Radiometric Compensation for Ubiquitous Projection

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Abstract—**Integrating a pico-projector with a multimedia device allows a nearby wall, desk, or human body to be conveniently used as the projection surface. Ubiquitous projection is no longer a fiction, and the miniature of projector brings about a new form of social interaction and augmented reality applications. This paper gives an overview of the key advances in radiometric compensation for ubiquitous projection and discusses the technical issues associated with the physical limitations of projectors and cameras in spatial resolution and dynamic range. Existing techniques that can be applied to address these issues are reviewed, and open issues for future research are discussed.**

I. INTRODUCTION

The need for miniature devices and technologies grows as the platform for personal computing and communication has expanded from PCs to handheld devices in recent years. However, smaller devices are not always easier to use than bigger ones. In fact, there is a strong move to make the screen and the keyboard always a little bigger for handheld devices. For example, the latest released smart phones such as New HTC One, Sony Xperia Z, Samsung S4, and iPhone 5 all come with a bigger screen than their predecessors. The move is due to the ever increasing need for user friendliness. Large touch screens are surely more user friendly. However, there is definitely a limit to the size growth because device mobility and dimension cannot be traded off indefinitely.

As such, it has been an interesting topic to investigate how mobility and user friendliness can be achieved at the same time. Indeed, new devices with better human computer interaction (HCI) have sprouted at an amazing pace, and new technologies for virtual keyboard, speech recognition, foldable display, holography, and 3D display have emerged. Among them, pico-projector holds the promise for resolving the display limitation of small devices anywhere and anytime by using a nearby wall, desk, or body as the projection surface [1]. The age of ubiquitous projection has come.

The capability of a pico-projector can be further expanded by adding a digital camera to the pico-projector to provide visual feedback. The integrated system, called procam, opens up a new range of applications. For example, multiple users each equipped with a procam can project images on a common projection surface to play interactive games, where each user controls a character to interact with the characters created by other players [7]-[10]. Similarly, participants in a business meeting can easily exchange digital content, such as contact information or media files, with each other by projecting a QR code of the content on, for example, a wall and having the other recipients read the code using their procams [3]-[6]. To enhance student performance, teachers may interactively illustrate the lecture materials to the student by using procam and augmented reality technology [2].

Besides providing new functions, the incorporation of a camera allows a procam system to refine the projection quality according to the characteristics of the projection surface obtained through the visual feedback [12].

The kind of projection surfaces, such as walls and desks, available for ubiquitous projection are hardly as perfect as the professional white screen. Imperfect projection surfaces introduce color distortion to the projected image. For example, when an image is projected on a wood surface, the color and grain pattern of the wood would blend with the image and affects the image appearance. Similarly, when an image is projected on a shiny surface, the specular highlight [44] on the surface would affect the color appearance of the image.

In this work, radiometric compensation refers to the image operation that attempts to minimize the perceptible artifacts of an image caused by an undesirable projection surface while preserving the photometric (brightness and contrast) quality of the image as much as possible. By radiometric compensation, a projector can adapt the image to the projection surface.

However, in practice, procam systems are not free of limitations. The camera has finite image resolution, dynamic range, and gamut, and so does the pico-projector. These device-dependent limitations affect the performance of radiometric compensation. For example, when the resolution of the camera (projector) is not enough to capture (display) the spatial frequency of the texture on the projection surface, undesirable blockiness appears in the projected image. Similarly, when the camera has a small gamut, color distortion is resulted.

This paper examines the effects of such device limitations on radiometric compensation and provides a review of related techniques that can be applied to address the problems. The insightful discussion of why only limited resolution, dynamic range, and gamut of a procam can be utilized for radiometric compensation leads itself to a guideline for choosing a suitable combination of projector and camera to maximize the overall system performance. Possible future research on radiometric compensation for interactive applications is discussed. In particular, how the user information and the characteristics of human visual system can be used to enhance the performance of radiometric compensation is suggested.

