p_c}$. By substituting zero, there are physical difference between target color and reflected light. However, they will be compensated perceptually by projection color to the surrounding areas $\boldsymbol{p_s}$. $\boldsymbol{p_s}$ can be calculated by following equation.

$$\boldsymbol{p_s}=\frac{\mathbf{K_c}}{\mathbf{K_t}}(\boldsymbol{p_c}+\boldsymbol{c_0})-\boldsymbol{c_0} \tag{33}$$

Calculated $\boldsymbol{p_s}$ by eq. (33) and $\boldsymbol{p_c}$ make the residual of the cost function eq. (23) zero. Thus, I can induce color constancy and present the target color by projecting p_c to the center area and p_s to the surrounding area. When all the values of p_c are positive, calculated values become $p_{s,r}=p_{s,g}=p_{s,b}$, which means $\boldsymbol{p_s}$ is achromatic color. In addition, when original color and target color is too far, sometimes $\boldsymbol{p_s}$ have negative values. It means that the target color cannot be presented even perceptually with that set-up.

4.4 Experiment

I conducted a user study for confirming following three hypothesises, proposed method can 1) induce color constancy, 2) broaden a presentable color range of

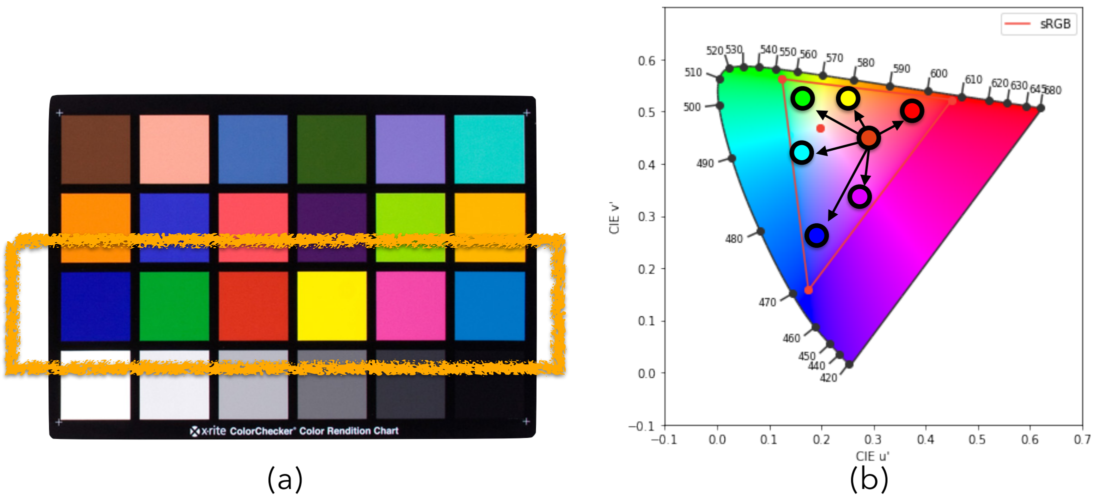


Figure 24. (a) Six colors with orange frame are used as projection target in the user study. (b) Examples of six directions when I control color from red at the user study.

a projector, 3) shift perceptual colors to desirable directions. In this section, I explain the detail of the user study and show results of it.

4.4.1 Procedure

The six colors in the third row of X-rite Color Checker was used as projection targets, which are shown in Fig. 24 (a). I controlled reflected light from the color checker by projection and compared perceived colors by two methods: proposed method and naïve overlaying projection. Naïve overlaying projection keeps projection $\boldsymbol{p_s}$ to the surrounding area as constant achromatic color in order not to induce the illusion. I changed from the six original colors to the other six colors which are the farthest directions, red, green, blue, yellow, magenta, and cyan, individually. For example, when I change from the red, I change it to red, green, blue, yellow, magenta, and cyan as much as possible. The six directions of this situation is shown in Fig. 24 (b). proposed method presents the perceptually farthest colors with illusion and naïve overlaying projection present the physically farthest colors without illusion. There were 6 original colors x 6 directions x 2 methods = 72 conditions. I used EPSON EH-TW5650 projector for controlling colors and XIMEA MQ013CG-E2 camera for monitoring controlled colors. In addition, I control and keep the environmental light of the experiment space about 1000 lx, which is enough illuminance for daily life.

The participants performed a matching task. I controlled one color to another color by projection, and the participants see it and find out the closest color from a color sample (PANTONE FORMULA GUIDE Solid Uncoated). The projection target is placed in front of a participant, and the distance between each participant and the projection target was about 1 meter. The color sample was placed nearby a participant, and a participant takes and sees it freely. Ten naïve participants took part in the experiment. All had normal or corrected-to-normal visual acuity and normal color vision. Each participant completed the matching task for all 72 conditions in a randomized order.

The overview of experimental set-up is shown in Fig. 25, and the configuration of the equipment is shown in Fig. 26. A participant sit near the camera in order to make sure that reflected light to the camera and a participant's eyes are almost same. Color sensitivity of the camera and human eyes are not same, so captured colors by the camera and perceived colors may different. However, I set gamma of the camera as 1 to use the camera as measuring equipment of intensity of reflected light in each pixel. Thus, I do not assume captured images and perceived appearance are same. Additionally, I set the distance between the color checker and a participant for about 1.5m and the luminance of the environment for about 1,000 lx.

