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Coded Aperture Optimization for Mitigating Aberration in Large-format Fresnel Lens towards Shadowless Projection Mapping

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ABSTRACT

Projection mapping (PM), a spatial augmented reality technique, allows multiple users to experience augmentation without wearing devices. However, when the users' bodies occlude projection lights, the projected imagery becomes completely invisible due to cast shadows. One approach to shadowless PM is to use a large-aperture (LA) projector that focuses projection light across a wide viewing angle with a large-format Fresnel lens. However, LA projectors often suffer from significant blur in projected images due to lens aberrations, stray light, and veiling glare. In this study, we address the projection blur by sequentially optimizing the coded aperture and the pre-sharpening process of the projection images. We designate a method for simulating the point spread function of the LA projector using differentiable ray tracing, optimizing both the coded mask pattern and the projection image. Finally, we validate the effectiveness of these techniques through simulation experiments.

Keywords: Fresnel lens-based shadowless projector, Coded aperture projection, Differentiable ray tracing

1. INTRODUCTION

Projection mapping (PM) enables multiple users to experience augmentations on a real object without wearing any devices. However, PM systems offten suffer from a cast shadows problem which leads to a partial loss of the projected results. Shadow suppression can be achieved by a large-aperture (LA) projection approach that uses a single projector equipped with a large-format Fresnel lens as the projection lens.[1,2] In the LA projection system, diffused light from a point source is widely spread onto the optical element and then focused onto the projection surface. This allows for shadow suppression by providing an aperture that is sufficiently wider than an occluder. However, projected results of an LA projector are known to be significant blurred. Due to its large aperture, the depth of field of an LA projector is shallower than that of a standard projector. Additionally, using a Fresnel lens for imaging application suffers from stray lights and veiling glare due to its surface profile.[3]

Therefore, in this paper, we apply the coded aperture approach, which has been widely used in the field of computational imaging, for an LA projector to enhance the software-based deblurring performance. We introduce a *coded LA projector*, which is attached a spatially-coded amplitude transmittance mask to the LA Fresnel lens. If considering only the frequency response characteristics, the optimal code pattern is narrow aperture like a pinhole. However, it significantly reduce the light transmittance in our LA projector setup. Therefore, we optimize the coded LA mask in terms of not only deblurring but also transmittance and shadow suppression.

2. METHOD

2.1 Differentiable PSF simulation for Fresnel lens

The proposed coded LA projector consists of an LA Fresnel lens and an attached mask. First, we formulate the surface profile of the Fresnel lens. A Fresnel lens is composed of concentric annular segments and have light-collecting characteristics as well as an ordinary refractive lens. Each annular segment is designed to have

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a common focal length, and the larger number of segments leads to a thinner form factor for a large lense. To mathematically model the surface profile of the Fresnel lens, we need to calculate the *apex angle* θ between the adjacent conical and cylindrical surfaces of each segment. Each annular segment is designed to collimate light incident on the bottom surface from a diffuse point source located at the focal length, utilizing refraction at the conical surface. In summary, we calculate the apex angle θ_k so that a ray entering the center of the planar surface of the k-th prism is emitted from the conical surface parallel to the optical axis.

A projector's PSF can be simulated by recording the intersection points on the projection surface of rays spatially-distributed from a point light source. We trace rectangularly distributed rays from a point on the light source plane $z = z_{src}$ based on Snell's law and vectorization. Let i, j denote the indices of these rays sampled along the horizontal and vertical directions on the source plane, respectively. We can determine the position $(x_{i,j}, y_{i,j})$ (decimal) where it intersects the projection surface. Next, the position (decimal) should be mapped to image space (integer); however, the rounding-off operation is non-differentiable. To avoid rounding and achieve differentiable ray tracing, we apply Gaussianization to each ray on the projection plane, and obtain the PSFs of our projector as the summation of these Gaussians.[4]

2.2 Optimization for Coded Aperture

The amplitude transmission mask image M ($\forall \mathbf{x}_1,\ 0$ [shielding] $\leq M(\mathbf{x}_1) \leq 1$|[transparent], $\mathbf{x}_1$: pixel coordinate for a mask image) in the proposed system should be optimized in terms of deblurring. Note that we assume that the mask is static in this study because it is not practical to implement a large dynamic mask for the LA Fresnel lens (Diameter of our lens is 500 mm). In order to make a static mask applicable to various projection contents, we perform PSF-based mask optimization. To accurately determine the PSF of a projection system, the PSFs should be obtained at all pixels in the light source plane ($z = z_{src}$) by emitting a large number of rays; however, this is computationally costly. Therefore, we uniformly sample $N_x \times N_y$ distinct points from the light source plane and obtained $N_x \times N_y$ corresponding PSFs on an object plane. Due to the limited GPU memory, only one PSF is calculated and the mask pattern is updated for each iteration in our implementation. The order in which each PSF was evaluated is randomly shuffled, and the mask is updated based on $N_x \times N_y$ PSFs in one epoch ($= N_x \times N_y$ iterations).

