Adding an axially symmetric phase-coded mask and applying an appropriate metric to characterize image blur can provide distance estimates for individual images using a single camera.

Numerous techniques allow depth estimation using passive imaging systems. For instance, depth-from-disparity methods\(^1\) can perform passive depth estimation but need two cameras. The depth-from-defocus method\(^2\) is based on the concept that the blur radius of each defocused image is different. However, the defocus in front or behind the focal plane may have the same radius, which could cause ambiguities. Other methods include depth from automatic focusing\(^3\) and depth from automatic defocus.\(^4\) However, they require use of many images, which implies that they are time-consuming. Therefore, a compact depth-estimation system that only requires a single camera and a single image (but without being affected by ambiguities) would represent a breakthrough.

In recent years, novel passive systems allowing depth estimation from a single shot have been achieved with imaging systems that capture light fields, provided that appropriate post-processing techniques are applied.\(^5, 6\) Light-field technology usually requires a microlens array to capture the scene for different fields of view. It applies digital refocusing to the captured image to obtain depth information. Unfortunately, a tradeoff between spatial and angular resolution exists, and a lot of memory is required to store light-field data.

Our depth camera comprises a diffraction-limited optical system with an effective focal length of 6.9mm, an \(F/3.8\) focal ratio, a 60° field of view, and an axially symmetric phase mask (see Figure 1). We first introduce a new method to evaluate distances within a given range by employing a blur metric (BM). Since the BM is distance-dependent, we can design an axially symmetric phase-coded mask. In addition, the phase mask both increases the similarity of the point-spread function (PSF) across the full field of view and gives rise to a monotonic variation of the BM (within a given range) compared with the diffraction-limited system.

We optimized the phase mask using the ZEMAX optical software, combined with Matlab. The wavefront distribution, \(W\), of the phase can be expressed as \(W(x, y) = A(x^4 + y^4) + B(x^2y^2)\), where \(A\) and \(B\) represent the phase variance along the \(x\) and \(y\) axes and in the \(x-y\) coupling direction, respectively. Figure 2 shows the pseudorandom pattern used as our input image, the on-axis PSF at a focal distance of 100cm, and the simulated Figure 1. 2D layout of our depth camera.

Figure 2. (left) Pseudorandom pattern. (middle) On-axis point-spread function at a distance of 100cm. (right) Simulated image.

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**Figure 3.** Comparison between diffraction-limited and phase-coded systems. BM: Blur metric. V, H: Filters. The central wavelengths of the V and H filters are in the visible and near-IR regimes, respectively.

**Figure 4.** Calibration curve and best-fitting equation. x, y: Distance, BM.

To enhance the depth-estimation precision, we captured images at distances between 20 and 120cm in steps of 5cm and calculated the BM in both the horizontal and vertical directions. We subsequently averaged the BMs in both directions. Finally, we found the best fit to the BM-distance curve by employing a sixth-order polynomial approximation and used the best-fitting curve for distance calibration (see Figure 4). Our experiment was designed to evaluate distances at which sample images are located. We chose 16 distances randomly that were also different from those used for calibration, without knowing the actual distances but relying only on the best-fitting equation. Based on Figure 5, the worst precision occurred at distances of 99 and 113cm (≈5.56% mismatch), while the average precision was approximately 2.15%.

In summary, we have presented an optical-design method based on an axially symmetric phase mask that provides a monotonically varying BM for depth estimation and also increases the PSF similarity across the entire field of view. Using experiments and simulations, we demonstrated an appropriate BM for distance evaluation within a given range. The average precision of the resulting depth estimation was approximately 2.15%. Future study will focus on finding more appropriate phase masks, which would both maintain BM monotonic variations and increase the BM’s first derivative within a given range, which is required to achieve higher precision.
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