4.4.2 Results

I examined following two points from the data: 1. presentable color range can be broadened by PII, 2. perceptual color can be shifted to desirable directions by PII. First, I computed the average values of each condition from results of all the participants in order to examine the first one. I plotted these average values and filled the surrounded regions on u'v' color chromaticity diagram, which attempts perceptually uniformity. The surrounded regions are colorized by blue and red for with and without proposed method, PII, respectively. The results are shown in Fig. 27. In all conditions, blue colored regions are larger than red colored regions. I also calculated amplification ratio between regions of naïve projection

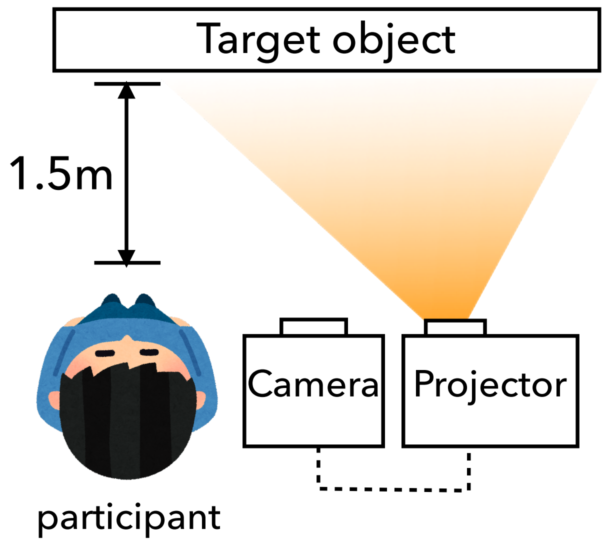


Figure 25. Overview of the experimental set-up.

and proposed method. I compared the size of the each area in u'v' chromaticity diagram. These values are shown in Fig 27 as well. The presentable color range in the u'v' diagrams become at least 1.3 times larger and 6 times larger in the largest case.

Secondly, I examined that proposed method can shift perceptual color to desirable directions or not. I computed pairs of vectors: 1. vectors from the original colors to the result colors by naive projection, 2. vectors from the original colors to the result colors by proposed method. I calculated the angles of each pair. If calculated angles are near 0, it means that proposed method can control perceptual colors to desirable colors, which is same to the direction of naïve projection. The box plots are shown in Fig. 28. The red lines on Fig. 28 are the lines of 30 degree. I set 6 target colors. Thus, I examined the directions by checking the angles are less than 30 degree (=360 degree /6 colors) or not. With my current technology, it is difficult to present perceptual colors precisely, and there are individual differences of color perception. Thus, I examine directions roughly by this method. As a result, when target colors and original colors are same or similar, the angles become bigger. By contrast, when the target colors and the original colors are far, the angles become smaller. This tendency can be found from the results of the length shown in Fig. 29 as well.

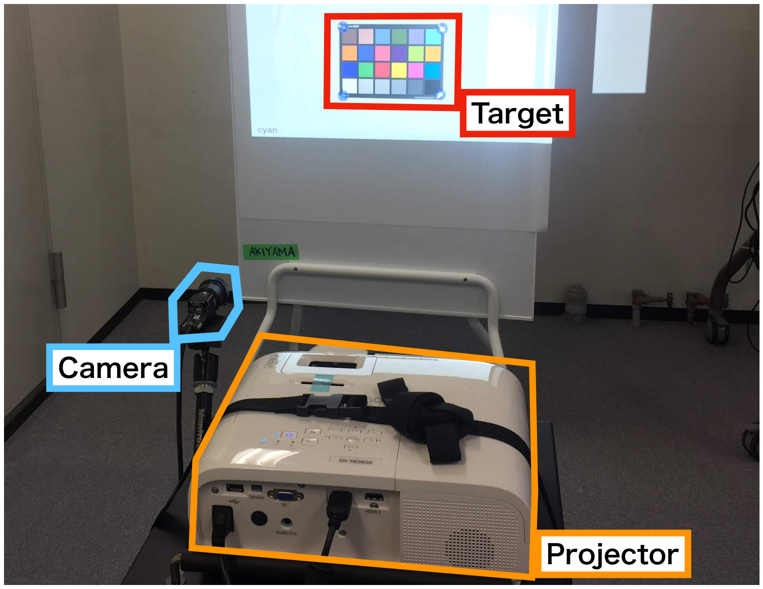


Figure 26. Set-up for user study.

I compared the length of the same pairs of vectors by one-sided T-test in order to figure out that proposed method can present further colors compared to naïve projection. The results are shown in Fig. 29. I found that there are significant differences between two when the original color and the target color are completely or nearly complementary color relationship. For example, when the original color is blue, there are significant differences in the case of red, green, or yellow. Red, green, and yellow are all far from blue. In contrast, the other colors, blue, magenta, and cyan, mainly contains blue element and near to blue. From these results, I can say proposed method can broaden the presentable color range of projectors to the complementary directions. Judging from all the results here, the PII method can broaden presentable color range of projectors to complementary color direction from objects ' original color and control perceptual color accurately. In contrast, the PII method is not so effective when chromaticity of an original color and a target color are similar.