To evaluate the mask pattern, we propose the following loss functions, *MTF Loss* $\mathcal{L}_{MTF}$, *Transmission Loss* $\mathcal{L}_{trans}$ These losses are linearly added, and the final loss function for the mask optimization in a code LA projector is computed. The formulated optimization problem is described as follows:

$$M^* = \underset{M}{\arg\min} \quad \mathcal{L}_{MTF} + a\mathcal{L}_{trans}, \tag{1a}$$

$$\text{subject to} \quad \forall \mathbf{x}_1,\ 0 \leq M(\mathbf{x}_1) \leq 1, \tag{1b}$$

where a is a weight coefficients for $\mathcal{L}_{trans}$. To solve this optimization problem, Adam is utilized with a learning rate of 0.05. The initial value is a small aperture with a diameter equal to 1/2 of the Fresnel lens aperture diameter.

MTF loss: $\mathcal{L}_{MTF}$

MTF loss $\mathcal{L}_{MTF}$ is a loss function to make the system's frequency response more broadband. In each iteration, the simulated PSF h_M is evaluated by the following function:

$$\mathcal{L}_{MTF} = (-1) \times \text{mean}(\text{MTF}(h_M)), \tag{2a}$$

$$\text{MTF}(h) = \text{normalize}(|\mathcal{F}(h)|), \tag{2b}$$

where mean$(\cdot)$ is the operator for mean value of the image, normalize$(\cdot)$ is the normalization operator that sets a zero frequency value to 1, $|\cdot|$ represents the absolute value. The frequency response of the projection system can be made broadband by maximizing the mean value of the normalized MTF. In order to treat this maximization problem as a minimization problem, we use the product of (-1) as the loss function.

Transmission loss: $\mathcal{L}_{trans}$

If optimization is performed by focusing only on the spatial frequencies of the PSF, the resulting mask will have a narrow shape similar to a pinhole, and the light transmission efficiency will significantly decrease. In addition, when the projection ray passes only through the center of the mask, the shadow suppression performance also deteriorates. To evaluate where and how the mask actually transmits the projection rays, we introduce the *contribution map* λ. This is an intensity map at the bottom surface of the Fresnel lens of the projection rays that contributed to the PSF. Transmission loss guarantees that the amplitude mask does not shield more than the user-defined ratio τ of the projection rays. This contributes not only to transmittance but also to high shadow suppression performance. Specifically, it is calculated as follows:

$$\mathcal{L}_{trans} = \left(\frac{\mathrm{mean}(\lambda_M)}{\mathrm{mean}(\lambda_{\mathrm{open}})} - \tau \right)^2, \tag{3}$$

where λ_{open} is the contribution map when the all pixels of the mask M are 1 [transparent]. Note that $\mathrm{mean}(\lambda_{\mathrm{open}})$ is not always 1 due to total reflection occurred at the Fresnel lens surface.

2.3 Optimization for Projection image

First, we calculate spatially-varying PSFs in an object plane using the optimized mask M^* . Based on the PSFs, we then calculate compensation image for each depth plane. The compensation image I^* is calculated by the following optimization:

$$I^* = \underset{I_{z_k}}{\arg\min} \quad ||T - f(I)||^2, \tag{4a}$$

$$\text{subject to} \quad \forall \mathbf{x}_2,\ 0 \leq I(\mathbf{x}_2) \leq 255, \tag{4b}$$

where $\mathbf{x}_2$ is the pixel coordinate for a projection image. Equation 4b represents the dynamic range of the projector. $f(\cdot)$ is the degradation function based on the simulated PSF. The projection image is divided into $p \times q$ patches, and the degraded image is calculated using the $p \times q$ PSFs at the center pixel of each patch. The values of pixels in the degraded image where the PSF is not sampled are calculated using bilinear interpolation.[5]

$$f(I) = \left\{ \frac{\sum_p \sum_q s_{u,v}^{p,q}\ I_{deg}^{p,q}}{\sum_p \sum_q s_{u,v}^{p,q}} \right\}_{u,v}, \tag{5a}$$

$$I_{deg}^{p,q} = \mathcal{F}^{-1}\left(\mathcal{F}(h^{p,q})\ \mathcal{F}(I)\right), \tag{5b}$$

where $s_{u,v}^{p,q}$ is the bilinear interpolation coefficient at pixel (u, v), I is the projection image. To solve this optimization problem, Adam is utilized with a learning rate of 0.05, and the initial value is a target image T.