The remainder of the paper is organized as follows. Section II provides an overview of existing radiometric compensation techniques. Section III presents technical issues due to device

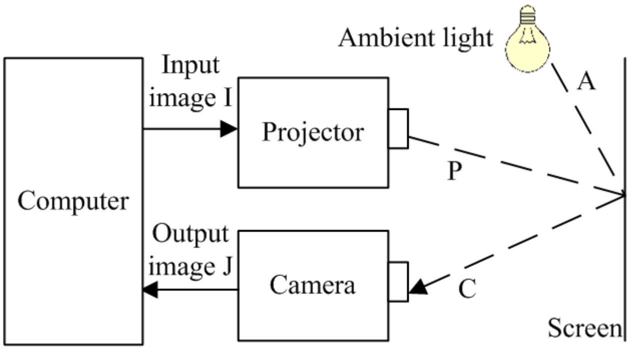


Fig. 1. The configuration of a procam system.

limitations. Section IV discusses potential issues and suggests the direction of future research. Finally, Section V draws the conclusion.

II. REVIEW OF RADIOMETRIC COMPENSATION TECHNIQUES

Radiometric compensation generally consists of three main steps: model selection, model estimation, and image compensation. This section reviews the characteristics of existing radiometric models, examines the pros and cons of two main methods for model estimation, and discusses the general procedure for radiometric compensation.

A. Radiometric Models

A procam system consists of three main components: a projector, a camera, and a computer. As shown in Fig. 1, the image generated by the computer is projected on a surface illuminated by ambient light. The camera takes a picture of the image and feeds it to the computer. The same process may repeat for a number of images. Then the computer analyzes the captured images to obtain the radiometric characteristics of the projector, camera, and projection surface.

The radiometric characteristic of a procam system is described by a radiometeric model, which relates the input image intensity to the output image intensity. The same definition applies to every component of a procam system as well except that the term image intensity is replaced by the term irradiance when the input or output of the component is the light. For example, the radiometric model of a camera describes the relation between the irradiance of the light input to the camera and the output image intensity.

The most commonly adopted procam model for describing the radiometric conversion process all the way from the input intensity of the projector to the output intensity of the camera is proposed by Nayar et al. This model assumes that the intra-reflection of the projection surface is negligible and treats each pixel independently. For each pixel, this model characterizes the relation between the input intensity I and the output irradiance P of a projector by a nonlinear transfer function f_P,

$$P = f_P(I)\,, \tag{1}$$

where P and I are three-dimensional vectors, with each dimension representing a color channel. A 3×3 matrix M is used to model the light reflection of the screen and the spectral mismatch between the color filter of the projector and that of the camera. Denote the color shift caused by the ambient light by A. Then the irradiance C captured by the camera is related to A and P by

$$C = MP + A\,, \tag{2}$$

where C and A are three-dimensional vectors. The camera response is modeled as a nonlinear function of C,

$$J = f_C(C)\,, \tag{3}$$

where J is the output intensity of the camera and f_C is the nonlinear transfer function.

Variants of the model have been proposed. Yoshida et al. proposed a 3×4 matrix to simultaneously model the screen reflection, spectral mismatch between color filters, and the color shift of ambient light [11]. Grossberg et al. reformulated the equations of the model and proposed an efficient algorithm for model estimation [12], and Fujii et al. extended the model to deal with a moving procam [13].

The above models treat each pixel independently without considering intra-reflection of non-planar projection surfaces. Wetzstein and Bimber [14] address this issue by describing the light transportation from the projector to the camera as follows:

$$\begin{bmatrix} r_R - e_R \\ r_G - e_G \\ r_B - e_B \end{bmatrix} = \begin{bmatrix} T_R^R & T_R^G & T_R^B \\ T_G^R & T_G^G & T_G^B \\ T_B^R & T_B^G & T_B^B \end{bmatrix} \begin{bmatrix} i_R \\ i_G \\ i_B \end{bmatrix}, \tag{4}$$

where r_λ denotes the camera image corresponding to a color channel λ (R, G, or B), i_η is the η-channel (R, G, or B) of the projection image, and e_λ is the λ-channel of an offset image that accounts for the effect of ambient light and the black level of projector. Intra-reflection, diffusion, and refraction are accounted for by the light transport matrix T_λ^η that describes the contribution of each projector channel η to a camera channel λ. In our view, this model is the most complete one in the literature.

