Adaptive Radiometric Compensation on Deforming Surfaces

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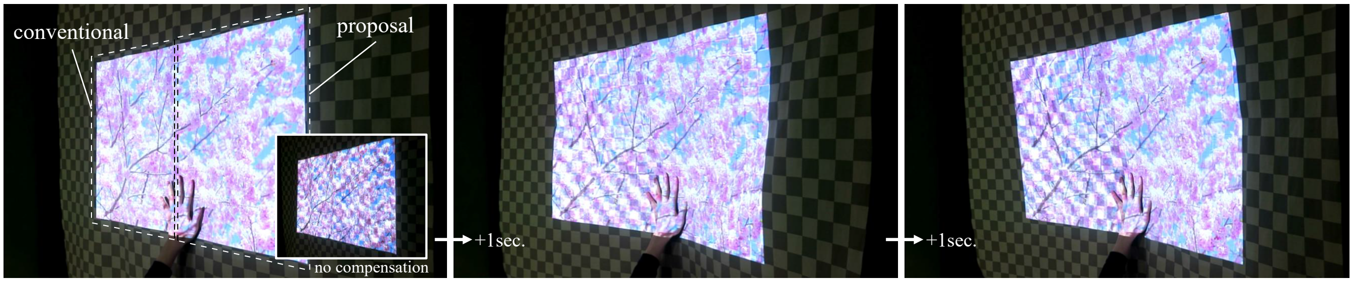

Figure 1: Radiometric compensation result for a curtain continuously deformed by hand. The left-hand side of each image is the result of using the initial inter-pixel correspondence, and the right-hand side is the result of using the proposed method.

ABSTRACT

In this research, we propose an adaptive radiometric compensation method, which uses only a projector and a camera, on continuously deforming projection surfaces. Radiometric compensation has been widely studied as a technique for making various objects usable as screens, by canceling out the influence of the color and pattern of the projection target. However, since it is necessary to continuously maintain the inter-pixel correspondence between a projector and a camera, to date, the projection target has been limited to stationary objects. Therefore, we propose a method to estimate the inter-pixel correspondence in real-time, using only a normal projector and camera. The method expands the scope of application of projection mapping greatly, by applying radiometric compensation to deforming clothes, and making them available as screens.

CCS CONCEPTS

• **Human-centered computing → Mixed / augmented reality**.

KEYWORDS

radiometric compensation, inter-pixel correspondence, response function, reflectance, non-rigid surface, deformation

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1 INTRODUCTION

In recent years, projectors, which have become popular as devices for projecting images on screens, have been used in various places without screens. This tendency is expected to accelerate in the future, with the spread of portable low-priced mobile projectors. It is strongly desired to project on non-rigid surfaces that not only have colors and patterns but also that deform freely. As an example, if it becomes possible to dynamically cancel out the color and pattern upon clothes worn by people and curtains used indoors, impressive effects can be generated in space production such as stage theater and entertainment in theme parks.

Conventional radiometric compensation has been performed using a projector-camera (ProCam) system. However, these systems are not good at projecting onto moving or deforming objects whose inter-pixel correspondence changes, therefore, special projection, measuring devices, and optical designs have been required [Zollmann and Bimber 2007]. Coaxial optics using a beam-splitter were expected to be a solution to that problem, but were found to be extremely incompatible with radiometric compensation, due to the limitation of placing the camera to halve the projected light. Hence, the scope of application of radiometric compensation has been greatly restricted.

2 PROPOSED METHOD

In this research, we aim to develop an adaptive radiometric compensation method that can be applied to continuously deforming non-rigid surfaces, by estimating the inter-pixel correspondence by using a simple ProCam. As a non-rigid object to be projected on, we assume a suspended flexible cloth such as a curtain. For radiometric compensation, we use the response function that was used in previous research. For the estimation of the inter-pixel correspondence, we use the reflectance estimated based on the response function, which is not affected by the projected image. In addition, since the number of target pixels for inter-pixel correspondence estimation

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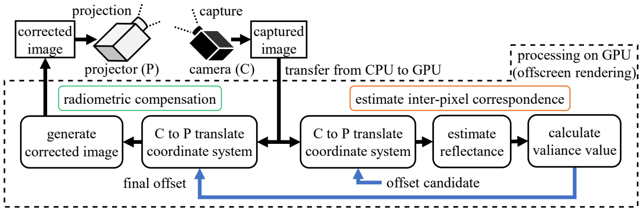

Figure 2: Overview of the proposed compensation process.

is enormous, we aim for real-time processing using a GPU. An overview of the proposed method is shown in Figure 2.

