Appearance Control in Dynamic Light Environments with a Projector-Camera System

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Abstract

Appearance of objects change from their original colors according to a lighting condition. Nowadays, a projector-camera system can act a tool to control colors or textures of objects in each small area divided in pixel level by light projection onto their physical surfaces. Conventional system can change the appearance in real-time under constant environmental lights. However, the change of environmental lights also influence the appearance. Therefore, we propose an advanced appearance control method considering the change of the environmental lights. In particular, we use a projector-camera system consisting of two cameras and one 3D projector. In addition, we apply liquid crystal shutter filters in order to estimate reflectances and variations of environmental lights separately simultaneously in real-time. In this paper, we show our theory for the estimation and results under different conditions of environmental lights.

Index Terms: H.5.1 [Information Interfaces and Presentation]: Multimedia and Informations Systems—Artificial, augmented, and virtual realities; I.4 [Image Processing and Computer Vision]: Scene Analysis—Color

1 Introduction

Colors and textures are essential elements affecting the appearance of objects. In general, these elements influence to human perception and cognition visually. In these days, projection mapping technologies are advanced and can control colors and textures on surfaces of physical objects. They have contributed to entertainment events, museum events, and educational and medical situations, all of which are related to human activities. We believe that improvement of these technologies are necessary studies. In addition, we need to consider human color perception such as color constancy for advanced appearance control.

In this work, we focus on an appearance control technology with a projector-camera system, which can project a controlled light onto a physical surface. The basic technique of appearance control is optical compensation. Nayer et al. [10] and Grossberg et al. [7] proposed an optical compensation method for static situations. Thereafter, Fujii at el. [6] proposed a method for removing appearance in dynamic situations. Enhancing an original appearance is another technique of appearance control [3], [4] . At initial stage, projection technologies needed to get the appearance of the object in a white light in advance, in other word, they can be used in only static situations. For introducing a feedback structure into appearance enhancement, Amano et al. [1] and Bimber et al.[5] real-time appearance control systems that doesn't need a pre-capture of objects' appearance. By applying a control theory, Amano et al. [2] proposed a new method for dynamic appearance control that employed the Model Predictive Control (MPC) algorithm. The introduction of MPC made the appearance control system robust and easier to find suitable parameter for the control. However, that feedback system with MPC cannot control the appearance correctly when environmental lights are changing since the system regards the environmental lights are constant. The system processes the change of the environmental light as the change of reflectances. Moreover, it cannot be applied to most of real situations, in which the environmental light is changing dynamically.

We propose a method to estimate reflectances of the object surface and variations of environmental lights separately simultaneously in real-time. By estimating them separately, our appearance control system becomes robust against the change of environmental light. In particular, we develop a projector-camera system that consists of one 3D projector, two cameras, and liquid crystal shutter filters to estimate reflectances and variations of the environmental light. Liquid crystal shutter filters synchronize to the projector and divide the view of the projection in a time line. By attaching them onto each camera lens, one camera can observe only the environmental light, while the other acquires most of all visible lights.

A major contribution of this paper is an algorithm for appearance control that needs no optical calibration in each time when the environmental lights change. Even if the environmental lights changes a little, it might not affect human visual perception so much due to color constancy. However, there is a risk that difference between the appearance perceived by humans and the target image of the projector makes the system unstable when the environmental lights changes enough. While our technique does not measure human visual perception directly, we think it is necessary to discuss about the perception with our technology in this field. Our method is still at the first stage, but we believe our method can let us bring projector-camera systems most of place even with environmental light changes dynamically. For example, we might be able to change colors of objects in outdoor environments. Furthermore, it can be used as a smart illuminator to make it easier to read a newspaper or to see photos anywhere. Our system doesn't need any additional calibrations for the change of environmental light even when other lightings are switched on or off.

