A novel methodology for photometric compensation of projection display on patterned screen

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We propose a novel methodology based on the projector-camera (ProCam) system to address the photometric compensation issue for the projection display on the patterned screen. The patterned screen is treated as the combination of a perfect white screen and a color modulator. The perfect white screen is used to automatically and accurately characterize the ProCam system offline using the polynomial model, and the parameters of the color modulator can be efficiently recovered by employing only two gray images based on the linear reflectance model. The experimental results show that the color artifacts of the display image can be greatly improved with this methodology, which demonstrates its feasibility and validity in the photometric compensation.

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Projectors are presently becoming very popular owing to their descending cost, portability[1], and underlying visualization[2]. As a result, many occasions will occur like that the projectors are used on various screens such as the painting wall, combined corner, textured ceiling, and even the arbitrary surfaces, rather than a perfect white flat screen[3]. Herewith, to relax this rigid requirement and to obtain the similar or even identical projection output on arbitrary surfaces, photometric and geometric compensations for the resulting artificialities[4] of the projection output are naturally expected. In recent years, a new projection system combining the projector with the camera together (ProCam system for short) has been developed for this issue, and several compensation algorithms have been put forward based on such systems[4−8]. However, the existing methods are more or less depending on the prior calibration information of the projector or the camera and assume that the channel responses of the projector are independent, which greatly limits their industrial applications. Aiming to overcome these disadvantages, a novel methodology based on the ProCam system is proposed in this paper to address the photometric compensation issue for the projection display on the patterned screen. The ProCam system of this study is composed of a video graphics array (VGA) NEC LT 30+ projector with a native resolution of 1024×768 pixels and a HITACHI HV-D30 camera with a resolution of 768×576 pixels. The images are projected onto the screen via a RADEON R9200SE display card and captured by an 8-bit Matrox Meteor II/Multi-channel frame-grabber.

The camera was adopted as a proxy for the viewer[7] and the spectral characteristics of the perfect white screen were assumed to be spatially uniform. Some patch images had been projected to compute the homography between the image plane of the projector and that of the camera. The projector and camera were both supposed to have three color channels (i.e., R, G, B) and the digital values (i.e., r, g, b) for one pixel of the image were simply defined as the vector $\mathbf{I} = (r, g, b)^{\mathrm{T}}$, where the superscript "T" represents the transpose of matrix and the same for the following representations. The patterned screen was treated as the combination of a perfect white screen and a color modulator of the same size. The photometric response process of the projection display on the patterned screen for the ProCam system is depicted in Fig. 1. Firstly, the input image was projected upon the perfect white screen, captured by the camera, and the ideal output image was produced. Then, the ideal output image together with the environmental lighting was modulated by the color modulator and the output image was finally obtained.

For each pixel in the projector's image plane, the input digital value $\mathbf{I}_{\mathrm{in}}$ is pre-transformed into the ideal output of the ProCam system on the perfect white screen, noted as $\mathbf{I}_{\mathrm{pre}}$. This process can be described as

$$\mathbf{I}_{\mathrm{pre}}\left(x', y'\right) = \boldsymbol{\alpha}\left(x', y'\right) f_{\mathrm{p}}\left(\mathbf{I}_{\mathrm{in}}\left(x, y\right)\right) + \mathbf{I}_{\mathrm{bk}}\left(x', y'\right), \quad (1)$$

where x, y are the coordinates of the pixel in the projector's image plane, and x', y' in the camera's image plane; f_{p} represents the nonlinear transformation function of the ProCam system with the perfect white screen, which is reasonably assumed to be identical for every pixel according to the fact that the response functions of the projector and the camera are shown to be spatially uniform[5,8]; the factor

$$\boldsymbol{\alpha} = \begin{bmatrix} \alpha_{\mathrm{R}} & 0 & 0 \\ 0 & \alpha_{\mathrm{G}} & 0 \\ 0 & 0 & \alpha_{\mathrm{B}} \end{bmatrix}^{\mathrm{T}}$$

with α_{R}, α_{G}, and α_{B} being constants allows the spatially inerratic variations introduced by the vignetting effect of the projector and the channel response imbalance of the ProCam system; the term $\mathbf{I}_{\mathrm{bk}}$ defines the black display output. In order to characterize the ProCam system, a flat-black image, of which all the RGB values are zeros, is firstly projected onto the perfect white screen to obtain $\mathbf{I}_{\mathrm{bk}}$. Then, a flat-white image with all the RGB values