3. SIMULATION EXPERIMENT

3.1 Implementation

We implemented the above-mentioned differentiable optical simulator for optimizing the aperture pattern of the proposed system. We used a workstation equipped with a GPU (NVIDIA RTX A6000, memory: 48 GB) and CPU (Intel Xeon Platinum 8260, memory: 768 GB) for PSF simulations and optimization calculations (implemented in PyTorch).

3.2 Image Quality Assessment

We compared the deblurring performance of our method with baseline method using a taget image of 512 × 512 pixels. The comparison conditions consisted of six combinations of three aperture factors (w/o mask, random, optimized) and two projection image factors (w/o deconvolution, w/ deconvolution).

The projection images and projected results for each condition are shown in Figure 1. The image quality of the projected results were evaluated using Structural SIMilarity (SSIM). Overall, the resolution and contrast

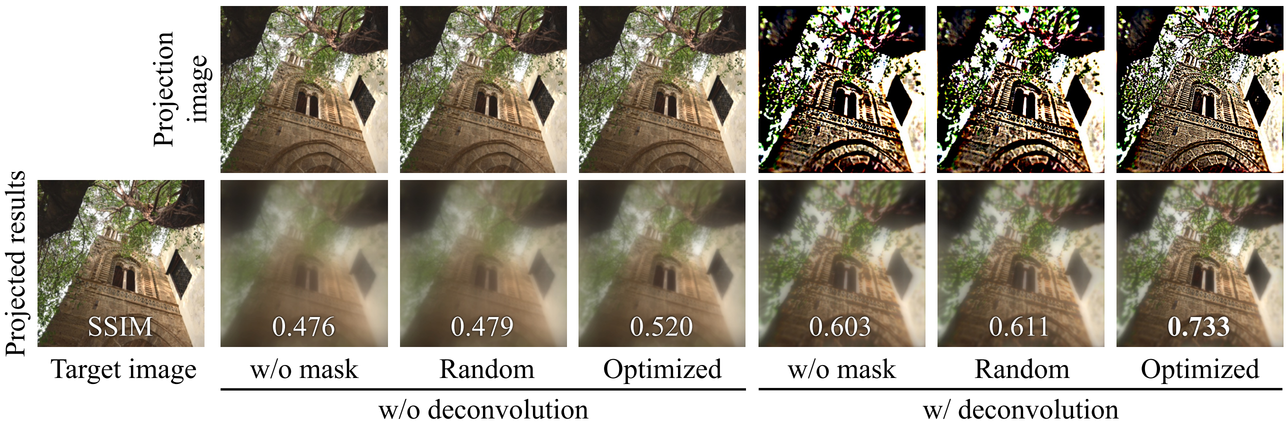

Figure 1. Comparison of projected results with baseline methods.

of the projected results were improved in the w/ deconvolution condition compared to the w/o deconvolution condition. Regarding the aperture factor, the w/o mask condition exhibited significant blur in the projected results leading to low spatial resolution and contrast. In the random condition, no significant improvement in spatial resolution or contrast was observed. On the other hand, the optimized aperture effectively suppressed blur more than the random condition, and achieved the highest evaluation score. Overall, these results provide objective evidence that projections aligned with the designed objective function have been achieved, and validate the deblurring performance of the proposed mask optimization framework.

4. CONCLUSION

In this study, we addressed the projection blur of the LA projector by sequentially optimizing the coded aperture and the pre-sharpening process of the projection images. As a result, we validated the effectiveness of these techniques through simulation experiments. For the future work, we will verify the effectiveness of the proposed method through projection using an actual prototype.

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REFERENCES

[1] Takeuchi, M., Kusuyama, H., Iwai, D., and Sato, K., "Projection mapping under environmental lighting by replacing room lights with heterogeneous projectors," *IEEE Transactions on Visualization and Computer Graphics* (2024).

[2] Kusuyama, H., Kageyama, Y., Iwai, D., and Sato, K., "A multi-aperture coaxial projector balancing shadow suppression and deblurring," *IEEE Transactions on Visualization and Computer Graphics* (2024).

[3] Bang, K., Jo, Y., Chae, M., and Lee, B., "Lenslet vr: thin, flat and wide-fov virtual reality display using fresnel lens and lenslet array," *IEEE Transactions on Visualization and Computer Graphics* (2021).

[4] Li, Z., Hou, Q., Wang, Z., Tan, F., Liu, J., and Zhang, W., "End-to-end learned single lens design using fast differentiable ray tracing," *Optics Letters* **46**(21), 5453–5456 (2021).

[5] Brown, M. S., Song, P., and Cham, T.-J., "Image pre-conditioning for out-of-focus projector blur," in [*2006 IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR'06)*], **2**, 1956–1963, IEEE (2006).