2 Related Work

Tsukamoto et al. [11] propose a technique for a cooperative multi projection system to compensate a color of projections. It is robust to the change of environmental light, and it can show ideal appearance even when the environmental lights change. However, as an assumption of technique, the system has a target image in advance, and the appearance is controlled as almost same to the target image. It is not particular situation only for this cooperative multi projec-

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tion system, but also general radiometric compensation techniques (e.g. [10], [7], and [6]). In other words, this technique doesn't need to estimate reflectances or environmental light because the system already have target images. In contrast, our system doesn't require any target image in advance. It needs to estimate the appearance of the target objects in a white light first, and generates a target image with additional image processing. Therefore, their method only can adjust the appearance to a given target image.

Mukaigawa et al. [8] propose a technique of light projection considering BRDF (Bi-directional Reflectance Distribution Function) to reproduce the appearance of a vase in any lighting situation. To use BRDF, this system needs to capture images lighted from every angles in advance. Also, Mukaigawa et al. [9] propose a method to measure BRDF in high speed. Although can measure BRDF in shorter time as compared to a previous system, it takes still about 50 seconds. Therefore, it assumes a statical environmental lighting and it is difficult to perform successive appearance manipulation in real time. In our system, we assume that a target surface is Lambertian surface, and all of lights reflect like Lambertian reflect in order to reduce calculation cost.

Amano et al. [2] propose a technique to control an appearance of a physical surface using a projector-camera system. In thier experiments, saturation enhancement, color removal, color phase control, edge enhancement, making blur, making unique brightness, and so on are shown as possible appearance control representations. These many representations are not limited to amusement applications, but also support for partially color-blind people. This technique estimates reflectances under an assumption of statical environmental lighting. Therefore, it is undesirable to be used in situation where the environmental lights change, such as an illuminated environment, including sunlight, or including cast shadow that made by users or some moving objects. We aim to make this method much robust against the change of the environmental lights by applying additional estimation of variation of environmental lights.

3 System Design

We aim to estimate reflectances of a target object surface and variations of environment lights simultaneously in real-time. Since it is difficult for only one camera to estimate both, we use two cameras in a projector-camera system. This section describes the system structure, an estimation method, and appearance control algorithm.

3.1 System Structure

Our system consists of a projector and two cameras. The projector has a 3D function that can switch pairs of images alternatively at high speed. One of the cameras assigned as the "main camera" and the other is the "sub camera". In addition, we use liquid crystal shutter filters (LCSF) in order to appropriately cut off projection light for the sub camera. By synchronization between these filters and to the projector, we can make a structure allowing only the main camera capture the projected light as shown in Fig. 1.

Let the relations between reflectances and lights in each camera be

$$I_{cm} = K(I_p + I_0 + I_f),$$

$$I_{cs} = K(I_0 + I_f),$$

where $I_{cm} \in R^3$ is light received by the main camera, $I_{cs} \in R^3$ is light received by the sub camera, $I_p \in R^3$ is projection light, $I_0 \in R^3$ is default environmental light, and $I_f \in R^3$ is variations of environmental light. I_p, I_0, I_f are mixed and reflected on the surface with reflectances $K \in R^{3\times3}$. By using the Lambertian model, we assume $I_{cm} \approx I'_c$. In other words, we consider that the captured view by the main camera is close to what we can see. Fig.2 shows the relationships between these lights.

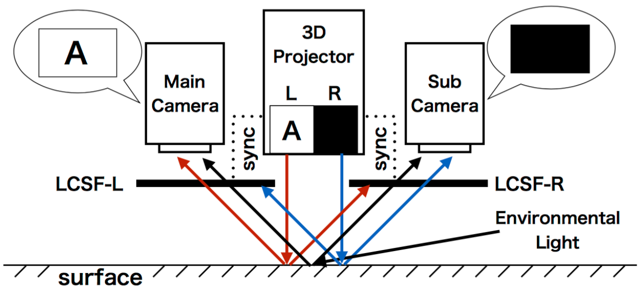


Figure 1: System structure: two alternative images are projected from a 3D projector, and each of those images is captured by a corresponding camera through a liquid crystal shutter filter.