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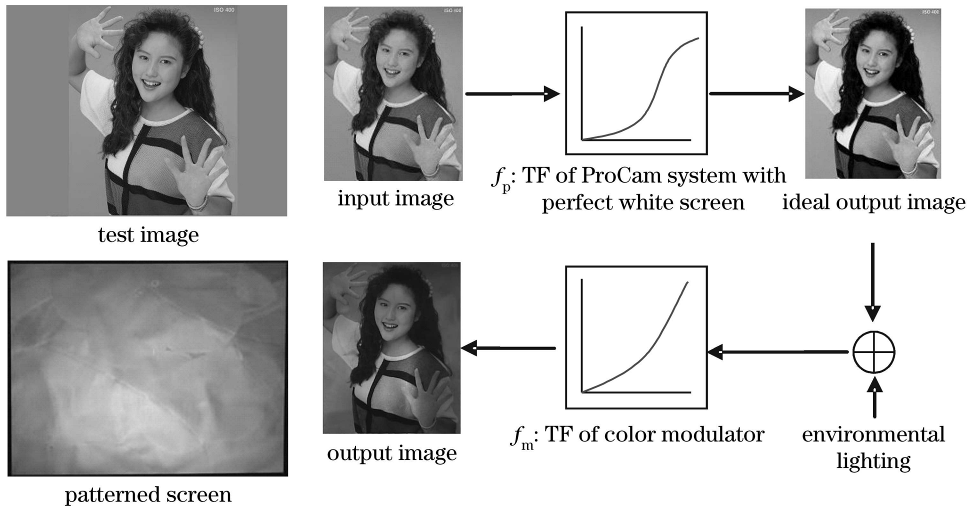

Fig. 1. Photometric response process of the projection display on the patterned screen for the ProCam system. TF: transformation function.

being the maximum 255 is needed to calculate the factor $\boldsymbol{\alpha}$. Finally, considering the nonlinear tone mapping of the ProCam system and the nonlinear channel coupling of the projector, a patch image regularly arranged with proper color samples is created to recover the function f_p and its reverse f_p^{-1} based on the polynomial model[9,10]. Fortunately, the characterization of the ProCam system can be automatically performed offline only once.

Now, $\mathbf{I}_\text{pre}$ and the environmental lighting $\mathbf{I}_\text{e}$ are processed by the color modulator, so that $\mathbf{I}_\text{out}$ will be obtained. The transmission function of the color modulator can generally be represented as a monotonic spectral response function f_m, and the relationship between $\mathbf{I}_\text{pre}$ and $\mathbf{I}_\text{out}$ can be depicted as

$$\begin{aligned}\mathbf{I}_\text{out}(x',y') = f_\text{m}\left(\mathbf{I}_\text{pre}(x',y') + \mathbf{I}_\text{e}(x',y')\right) \\ +\mathbf{I}_\text{dk}(x',y'),\end{aligned} \quad (2)$$

where f_m, $\mathbf{I}_\text{e}$, and $\mathbf{I}_\text{dk}$ are all different for individual pixels because of the spatial variation in the surface reflectance, the environmental lighting, and the dark noises of the camera. Moreover, based on the linear reflectance model that can accurately characterize a wide range of physical surfaces[7,11,12], Eq. (2) can be further simplified as

$$\begin{aligned}\mathbf{I}_\text{out}(x',y') \approx \boldsymbol{\alpha}(x',y')\,\mathbf{k}(x',y')\,f_\text{p}\left(\mathbf{I}_\text{in}(x,y)\right) \\ +\mathbf{I}_\text{BG}(x',y'),\end{aligned} \quad (3)$$

where $\mathbf{I}_\text{BG}(x',y') = \mathbf{k}(x',y')\left(\mathbf{I}_\text{bk}(x',y') + \mathbf{I}_\text{e}(x',y')\right) + \mathbf{I}_\text{dk}(x',y')$ is the background output, and the coefficient

$$\mathbf{k} = \begin{bmatrix} k_\text{R} & 0 & 0 \\ 0 & k_\text{G} & 0 \\ 0 & 0 & k_\text{B} \end{bmatrix}^\text{T}$$

with k_R, k_G, and k_B being constants is the linear modulation coefficient for the color modulator. To recover $\mathbf{k}$, only one flat-black image and one flat-gray image are needed for efficiency. However, if high accuracy is required, two or more images are desired to estimate the coefficient using the least square technique.