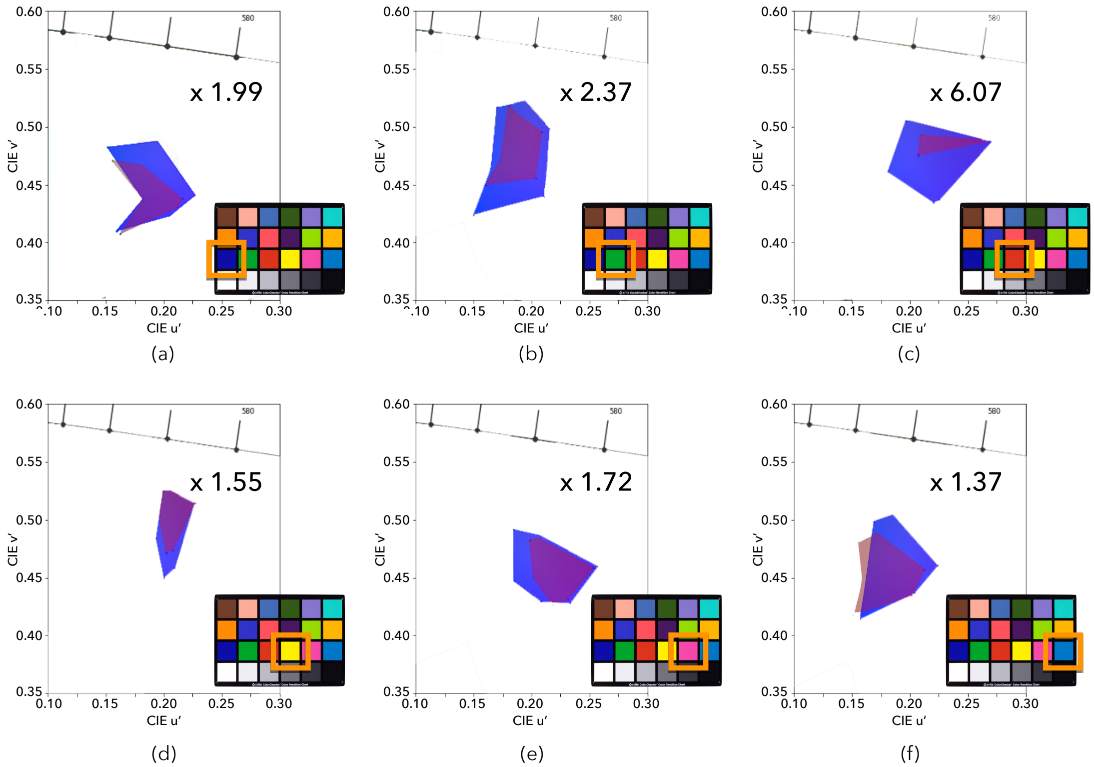


Figure 27. The presentable color ranges of each original color by naïve projection and PII method. The results of naïve projection are shown in red and that of PII method are shown in blue. The numbers shown in up-right of each figure are ratio of each pair of regions.

4.5 Discussion

From the user study, I found proposed method is effective when an original color of objects and a target color are nearly complementary color relationships. I think there are mainly two reasons caused by characteristics of color constancy.

First, human vision system estimates a color of illumination and weakens the color from sensed colors by eyes in order to perceive relatively original colors of real objects [59]. In my case, I create an illusion of uniformed illumination by non-uniformed projection. Observers misunderstand surrounding colored illumination as uniformed illumination, and they perceive a color of objects whose element of the surrounding illumination color is weakened. However, when the result colors