In addition, we need to consider differences of color spaces and view points between each device. It is necessary to know geometrical correspondence in one color space for an estimation method for reflectances and variations of environmental light.

First, we calibrate geometrical correspondences between pixels of the main and sub cameras. Even if we place the sub camera as close to the main camera as possible, it cannot be exactly the same view point unless we use a coaxial optical system. In our case, we transform the view of the sub camera to the view of the main camera by using the geometrical correspondences. Pixel mappings between coordinates of "the main camera and the projector" and "the sub camera and the projector" are calibrated with a general calibration method employing gray code pattern projection. From these two pixel mappings, the other pixel mapping between coordinates of the main and sub cameras can be calculated. The view of the sub camera can be transformed to that of the main camera using the pixel mapping.

Second, we calculate color mixing matrices since the color in each device needs to be represented in an unified color space. We use the color space of the main camera as the unified color space for the calculation of appearance control. The relationships between the cameras and a projector can be shown as

$$C_m = M_{mp}P + C_{m0}, \tag{1}$$

$$C_s = M_{sp}P + C_{s0}, \tag{2}$$

where M_{mp} is the color mixing matrix from the main camera color space to the projector color space, M_{sp} is the matrix from the sub camera to the projector, C_m is the captured image of main camera, C_s is the captured image of sub camera. In addition, C_m and C_s consist of the projected image P and the captured image without projection C_{m0} and C_{s0}, respectively. In this calibration phase, both cameras need to capture the reflected light of the projection. The filter for the sub camera must change the sync in order to obtain the projected light. This is the reason why the sub camera can take the projection light P in eq. (2), while the projection light is blocked in the control phase. After the calibrations for M_{mp} and M_{sp}, we also can convert the color of the sub camera into the main camera color space with using eq.(1) and eq.(2).

$$C_m = M_{mp}M_{sp}^{-1}(C_s - C_{s0}) + C_{m0}$$

3.2 Estimation Method of K and F

We use a projector-camera response model. A captured image of main camera C_m and a captured image of sub camera C_s are generated from the reflected light of the projections P, light with no projection C_{m0} and C_{s0}, and variations of environmental light F and F' as follows. We define P and F for the main camera color space,

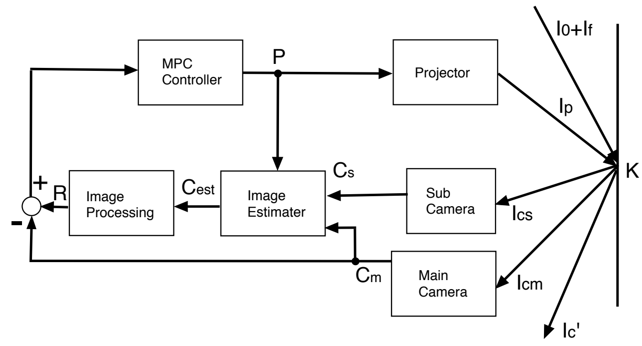


Figure 2: A process flow for appearance control with model predictive control algorithm.

F' for the sub camera color space. In this paper, we use ./ and $\odot$ as component-wise division and multiplication, respectively.

$$C_m = K\{(C_{mfull} - C_{m0}) \odot P + C_{m0} + F\}, \tag{3}$$

$$C_s = K(C_{s0} + F'). \tag{4}$$

In eq. (4), there is no projected light because of cutting off by LCSF.

Considering color mixing matrices, we can calculate an estimated variations of the environmental lights as follows;

$$\hat{F} = K^{-1} M_{ms} C_s - M_{ms} C_{s0}. \tag{5}$$

Considering eq. (3) and eq. (5), we can express estimated reflectances $\hat{K}$ without using $\hat{F}$.

$$\hat{K} = (C_m - M_{ms} C_s)./\{(C_{mfull} - C_{m0}) \odot P + C_{m0} - M_{ms} C_{s0}\} \tag{6}$$

Equations (5) and (6) show that we can calculate $\hat{K}$ and $\hat{F}$ simultaneously. Based on $\hat{K}$, the true appearance that under the white image $C_{white} = (1,1,1)^T$ is given by

$$C_{est} = \hat{K} C_{white}, \tag{7}$$

without interference from F theoretically.