Finally, given that the original image is the objective of the compensation output, the compensation input image can be computed as

$$\begin{aligned}\mathbf{I}_\text{com}(x,y) \approx f_\text{p}^{-1}\big((\mathbf{I}_\text{o}(x,y) - \mathbf{I}_\text{BG}(x',y')) \\ \times\boldsymbol{\alpha}^{-1}(x',y')\,\mathbf{k}^{-1}(x',y')\big),\end{aligned} \quad (4)$$

where $\mathbf{I}_\text{com}$ is the compensation input and $\mathbf{I}_\text{o}$ is the original input.

This methodology was tested on some flat patterned screens using the International Organization for Standardization (ISO) standard digital images, one group of which is shown in Fig. 1. As seen from the experimental results illustrated in Fig. 2, when the desired image (a) is directly projected onto the patterned screen, the display image (b) is non-uniform for the lightness and modulated by the colorful flower of the patterned screen. In contrast with the uncompensated output, when the compensation image (c) corresponding to the desired image is calculated using the proposed algorithm and then projected onto the screen, an output image very close to the desired image is displayed despite the dim colors on the

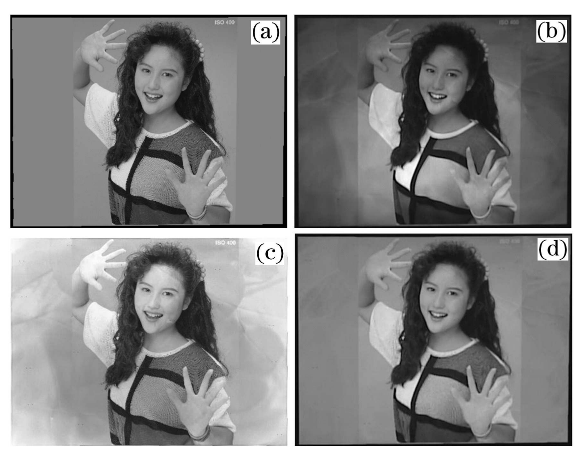

Fig. 2. Experimental results for the compensation algorithm. (a) Original (desired) image; (b) uncompensated output; (c) compensation image; (d) compensated output.

Table 1. Mean and RMS Errors of the Uncompensated Output (Unc.) and Compensated Output (Cmp.) for the Test Image on the Patterned Screen

Error	R		G		B	
	Unc.	Cmp.	Unc.	Cmp.	Unc.	Cmp.
Mean	35.4	8.0	33.2	6.8	31.5	8.5
RMS	42.4	12.9	38.9	12.4	38.7	15.0
Error	Y		U		V	
	Unc.	Cmp.	Unc.	Cmp.	Unc.	Cmp.
Mean	33.0	6.8	4.7	1.7	6.0	2.9
RMS	39.0	12.3	6.4	2.8	7.2	4.0

$Y = 0.299R + 0.587G + 0.114B$, $U = -0.148R - 0.289G + 0.437B$, $V = 0.615R - 0.515G - 0.100B$.

edge of the screen, where the color of the compensation image is out of the dynamic range of the projector. Choosing the original (desired) image, which is the geometric mapping output of the test image, as the reference, Table 1 gives the mean and root-mean-square (RMS) errors of the uncompensated output (abbreviated as Unc.) and compensated output (abbreviated as Cmp.), respectively, compared with the reference in the RGB and YUV space for the test image on the patterned screen as in Fig. 1. In the YUV space, Y and U, V components correspond to the lightness and chromaticity of the RGB colors, respectively. The experimental results indicate that the compensated output image has been remarkably corrected to be consistent with the desired image. The improvement of the Y component is more significant than the U and V components, which is mainly due to the spatial intensity variation of the projector and the specular reflectance of the display surface. Moreover, it can be seen by visual observation that the largest errors often occur on the sharp edges because of the limited resolution of the camera. If a camera with much higher resolution is adopted, the compensation accuracy would be improved.

In conclusion, based on the physical model that the patterned screen is treated as the combination of a perfect white screen and a color modulator, a novel methodology is efficiently developed to account for the photometric compensation issue for the projection display on the patterned screen with the ProCam system. Depending on the perfect white screen, the ProCam system can be accurately and automatically characterized offline for just a single time and then only two calibration images are necessary to recover the coefficients of the color modulator online, which is crucial to making the real-time compensation possible. This methodology has been applied to a variety of patterned screens and high quality display results are obtained. However, since the compensation accuracy is related to many aspects such as the input image content, the dynamic range of the projector, the reflectance characteristics of the screen, the compensation intent, etc., how to define the applicable range of the input images and the balance between the display quality and the minimum visible artificialities[13] should be further addressed in the future work.

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