It should be noted that all the above models need to perform geometric registration of the camera and projector images. This pre-processing step, which is beyond the scope of this paper, is omitted. The reader is referred to [15] for the details.

B. Model Estimation

A procam model is a characteristic function that relates I to J, as defined by (1) to (3). The three components described above model the projector response, surface reflectance, color filter mismatch, and camera response. Determining the parameters of each component model involves a sequence of operations to project a number of calibration patterns onto the projection surface and take picture of each projected image. Theoretically, it is a signal sampling process, where each pixel of the camera image is a sampled value of the curve corresponding to the procam characteristic function. Enough samples have to be collected so that the procam model can be constructed.

The methods for determining the parameters of a procam model can be categorized into two categories. The first category simultaneously determines the parameters of the three component models [16], and the second category adopts a divide and conquer approach and separates the camera model [17]–[19] from the other two models [11]–[13]. These two categories of methods are equally accurate, but they have different requirements. The first category has a larger memory requirement and a higher computational complexity, whereas the second category requires two separate calibration setups—one for the camera model and another for the other two models.

It should be noted that the radiometric models are position dependent. Here the position refers to the location of the procam with respect to the projection surface. However, the radiometric models are content independent. In other words, a radiometric model would work for all images. Therefore, the model of a static procam, once determined, can be used for any image. On the contrary, the model of a moving procam needs to be updated dynamically.

C. Color Adjustment

Once the parameters of the radiometric model are determined, a two-fold process is often adopted to generate the compensated image. To compensate the image such that the perceived image on the colored projection surface will look as if it were projected on a white screen, the image compensation process involves a sequence of steps. First, the irradiance R of the light coming off the hypothetical white screen is estimated from the intensity I of the input image by

$$R = M_W f_P(I) + A, \tag{5}$$

where the subscript W denotes white screen. Then, the compensated image I' is determined subject to the constraint

$$M_C f_P(I') + A = M_W f_P(I) + A\,, \tag{6}$$

where the subscript C denotes colored projection surface. This leads to

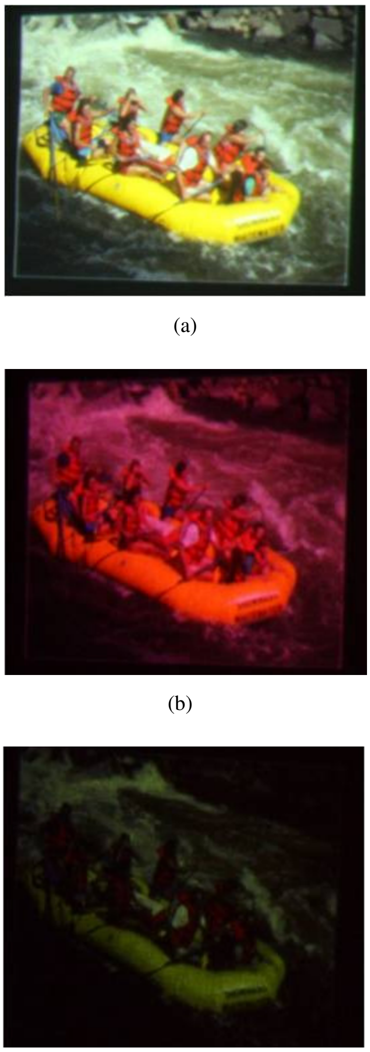
$$I' = f_P^{-1}(M_C^{-1} M_W f_P(I))\,. \tag{7}$$

III. DEVICE LIMITATIONS

Ideally, the above procedure should work. In practice, however, various issues associated with the device limitations arise. These issues deserve a close investigation.

A. Gamut of the Projection Surface

The procedure described in Section II. C. aims at reproducing the color and brightness of an image on a colored projection surface. However, not all colors are reproducible because a colored projection surface has a smaller gamut than a white screen. This should be easy to understand by considering the extreme case where a black surface absorbs all wavelengths of the visible light and reflects none. Therefore, when an image generated by the above image compensation procedure is projected on a colored projection surface, the out-of-gamut colors would be clipped, resulting in image degradations such as color distortion and loss of details.