The response function used in our method is modeled on the method of Nayar et al. [Nayar et al. 2003]. The projector input value $\bar{\mathrm{P}}$, which is corrected to achieve the camera observation value $\bar{\mathrm{C}}$ (the correction target), is

$$\bar{\mathrm{P}}_{(u,v)} = \mathrm{V}^{-1}\left(\left(\mathrm{A}^{(t-1)}\right)^{-1}\bar{\mathrm{C}}_{m(u,v)} - \mathrm{E}^{(t-1)}_{m(u,v)}\right), \tag{1}$$

where t is the elapsed time, A is the reflectance of the projection surface, V is the color-mixing matrix, E is the environmental lighting, and m is the correspondence between pixels (u, v) on the projected image and the pixels on the camera image. The environmental lighting E is approximated by the initial measurement value, and the reflectance A can be estimated by the closed-loop method [Nayar et al. 2003] shown in Equation 2.

$$A_K^{(t)} = \frac{C^{(t)}_{K,(\tilde{u}^{(t)},\tilde{v}^{(t)})}}{\bar{C}_{K,(\tilde{u},\tilde{v})}} A_K^{(t-1)}, \quad (K = R, G, B) \tag{2}$$

$$\left(\tilde{u}^{(t)}, \tilde{v}^{(t)}\right) = m^{(t)}(u, v) \tag{3}$$

Equation 2 is a model formula that is generally used for radiometric compensation, but since the correspondence $m(t)$ changes with the passage of time, the reflectance cannot be obtained from this equation alone. Therefore, in the present study, this correspondence $m(t)$ is estimated using the information obtained at time $t - 1$.

In our proposed method, the inter-pixel correspondence $m(t)$ is estimated based on the algorithm of Hashimoto et al. [Hashimoto and Yoshimura 2020]. First, inter-pixel correspondence candidates are generated by shifting the pre-measured initial inter-pixel correspondence for each pixel by the expected offset along the epipolar line. Next, the reflectance is estimated from Equation 2 using these candidates for the inter-pixel correspondence. Finally, the optimal offset is determined from the estimated reflectance. If the inter-pixel correspondence is incorrect, the estimated reflectance will have many artifacts. In addition, the reflectance in the region near a point on the projection surface is relatively constant. Therefore, the offset that minimizes the variance value in the neighboring region of the reflectance generated for each offset candidate is used as the final estimation result. In our research, in order to estimate the inter-pixel correspondence in real-time for all pixels, we implemented all compensation processes using GLSL.

3 RESULTS

We performed the proposed radiometric compensation on an actual swinging curtain. The projected image was 1280×800 pixels, 4500 lm, and the camera resolution was 1920×1200. We used NVIDIA GeForce 2080 Ti for the compensation processing. The projection target was a curtain with a checkered pattern, which was forced to swing due to wind from a circulator. The actual curtain movement, which is the ground truth, was measured by optical motion capture.

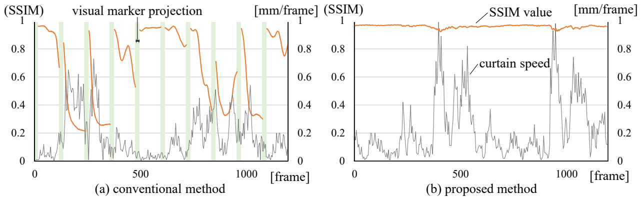

Figure 3: Correction accuracy for a swinging curtain.

Table 1: Processing time of proposed method.

		(ms)
processing item	$d = 1$	$d = 7$
transfer captured images to GPU	1.61	1.48
generate candidate	1.12	3.96
estimate reflectance	0.38	1.87
estimate offset	2.27	6.75
generate corrected image	0.73	0.60
total	6.12	14.67

Table 1 shows the processing time of the proposed system, where d is the search range for the offset ($2d$+1 points between pixels $-d$ and $+d$, inclusive). The minimum d was 1, and the maximum d that could be processed within the projector update rate of 60 FPS was 7. From the appearance of the actual compensation shown in Figure 1, the curtain pattern stood out on the entire surface when the inter-pixel correspondence was not estimated. On the other hand, the proposed method (d=6) greatly reduced this influence.

Next, we quantitatively evaluated the relationship between the continuously swinging curtain and the correction accuracy with the proposed method and the conventional method [Zollmann and Bimber 2007] using SSIM. This result is shown in Figure 3. Since the invisible markers in the conventional method were replaced with visible markers, the period for projecting them was excluded from the evaluation. From Figure 3, in the conventional method, the correction accuracy was high immediately after the start of SSIM measurement, but the accuracy gradually decreased after that. Whereas, in the proposed method, this reduction was greatly suppressed. In the future, we intend to expand the projection target in the proposed method to the clothes worn by moving people.

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