We can make a reference image R by processing some effect onto the estimated true appearance C_{est}. Then, we can calculate the subtraction between C_{est} and the current appearance C for a negative feedback loop. However, the error of estimated result C_{est} affects creation of R since the relationship C_{est} and R is sensitive. In other words, the error of C_{est} would also be enhanced during appearance enhancement, then the feedback may be unstable. For that reason, we need to consider about the model error and the reference trajectory. In section 3.3, we introduce a model predictive control algorithm.

3.3 Model Predictive Control

Amano et al. [2] proposed an appearance control with negative feedback based on Model Predictive Control (MPC) algorithm. The system has achieved high quality and robustness for appearance control as compared to conventional methods. This is the reason why we also apply MPC algorithm to our control function. Figure 2 shows the structure of our system with MPC controller.

To apply MPC algorithm, we use projector-camera response model considering variations of the environmental light $F(t)$ as

$$C_M(t+1) = \hat{K}\{(C_{full} - C_0) \odot P(t+1) + C_0 + F(t)\} \tag{8}$$

where $P(t)$, $C(t) \in ([0,1],[0,1],[0,1])$ are a normalized projection pattern and a captured image by the main camera at the step t. It should be noted here that all parameters related to camera in MPC process are generated by the main camera only and we avoid to put "m" as a symbol for the main camera. Image prediction that contains model error is written by

$$C_p(t+1) = C_M(t+1) + Error(t), \tag{9}$$

where

$$Error(t) = C(t) - C_M(t). \tag{10}$$

And the reference trajectory is

$$C_R(t+1) = \alpha C(t) + (1-\alpha) R(t+1). \tag{11}$$

Based on the control law $C_P(t+1) = C_R(t+1)$ with eq. (8) to eq. (11), we can get manipulating value as follows;

$$\begin{aligned} &P(t+1) \\ &= \hat{K}(t)^{-1}(1-\alpha)\{R(t+1) - C(t)\}./(C_{full} - C_0) \\ &\quad + \hat{K}(t)^{-1}\hat{K}(t-1)\{C_0 + F(t-1)\} - C_0 - F(t) \\ &\approx \hat{K}(t)^{-1}(1-\alpha)\{R(t+1) - C(t)\}./(C_{full} - C_0) + P(t). \end{aligned} \tag{12}$$

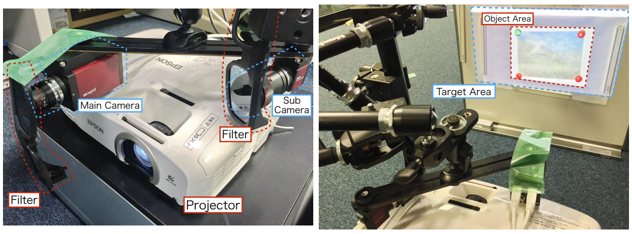
In eq. (12), there are approximations of $\hat{K}(t)^{-1}\hat{K}(t-1) \approx 1$ and $F(t-1) - F(t) \approx 0$. The equation could be simple, while there is a negative possibility that a system become unstable when K is small value. By comparing an equation in previous study [2] and eq. (12), we can find these two equations are completely same. Therefore, the MPC algorithm we use is the same one what Amano al et. show in a reference [2].

4 Prototype System

We explain a structure of our prototype system in this section. We use Allied Vision PIKE as a main camera and Allied Vision Guppy PRO as a sub camera. They are located close to a projector (EPSON ELPGS03) as shown in Fig 3 (a) in order to use large common space as the target area as shown in Fig 3 (b). We implement the prototype system with these 3 devices.