(a)

(b)

(c)

Figure 2. A test image projected on (a) a white surface and (b) a magenta surface. (c) A radiometric compensation result with too small scaling factor for each color channel.

To address this issue, many methods have been developed and can be divided into two categories: multi-projector approach and single-projector approach. The multi-projector methods [20]–[22] expand the gamut of the projection surface. Despite that the image colors can be fully reproduced, these methods result in a significant increase of system complexity and cost. The single-projector methods [23]–[29] solve the problem by scaling down the intensity of the projected image so that most colors of the image would fall within the gamut of the projection surface. Since dark surfaces such as a dark gray wall normally have a very small gamut, the magnitude of

TABLE I
COMPARISON BETWEEN EXISTING MOBILE PROJECTION TECHNOLOGIES

	2D MEMS	Color Filter LCOS	Color Sequential LCOS	Taxes Instrument DLP	AMOLED
Resolution	☆☆	☆	☆☆☆	☆	☆
Luminance	☆☆	☆☆	☆☆	☆☆☆	☆☆
Color Depth	☆	☆☆	☆☆☆	☆☆☆	☆☆☆
Color Saturation	☆☆☆	☆	☆☆	☆☆	☆☆☆
Contrast Ratio	☆☆☆	☆	☆☆	☆☆☆	☆☆☆
Mobility	☆☆	☆	☆☆	☆☆☆	☆☆☆
Price (Low)	☆	☆☆☆	☆☆☆	☆☆	☆

Rating: Normal(☆), Good(☆☆), and Excellent(☆☆☆)

the scaling needs to be small enough. Consequently, the resulting image would be too dark to perceive, leading to unpleasant viewing experience (Fig. 2). To solve the problem, a tradeoff between out-of-gamut colors and image brightness has to be considered in choosing the optimal scaling. Heuristic and perceptual quality metrics have been used to optimize the scaling.

To reproduce the color appearance of an image on the projection surface, it is also important to choose a proper color space to process the image. The methods described above use the Lab color space [30], which mainly considers the daylight illumination condition. However, the projector considered in this paper is often for indoor applications, for which the latest color appearance model ratified by the CIE technical committee, namely, CIECAM02 [31], is a better choice than the Lab color space. Wang et al. exploited this model to maintain the color appearance of the projected image [32]. They also simplified the model, which is nonlinear, to improve the computational efficiency.

Note that the gamut issue is similar in nature to the dynamic range reallocation issue of backlight-scaled images [37]-[39], where the image color distortion is caused by dim backlight. Therefore, the methods developed for dynamic range reallocation definitely worth a look.

B. Resolution of the Projector and Camera

The performance of radiometric compensation techniques is also limited by the resolution of camera. The camera digitally samples the image shown on the projection surface. The size of each sampled area depends on the camera sensor resolution and the distance of the camera to the projection surface. Perfect image reconstruction is the goal of radiometric compensation. According to the Nyquist-Shannon sampling theory, an image can be reconstructed from the sampled data if the highest spatial frequency of the image is no greater than one half of the sampling rate. The resolution of the camera automatically imposes a higher bound on the spatial frequency of the image that can be compensated.

Likewise, the resolution of the projector also controls the performance of radiometric compensation. The distortion caused by the texture of the projection surface cannot be properly compensated if the projector resolution is not high enough.

It should be noted that the HVS imposes an upper bound on the resolution requirement of projectors and cameras because any fine details beyond the sensitivity of human eyes are unnoticeable. Psychology experiments showed that the angular resolution of human eyes is about 50 cycles per degree (cpd) [40]. Translating it to linear resolution, one can immediately find out that the resolution requirement for projectors and cameras depends on the viewing distance.

C. Dynamic Range and Gamut of the Camera

The dynamic range and gamut of the camera play an important role in the estimation of procam model parameters. To achieve good radiometric compensation performance, it is important to accurately record the irradiance of the calibration patterns reflected off the projection surface. If a camera has insufficient dynamic range or gamut, luminance and color degradation is bound to occur and in turn affects the accuracy of the procam model. Therefore, it is important select proper cameras and projectors.