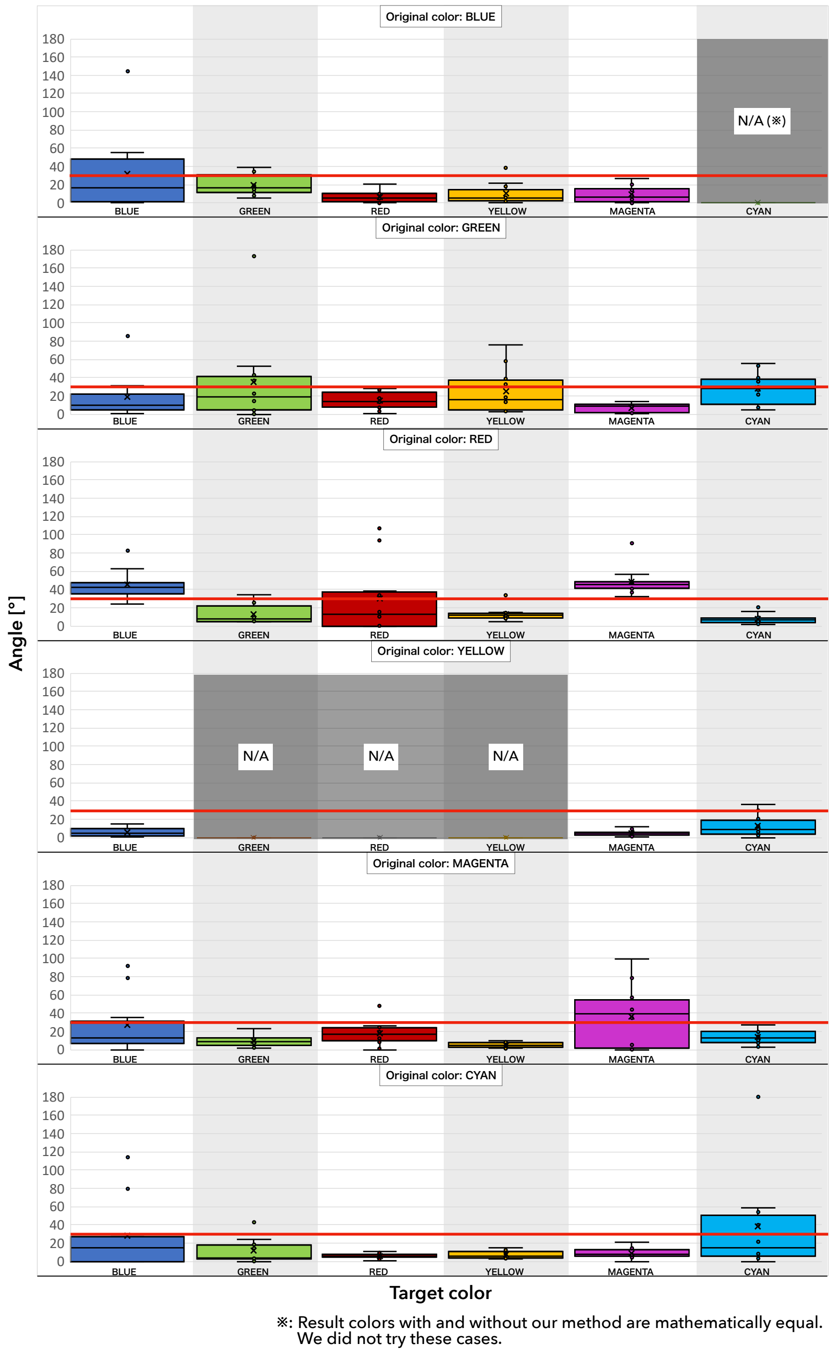


Figure 28. The results of angles between pairs of vectors: 1. from original colors to results colors by naïve projection, 2. from original colors to result colors by PII method.

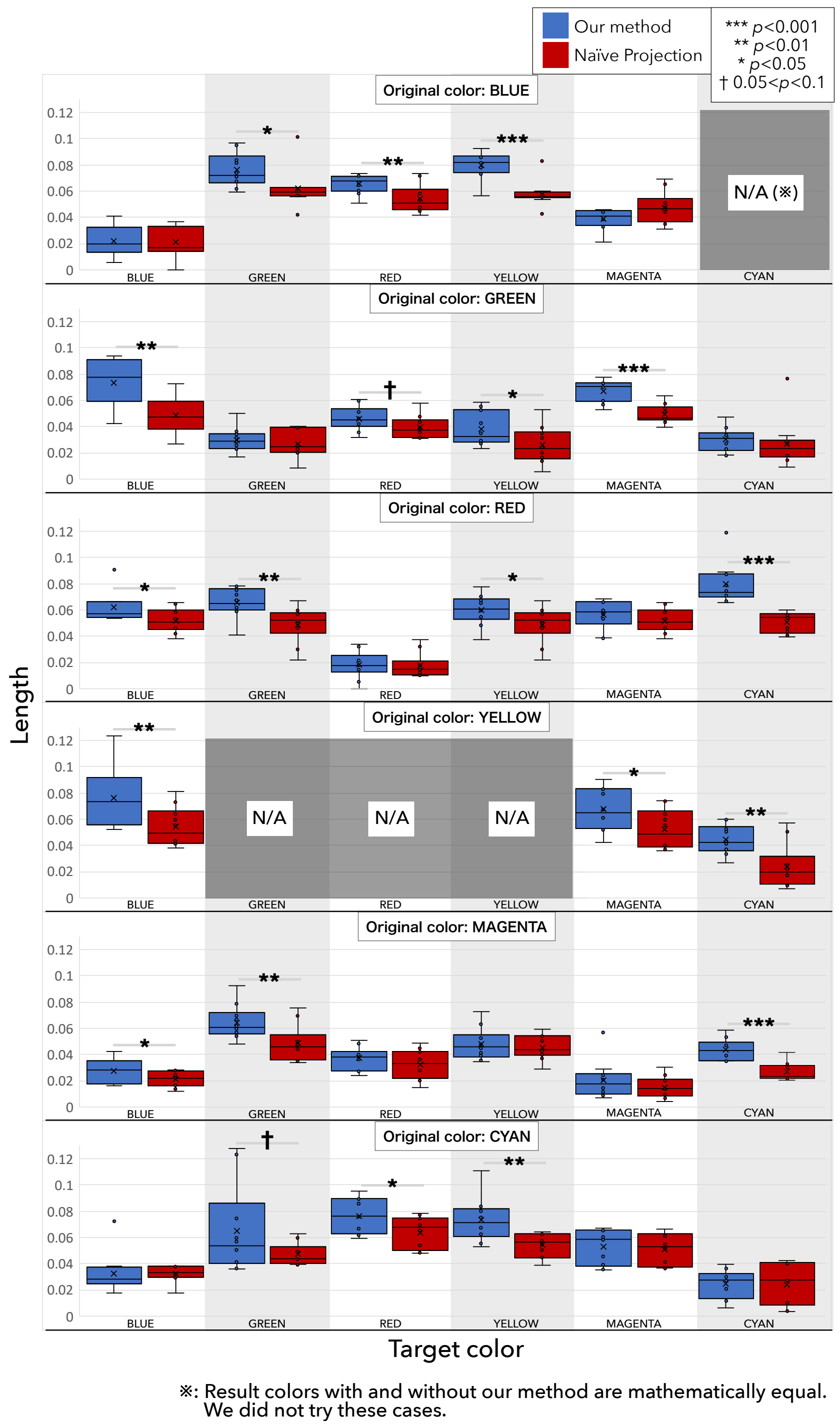


Figure 29. The results of comparing length of pairs of vectors: 1. from original colors to results colors by naïve projection, 2. from original colors to result colors by PII method.

are already almost pure color, it is difficult to weaken any elements to make the color purer or thicker. I think I can explain results of the user study with this characteristic. In Fig. 28 and Fig. 29, when original colors and target colors are similar, the angles become bigger and no significant difference in length. I think these are because result colors by naïve projection are thick enough, and color constancy effect become weak. In addition, when target colors mainly contain elements of original color, the results are similar. For example, in Fig. 28, when original color is green, the results of green, yellow, and cyan are bigger than 30 degree. In this case, yellow mainly contains green and red, and cyan contains green and blue. Thus, color constancy effect is also not so big in these cases, and errors become larger, I think.