We use a plane surface of a board board located in front of them, and put a white paper on it as target area. In our assumption, the surface to be projected is the Lambertian surface. Therefore, we limit the target object is printed papers. In addition, papers with images printed by a inkjet printer don't reflect lights on the surface so much like specular reflection as compared to ones printed by a laser printer. Also, in order to equalize the distance between the projector and the board, we install the projector parallel to the floor, and the board vertically to the projection axis. We preferred to avoid troubles caused by that the brightness of the projection has unevenness, while that kind of unbalanceness can be compensated in advance. We use EPSON ELPGS03 which is a pair of 3D active glasses with liquid crystal shutter filters, and put them onto each camera lens. We describe each spec of our equipment here; 2.7GHz CPU computer (MacBook Pro Intel Corei7 2.7GHz), C++ with libraries of OpenCV, and OpenGL for the implementation of the system. Table 1 shows a list of main equipment and tools for our implemented system.

In a practical case, we need to set 3D glasses appropriately according to situations. We use a L image channel of the 3D projector for appearance control by using side-by-side 3D mode. In any case, we locate the left filter to the main camera, while the sub camera needs to switch each filter according to the process phases. In the calibration phase, we must locate the left filter for the sub camera as well. On the other hand, in the appearance control phase, we need to change it with the right filter to block the projected light. Therefore,



(a) (b)

Figure 3: An implemented system with two cameras attached filters and a projector: (a) overview of the system, (b) a scene the projection light onto the target area controls appearance of the object.

Table 1: Equipment and tools for the implementation.

Main Camera	Allied Vision Pike (640x480)
Sub Camera	Allied Vision Guppy PRO (640x480)
Projector	EPSON EH-TW5200 (1080p)
Liquid Crystal Shutter Filter	EPSON ELPGS03
Computer	MacBook Pro OS X 10.9.2 Intel Core i7 @2.7GHz
Software	C++, OpenCV, OpenGL

the main camera can capture the projection and the environmental light, and the sub camera only can capture the environment light.

Figure 4 shows an estimated image C_{est} as shown in eq. (7) under the appearance control with the gray-scale effect without variations of environmental light F. This estimation should be the same to the method of Amano et al. Figure 5 show the results that are estimated true appearance related to K and estimated variations of environmental lights F in different situations. We prepared five different environmental light changes by using a flashlight; white, red, green, blue, and yellow. Through the results of (w2), (w5), (r2), (r5), (g2), (g5), (b2), (b5), (y2), (y5), interference onto the estimation of K seems not to be huge by adding the variations of environmental light except the situation with red light. Similarly, considering the results of (w3), (w6), (r3), (r6), (g3), (g6), (b3), (b6), (y3), (y6), the estimation of the variations of environmental light can extract F except the situation with red light. By looking at histogram data, sensibility of cameras against red color might be lower as compared to other color channels.

5 Discussion

Color constancy is one of human visual perceptions. A human eye can perceive an original color of an object even in different environmental lights. When we use a projector-camera system for appearance control, global illuminations such as room lights on a ceiling don't influence so much in order for a human eye to perceive the original color. Conversely, there is perceptible significant differences from original colors in small area such as pixel level. If the system has a function to estimate only reflectances of objects, it cannot detect the original color of objects in a dynamic light environment since the system regards change of environmental lights as change of reflectances. For example in case of saturation enhancement process, additional red environmental lights let the system estimate reflectance reddish, then the controlled appearance will be much more reddish even if a corresponding object color is blue. On the other hand, our system can distinguish environmental lights from reflectances. Therefore, our system would be able to provide a proper appearance for human vision considering color constancy by preparing reference images with colors of environmental lights. In addition, the system also can realize the original colors by compensating the environmental lights.

Figure 4: An estimated image under the condition that there is no variation of environmental light in gray-scalse effect process.