IV. ADDITIONAL ISSUES OF MOBILE PROJECTORS

Although in theory the model estimation and color adjustment techniques described above are applicable to mobile procams, such systems are rarely found in practice because of physical limitations in gamut, dynamic range and resolution.

Resolution, luminance, color depth, color saturation, and contrast ratio are the essential factors for consideration of a mobile projector. Each of these factors has a say in the projection quality. Among them, resolution, color depth, and contrast are closely related to the performance of radiometric compensation. Consider a textured projection surface. The texture of the projection surface can be perfectly compensated only if the following conditions are met:

- The projector resolution is high enough to generate a compensation pattern with exactly the same structure as the texture of the projection surface.
- The color depth of the projector is high enough to reproduce the color of the textured projection surface.
- The contrast ratio of the projector is higher than that of the texture of the surface.

Since the properties of mobile projectors vary with the projection technology adopted, it is important to pick an appropriate projector according to the above requirements. This section discusses the technical issues associated with mobile projectors and suggests a number of topics for future research.

A. Low Luminance

A comparison between existing projection technologies is shown in Table I. It can be seen that each technology has its pros and cons. However, low luminance is a common

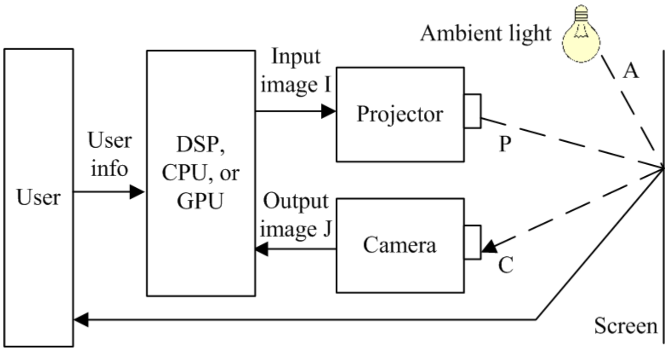


Fig. 3. The configuration of a mobile procam system taking viewing position into consideration.


(a)

(b)

(c)

Figure 4. A test image projected on a magenta surface and seen at different viewing angles. (a) Original image seen at 90°. (b) 90°-compensated image seen at 90°. (c) 90°-compensated image seen at 60°.

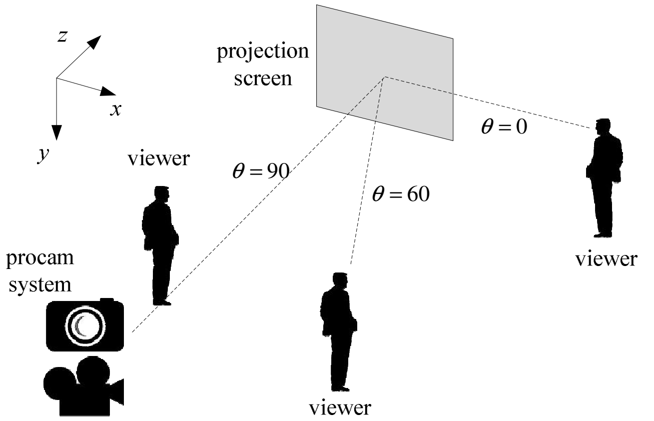


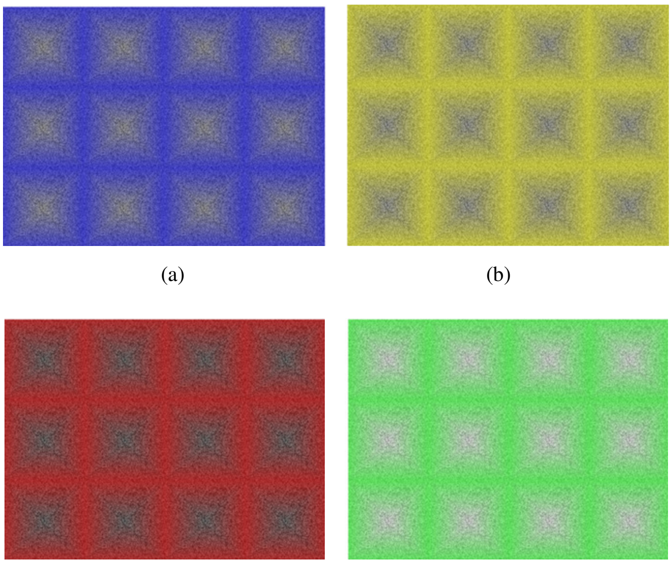
Fig. 5. The definition of viewing angle θ (measured in degree). θ=90 when the viewer stands right in front of the screen [41].