Secondly, color constancy effect is powerful when actual colors are near non-color [88]. Human vision system easily distinguishes gray color and non-gray color. However, it is not so easy to distinguish two near non-gray colors when they are thick even if difference of the two colors are the same with the gray and non-gray case [65]. When changing to complementary colors, actual result colors become near gray color, and perceptual colors shift from that color by PII method. In this case, perceptual colors can be shifted dynamically. In addition, simply speaking, color constancy subtract illumination color from the color which is reflected from the object in order to estimate original color of the objects. If our vision detects that uniformed in not illuminated, color constancy does not happen. For example, when I would like to change red color object to more vivid red color with projection, the projector will project red light onto the object. The result color is very thick, and green and blue elements are very little. In that situation, even if I project green or blue illumination to surroundings of the red object, color constancy never happen, because the reflected light from the red object hardly contain green and blue elements. This is also the reason proposed method is not effective when hue of original color and target color are similar.

The case of "original color: red and target color: blue" in Fig. 28 cannot be explained with color constancy effects explained above. This is because red and blue are far colors, however the result angle is over 30 degree. I think this is because brightness of surface. People perceive blue darker than green even if intensity of the two colors are completely the same [105]. In addition, people perceive blue darker in well-lit environments compared to dark environments by Purkinje effect [39]. Because of these reasons, the result colors were perceived as dark colors, and answers from participants are not stable.

In proposed model, original surrounding colors of objects are not included, nevertheless there may be effects by simultaneous color contrast. Simultaneous color contrast is one of the visual illusions that is affected by neighbor colors [2]. In this study, I focused on controlling colors relatively. Even if there is simultaneous color contrast effects in the scene, it still exist after projection. Thus, it does not affect the amount of change. However, considering simultaneous color contrast is required for absolute color reproduction. To improve the model to present perceptual color absolutely, I require to include simultaneous color contrast effect, and I also require to employ color appearance model which can simulate perceive color with color constancy effect more precisely.

4.6 Limitations and Future Work

There are several remaining issues to be addressed. First, proposed method does not take necessary size of projection to surrounding areas. Currently, when my system induces color constancy, the system projects surrounding projection as broad as possible. I do not require that much broad chromatic colored projection for inducing color constancy. However, there is no research about necessary area for inducing color constancy. For inducing color constancy, observers require to misunderstand that the projection to the surrounding areas are uniformed illumination to all areas. Thus, if the projection to the surrounding areas is too narrow, like projecting to only edges of a target area, color constancy is not induced. As future work, I would like to know minimum area of projection to the surrounding area for inducing color constancy by holding user study in order to minimize discomfort occurred by colored illumination to surrounding areas. When I cannot project colored illumination to surrounding areas, it is difficult to induce color constancy. In this situation, it may be possible to employ other illusions such as watercolor illusion [82]. The illusion is induced by colors of edges, and perceived colors shift perceptually [16, 82].

Secondly, I regard humans have perfect color constancy in their vision system. This means that humans can perfectly eliminate effects by colored illumination and perceive original colors of real objects completely. However, humans do not have such a perfect color constancy. When a color of illumination is thick, perceived color is shifted [59]. For example, when humans see blue objects under red illumination, he/she can perceive the object color as reddish-blue color, not true blue color. Because of this reason, my system cannot estimate accurate perceived colors. For accurate perceptual color reproduction, I require to employ a color appearance model which is modeling humans' imperfect color constancy. RLAB which is proposed by Fairchild[37] or a color appearance model which is proposed by Kuriki[58] take appearance under colored illumination into consideration. By employing these color appearance models, proposed method may present perceptual colors more accurately.

Thirdly, my algorithm does not include conditions of inducing color constancy. Generally, color constancy happens when uniformed colored illumination is lighted to a scene. My algorithm reproduces reflected light of uniformed colored light by projection. However, I do not know how humans determine that illumination is uniformed or not. Additionally, I also do not know other conditions such as luminance, color, necessary area and so on. Moreover, the effect of color constancy is different depending on colors of objects or scenes. For example, when a projected color and a color of an object are similar, it may be difficult for humans to distinguish the color of the light and the color of the object. The conditions are one of the reason why some observers are induced and some are not induced with my system. Psychological researchers are still trying to discover the conditions. Thus, I do not have knowledge or theory to insert to my algorithm. It is too difficult to discover the general conditions for inducing color constancy. However, it may be possible to discover the conditions which are specified to the projection system. Thus, I would like to explore them by user study as future study.

Current algorithm focuses on change a color to another color. In other words, my system currently cannot change multiple colors. There are two solutions to apply multiple colors. One solution is simply creating a large perceptually uniformed colored illuminated area which include multiple target areas inside. However, this solution can be used when all directions from each original color to each target color are similar. For example, changing both red and green regions to blue direction is possible. In contrast, when I would like to change red region to green and green region to blue, it is not possible to present both colors by using one uniformed illumination. In that case, when multiple regions are geometrically separated, I can create multiple perceptually uniformed colored illuminated areas. However, it means that several separated areas which are illuminated with different illumination exist in one scene. It is unusual situation, and it also may occur discomfort.