A novel point of our system is to estimate variation of environmental lights as the same time to estimate reflectances. As variation of environmental lights, we expect a positive and a negative value such as additional lighting or shadow by blocking lighting, respectively. In case of the positive, we may make a function to estimate a light source direction using light gradients. If the system can detect the light direction, the appearance would be controlled such as additional shadowing on target images. On the other hand, we can extract shadow on a projection area using the negative variations of environmental lights. By extracting the shadow areas, we may make functions to diminish or enhance the shadow for some applications such as art work or novel user interface.

6 Conclusion and Future Work

In this paper, we confirmed that the method to estimate reflectances K and variations of environmental light, which is F, for the appearance control system using two cameras and one 3D projector. Through this work, we could show the possibility for improvement of the robustness of the appearance control system even though the environmental lights change dynamically. However, the quality of estimation is not enough high yet. For example, red color channel is still not controlled well as shown in Fig. 5 (r3). In order to apply our system for human visual perceptual experiments or applications, we need to cover a high dynamic range for appearance control. In addition, attractive applications should be implemented with this technology in the future.

Acknowledgements

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References

[1] T. Amano and H. Kato. Real world dynamic appearance enhancement with procam feedback. In *Proceedings of the 5th ACM/IEEE International Workshop on Projector Camera Systems*, page 5, 2008.

[2] T. Amano and H. Kato. Appearance control using projection with model predictive control. In *20th International Conference on Pattern Recognition*, pages 2832–2835, 2010.

[3] T. Amano and R. Suzuki. Virtual recovery of the deteriorated art object based on ar technology. In *IEEE Conference on Computer Vision and Pattern Recognition*, pages 1–2, 2007.

[4] O. Bimber and D. Iwai. Superimposing dynamic range. In *ACM Transactions on Graphics*, volume 27, page 150, 2008.

[5] O. Bimber, D. Klöck, T. Amano, A. Grundhöfer, and D. Kurz. Closed-loop feedback illumination for optical inverse tone-mapping in light microscopy. In *IEEE Transactions on Visualization and Computer Graphics*, volume 17, pages 857–870, 2011.

[6] K. Fujii, M. D. Grossberg, and S. K. Nayar. A projector-camera system with real-time photometric adaptation for dynamic environments. In *IEEE Computer Society Conference on Computer Vision and Pattern Recognition*, volume 1, pages 814–821, 2005.

[7] M. D. Grossberg, H. Peri, S. K. Nayar, and P. N. Belhumeur. Making one object look like another: Controlling appearance using a projector-camera system. In *Proceedings of the 2004 IEEE Computer Society Conference on Computer Vision and Pattern Recognition*, volume 1, pages 452–459, 2004.

[8] Y. Mukaigawa, M. Nishiyama, and T. Shakunaga. Virtual photometric environment using projector. In *Proceedings of International Conference on Virtual Systems and Multimedia*, pages 544–553, 2004.

[9] Y. Mukaigawa, K. Sumino, and Y. Yagi. Rapid brdf measurement using an ellipsoidal mirror and a projector. In *IPSJ Transactions on Computer Vision and Applications*, volume 1, pages 21–32. Information Processing Society of Japan, 2009.

[10] S. K. Nayar, H. Peri, M. D. Grossberg, and P. N. Belhumeur. A projection system with radiometric compensation for screen imperfections. In *ICCV workshop on projector-camera systems*, volume 3, 2003.

[11] J. Tsukamoto, D. Iwai, and K. Kashima. Radiometric compensation for cooperative distributed multi-projection system through 2-dof distributed control. In *IEEE Transactions on Visualization and Computer Graphics*, volume 21, pages 1221–1229, 2015.