weakness. The luminance level of a conventional mobile projector is usually below 150 lumens, which is much smaller than that of a traditional projector (normally larger than 1000 lumens). Accordingly, the image generated by a mobile projector appears much darker than that generated by a traditional projector. The low luminance certainly makes radiometric compensation more challenging for mobile projectors. In addition to the gamut mapping described in Section II.C, a dynamic range mapping is also needed to preserve the brightness of the projected image. Existing dynamic range compression methods [33]-[36] developed in the HDR imaging field may be adopted to address the brightness issue. However, only limited projection quality improvement can be achieved by radiometric compensation. The dynamic range in the HDR imaging case is the same for each pixel of the display, but the reproducible brightness range varies from pixel to pixel in the radiometric compensation case due to the texture variation of the projection surface. To our best knowledge, this issue has not been addressed in the literature. It is surely a topic for future research.

B. View-Dependent Compensation

Fig. 3 shows the configuration of a mobile procam system. Compared to Fig. 1, an extra block generating viewing information is added to the system.

One fundamental assumption of most radiometric compensation techniques is that the camera is placed where the viewer is. This assumption is not true when the viewer is allowed to move freely while the camera is fixed to the projector. Consider further the case where the projection surface is reflective. Specular highlight would appear on the projection surface and easily ruin the projection quality [44]. As the position of the specular highlight changes with the viewer's position, any radiometric compensation technique that assumes a fixed viewer configuration would fail to compensate for the effect of highlight on image appearance. Fig. 4 shows an example with viewing angle defined in Fig. 5. The technique developed by Kao et al. [41] can estimate the



(a) (b)

(c) (d)

Fig. 6. Chromatic Vasarely illusion. A repeated cross-shaped pattern is superimposed on a uniform background image of four different colors. The color of the cross-shaped pattern is gray, but it illusorily appears to be (a) yellow, (b) blue, (c) cyan, and (d) magenta [45].

specular highlight seen from any position and achieve view-dependent compensation without moving the camera.

C. *Adaptation of HVS*

It is necessary to consider the properties of HVS in the compensation process as well because the ultimate judge of projection quality is human, not camera.

The radiometric compensation methods described above are based on the assumption that two images with exactly the same luminance and color would appear the same. This assumption, however, may not be true. In fact, our eyes have the capability to automatically adapt to the environment and have different perceptions of a color when it is surrounded by different colors. This HVS characteristic can be illustrated by the famous chromatic Vasarely illusion shown in Fig. 6(a), where the only colors used are gray (for the repeated cross-shaped pattern) and blue (for the background), but the gray repeated pattern appears to be illusory yellow to our eyes. Similar illusions can be observed in Figs. 6(b)-(d). Such color adaptation capability of human eyes has to be considered for mobile projectors because the mobile projectors are usually used for short-range image display, creating a viewing scenario similar to that of the chromatic Vasarely illusion. Wang et al. shifted the color of compensated image toward the color of the projection surface to achieve better perceptual image quality [42]. A similar image enhancement technique was developed for traditional displays [43].

V. CONCLUSION

In this paper, we have reviewed existing radiometric compensation techniques for ubiquitous projection and discussed the technical issues associated with the limited gamut, resolution, and dynamic range of procam devices. Because the projection surface used for ubiquitous projection usually has a small gamut, the projection quality can be improved by optimizing the tradeoff between the out-of-gamut colors and the image brightness. To satisfactorily compensate for the texture of a projection surface, a procam should have sufficient resolution and dynamic range for the camera and the projector. In addition, it is pointed out that the viewing position and the color adaptation of HVS should be taken into consideration in the design of radiometric compensation techniques for mobile projectors. The discussion on the various limiting factors of the procam devices leads itself to a useful guideline for the selection of suitable projectors and cameras to maximize the overall system performance.

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