4.7 Application

Based on proposed method, I developed an application which can automatically control perceptual colors by inducing color constancy. The system consists of a projector, a camera, and a computer. Currently, I am focusing on changing one color to another color. I need to select one color from a captured image as an original color and select one color as a desirable color. After selecting, the system automatically creates a projection image in order to present the desirable color. If the desirable color can be presented without proposed method, a projection color to surrounding areas will be achromatic color. In contrast, if the desirable color cannot be presented by naïve projection, a projection color to surrounding areas will be achromatic color for inducing color constancy. The three projected results are shown in Fig. 30. In the third row, the result images by proposed method and naïve projection are shown. Although physical colors of each pairs are completely the same, perceptual colors are different.

As applications of this study, I think my technique can be used for advertisement use. By changing colors of printed posters or real objects dynamically, they can catch the eyes. In actual scene, environments are too bright for using projectors. However, presentable color range of projectors can be broadened by proposed method. Thus, with proposed method, colors of static objects can be controlled dramatically. In addition, I think projection mapping events can be held in well-lit environments with proposed method. Most of projection mapping events held outside at night or in dark rooms in order to get enough presentable color range of projectors. With proposed method, the presentable color range can be broadened, and I may obtain enough color range for the projection mapping. In addition, I think my system has possibility to support vision of color-deficiency people. Color-deficiency people are not good at or cannot perceive specified color because of anomaly or lack of cones. In other words, their brains are the same with normal vision people, and they also have color constancy system. my system can shift perceptual colors without changing actual colors. Thus, even if color-deficiency people cannot perceive specified thick color, my system may show thicker colors which they normally cannot see. There are research which support color-deficiency people with devices such as mobile phones[92], OST-HMDs[60], or projectors[15]. Additionally, there are lenses which block confusing wavelength of light for glasses [36] or for contact lenses [21]. While these works above help people distinguish confusing colors for them, it is difficult to show true colors. I think proposed method has potential to show true colors for color-deficiency people, and it would be a powerful application of this work.

In combination with the first study which I explain in Chapter 3, more applications become possible. The system in Chapter 3 provides estimated reflectance and environmental light. With these data, suitable projection that depends on the environments can be calculated. For example, when environmental light already have color, color constancy is already induced. In that situation, actual color and perceived color are already different. By representing colors considering existing colored environmental light, projectors may not need to project illumination to surrounding areas. In addition, we rarely feel discomfort when whole environmental light have color. Thus, this may be one solution for avoiding discomfort. Moreover, if the light equipment can control color of illumination partially, the color range of projectors become more broader. When I change color of whole environmental light, the light is also lighted to the target area, and the light to that area may be needless for presenting another color. Thus, if the light equipment can light except the target area, the perceptual presentable color range of projectors become broader compared to the range with environmental light to the whole areas.