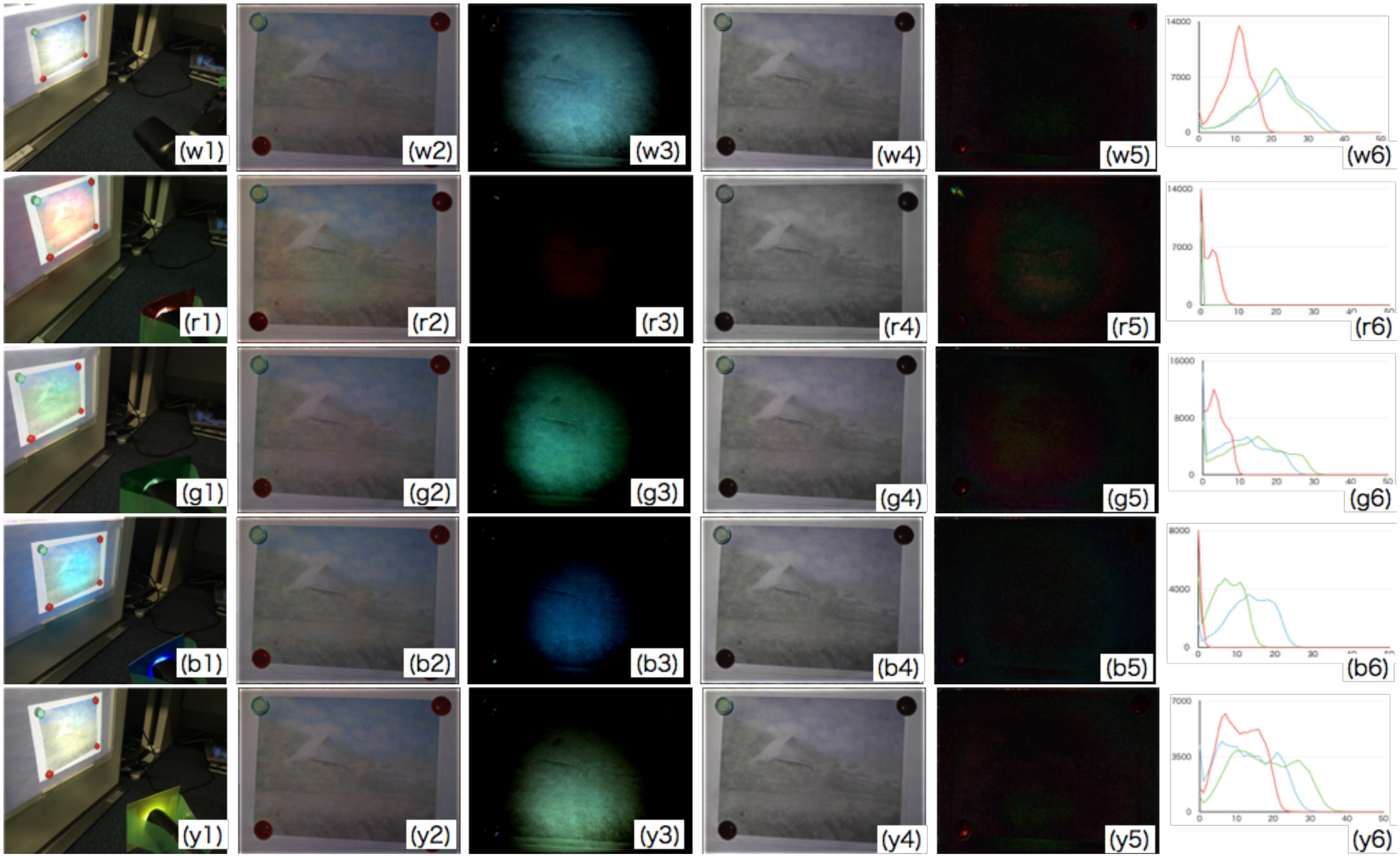

Figure 5: Experimental results with five different color lights as additional environmental lights in the following order; white, red, green, blue, and yellow. first column: scenes that an environmental lights change by a flashlight, second column: estimated true appearance, third column: estimated environmental light variations [×5], fourth column: captured images of the main camera, fifth column: difference between the images of second column and the image of Fig. 4 [×5], sixth column: histograms of the environmental light that is the photos of third column. White, red, green, blue, and yellow lights are used in each rows.