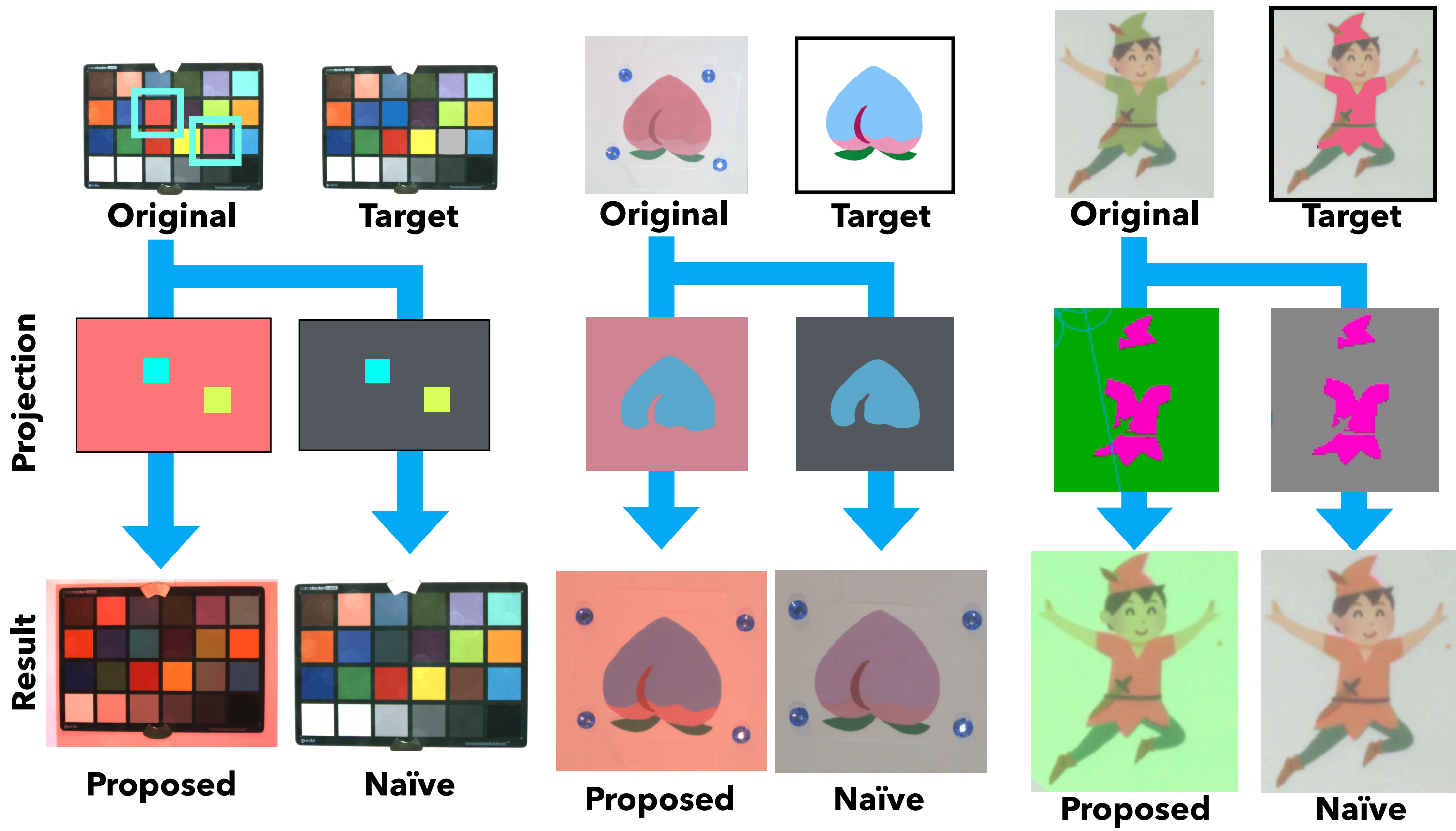


Figure 30. Projection results. This figure shows the controlled appearance by proposed method and naïve projection.

4.8 Conclusion

I proposed the projection technique which can broaden presentable color range of projectors perceptually by inducing color constancy. Through my user study, I confirm that proposed method is effective for broadening presentable color range of projectors, and I can shift perceptual colors to desirable directions when target colors are far from original colors.

In research field of augmented reality, perceptually-based approaches are proposed recently [12][107][42]. These approaches employ effects of human vision system in order to archive research goals that are physically difficult or impossible. I believe I need to take perception into consideration to augmented reality. I think my study shows effectiveness of perceptually-based approach, which may become mainstream of augmented reality research.

5. Conclusion

This concluding chapter summarizes research problems that must be addressed and discuss my approaches and contributions. In addition, some remaining issues to be addressed are shown as Future Research.

5.1 Contribution and Summary

This study investigated the problems in practical uses of projection-based appearance cnotrol. I considered them to increase controllablity from two aspects. First one is reflectance estimation method robustly against dynamic environmental light, and second one is controlling perceptual colors by inducing color constancy. Summarized details of the studies are provided as follow.

5.1.1 Robust Reflectance Estimation for Appearance Control with a Projector-Camera System in a Dynamic Light Environment (Chapter 3)

I proposed a method for robustly estimating an object's reflectance despite dynamic changes in the environmental light as a basic technology for appearance control with a projector–camera system. The concept is based on the creation of two different light conditions, capturing images of the same scene under the two conditions. Through several experiments, I verified that proposed method can estimate reflectance of a target object robustly against dynamic environmental light. The contributions of this study are shown as follows.

- The appearance control system can be applied even when both the reflectance and environmental light are dynamically changing.
- Colors can be presented exactly as desired when the color is inside of the presentable range of a projector. The conventional methods could only present relative colors.
- The system can continue to operate as expected without additional calibration, even when the lighting conditions change.

Conventional projection-based appearance control system only can apply to the environments whose light condisions are constant. my robust reflectance estimation method enables the appearance control system to apply dynamic light environments. In addition, by obtaining the information of both reflectance and enviornmental light, the appearance control system can present absolute colors. Conventional methods capture environmental light in advance and present relative colors from original colors of the target objects. In contrast, proposed method estimates both information of reflectance and environmental light. With the information, the system can control reflected light from the objects absolutely, and it means that the system can present absolute colors. Finally, the system with conventional methods required re-calibration in every change of environmental light. It is because the system cannot distinguish changes of reflectance and environmental light. proposed method can estimate them separately, and it does not require re-calibration. Thus, proposed method make appearance control system calibration-less.

5.1.2 Perceptual Appearance Control by Projection-Induced Illusion (Chapter 4)

I proposed the projection technique which can broaden presentable color range of projectors perceptually by inducing color constancy. Through my user study, I confirm that proposed method can induce color contancy and shift perceptual colors to roughly desirable directions when the desiable colors are far from original colors of the objects. The contributions of this study are shown as follows.

- Presentable color range of projection-based appearance control become broader.
- Appearance simulation of the real objects with changing reflectance and a color of environmental light become possible.

Through my user study, I confirmed that presentable color range of projectors become broader perceptually compared to physical presentable color range. In practical situation, presentable color range of projectors is often not enough for presenting desirable appearance. With proposed method, the range become perceptually broader, and it connects to broaden application fields of projection-based appearance control. In addition, a projector–camera system with proposed method perceptually controls colors of the objects and environmental light separately. It means that proposed method can simulate appearance with various refectance under various environmental light. I think this simulation has possibility for various applications. For example, it can be used for supporting designing tasks. Users can check appearance with another colors under various colored illumination without printing or creating actual products by controlling appearance by light projection.

5.1.3 Overall summary

With the studies that I explained in Chapter 3 and 4, controllability of colors in projector-based appearance control increases. By summarizing the contributions in section 5.1.1 and 5.1.2, the application fields of projection-based appearance control become larger. In particular, proposed methods enable appearance control systems to be applied in dynamic well-lit environments. Many appearance control research which assume dark environments or static light conditions can be utilized in more practical situations, like office, school, or home. In addition, proposed methods indicate improvement of expressiveness of appearance control system by manipulating colors based on human perception. There are possibilities to control appearance based on implicit preference or for controlling human perception or affections. Summarizing the above, proposed methods increase controllability of colors in projection-based appearance control, and this is helpful to broaden applicable situations of all existing appearance control studies. Additionally, proposed methods includes human perception factors, and it indicates future perspective of projection research or AR / VR research to produce visual information based on not physical values but human perception.

5.2 Future Research

This section concludes with discussion about future directions for further research.

5.2.1 Robust Reflectance Estimation for Appearance Control with a Projector-Camera System in a Dynamic Light Environment

In proposed method for reflectance estimation, there are some limitations I found which I would like to solve in the future. Some issues required to be addressed in the future are shown as follows.

- Slight flickering perception may happen.
- The system cannot estimate illumination from light source which have temporal flickering.
- Current implementation basically focusing on only 2-dimensional objects.

proposed method switches projection on / off at high speed, and the switching projection often leads flickering perception to observers. I conjuncture there two reasons to induce this flickering perception in my set-up. The first reason is that the projection to the white surface switches to bright white and black, and the second one is that the framerate of the projector is not high enough. The white/black alternate projection happens because my algorithm does not track the objects. By tracking objects and reduce projection to the unnecessary areas, the first one can be solved. The second one can be simply solved by using a higher framerate projector–camera system. Secondly, my current estimation algorithm cannot apply to environmental light, which has temporal flickering. Depending on the frequency of light sources, a flickering of the light sources appears on captured images. In this case, the system cannot estimate reflectance robustly against the external light. One way to solve this problem is by implementing a system with higher framerate devices. By implementing high-speed devices, the cameras capture both bright and dark moments of environmental light. By the statistical process, the system can omit captured images without environmental light. Finally, my system is mainly focusing on only 2D objects. It is possible to control the appearance of 3D objects by doing geometrical calibration with the 3D object and obtaining pixel relationships of camera capture and projection on the surface of the 3D objects. However, in that case, I cannot move the 3D objects even in pixel level. This is because the relationships will be broken. In order to apply to 3D objects, one solution is using an optically-aligned projector–camera system. With the projector–camera system, the relationships of pixels between camera capture and projection are constant, and they do not depend on the objects. Thus, I can even implement a portable appearance control system with an optically-aligned projector–camera system. The applications of appearance control with my estimation method will become broader with the optically-aligned system.

5.2.2 Perceptual Appearance Control by Projection-Induced Illusion

My perceptual appearance controlling method has limitations. I would like to show future directions of this study by showing the remaining problems. Some issues required to be addressed in the future are shown as follows.

- Neccessary extent of projection to surrounding areas is unknown.
- Color appearance model I am using cannot estimate perceive color precisely.

There are several remaining issues to be addressed.

First, proposed method does not take the necessary size of projection to surrounding areas. Currently, when my system induces color constancy, the system projects surrounding projection as broad as possible. There is no knowledge about the necessary conditions for inducing color constancy. If I can gure out the condition, I can minimize the extent of colored projection to the surrounding areas. I think large colored projection to unnecessary areas is annoying and leads discomfort to observers. Thus, I can reduce it be the extent minimization. Secondly, the color appearance model which I am using is straightforward, and it regards humans have perfect color constancy. It means that human vision can entirely cancel the effects of colored illumination and perceive the original colors of objects completely, which is the ability humans do not have. By employing a color appearance model which models humans' imperfect color constancy, my system may present colors more presicely.

List of Publication

Journal

1. Ryo Akiyama, Goshiro Yamamoto, Toshiyuki Amano, Takafumi Taketomi, Alexander Plopski, Christian Sandor, and Hirokazu Kato. "Robust Reflectance Estimation for Projection-Based Appearance Control in a Dynamic Light Environment" *IEEE Transactions on Visualization and Computer Graphics,*

International Conference

1. Ryo Akiyama, Goshiro Yamamoto, Toshiyuki Amano, Takafumi Taketomi, Alexander Plopski, Christian Sandor, and Hirokazu Kato. "Perceptual Appearance Control by Projection-Induces Illusion." In *Proceedings of IEEE International Conference on Virtual Reality*, Osaka, Japan, 2 pages, March, 2019

2. Ryo Akiyama, Goshiro Yamamoto, Toshiyuki Amano, Takafumi Taketomi, Alexander Plopski, Christian Sandor, and Hirokazu Kato. "Light Projection-Induced Illusion for Controlling Object Color." In *Proceedings of IEEE International Conference on Virtual Reality*, Reutlingen, Germany, 2 pages, March, 2018

3. Ryo Akiyama, Alexander Plopski, Christian Sandor, Daniel Saakes, Takafumi Taketomi, and Hirokazu Kato. "Applications of Augmented Reality and IoT Combination." In *Proceedings of Asia-Pacific Workshop on Mixed-Reality*, 2017.

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Domestic Conference

1. 秋山 諒，吹上大樹，澤山正貴，河邉隆寛，西田眞也，“ プロジェクションマッピングの「投影感」—光学的・空間的要因の検討” 日本視覚学会 2019 年冬季大会.

2. 秋山 諒，山本 豪志朗，天野 敏之，武富 貴史，プロプスキ アレクサンダー，サンドア クリスチャン，加藤 博一,“ 色恒常性を利用したプロジェクタの色域の知覚的拡張 ” 第 21 回 画像の認識・理解シンポジウム (MIRU 2018) Extended Abstract PS2-52, 2018.

3. 秋山 諒，山本 豪志朗，天野 敏之，武富 貴史，プロプスキ アレクサンダー，サンドア クリスチャン，加藤 博一,“ 知覚量に基づく光投影による色制御実現に向けた色知覚モデルの検討” 日本バーチャルリアリティ学会複合現実感研究会, MR2017-16, 2017.

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