Towards Occlusion-Aware Multifocal Displays — Supplemental Material

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A IMPLEMENTATION DETAILS

In the section, we provide details in building our proof-of-concept ConeTilt display, which is shown in Fig. 9. Our prototype directly follows the schematic shown in Fig. 5 and is built with off-the-shelf components. We list the components in Fig. 19.

A.1 System Overview

The light comes from a green LED whose spectrum is centered at 520 nm. We put a diffuser in front of the LED and build a 1:3 afocal system to ensure uniform illumination on the DMD. After reflected by the DMD, the light is relayed by the first $4f$ system with $f = 100$ mm and passes through a light polarizer, which is used to enable the phase-only mode on the SLM. We set the target wavelength of the phase SLM to 520 nm. Since our phase SLM is reflective, we place a beamsplitter in front of the SLM. We use a pellicle beamsplitter to avoid the ghosting and optical-axis shift caused by cube- or plate-beamsplitters. This is only to simplify the implementation. The aperture of the second $4f$ system crops any light that exceeds the original range of the light cone. Finally, the light goes through the focus tunable lens and reach in eye/camera. The distance between the relayed phase SLM/DMD and the tunable lens is 58 mm. To control the focus tunable lens, we follow the implementation of Chang et al. [2018] and build a focal-length tracking system and the control circuit. Since the focus of the paper is on ConeTilt, we refer to their paper for the details. Note that the DMD micromirrors flip along their diagonal axes. To account for this, we rotated the DMD, the phase SLM, and the camera by 45 degrees.

A.2 Calibration and Alignment

To calibrate the system, we place a beamsplitter, between the second $4f$ system and the tunable lens. The beamsplitter forks the optical path for extra cameras without being affected by the tunable lens, and we remove the beamsplitter once calibration is completed. We connect two cameras (marked by blue in Fig. 9) — one focuses on the phase SLM and the other on the infinity (i.e., the aperture plane of the first $4f$ system).

In the following, we provide our calibration procedure.

(1) *Virtually Attaching the Phase SLM and the DMD.* We focus the calibration camera (blue 1 in Fig. 9) on the phase SLM and move the DMD till it is in sharp focus. Note that the phase SLM pixels are transparent, and this makes the calibration process more difficult.

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- (orange 1) DMD (TI DLP 7000)
- (orange 2) 1st circular aperture (Thorlabs SM1D12C)
- (orange 3) pellicle beamsplitter (Thorlabs CM1-BP145B1)
- (orange 4) linear polarizer (Edmund Optics 86-178)
- (orange 5) phase SLM (Holoeye LETO)
- (orange 6) 2nd circular aperture (Thorlabs SM1D12C)
- (orange 7) field lens (f=60mm)
- (orange 8) focus tunable lens (Optotune EL-10-30)
- (yellow 1) LED (LED Engin LZP-L4MD00)
- (yellow 2) 1:3 afocal relay (30mm Thorlabs AC254-030-A : 100mm Thorlabs AC254-100-A)
- (green 1) 1:1 4f relay (100mm : 100mm, Thorlabs AC254-100-A)
- (green 2) 1:1 4f relay (100mm : 100mm, Thorlabs AC254-100-A)
- (blue 1) calibration camera
- (blue 2) calibration camera
- (purple 1) focal length tracking optics
- (purple 2) focal length tracking circuits

Fig. 19. **Components used in our prototype.** Please cross-reference Fig. 9 for the color encoding and numbering.

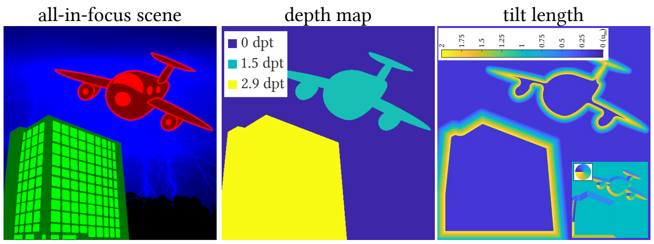
Fortunately, we find that when the input polarization of the SLM is in 45 degree with respect to its long axis, the SLM operates in amplitude mode and enables us to display visible patterns. The trick makes the calibration process more accurate.

(2) *Adjust the Tilt of the Phase SLM.* We temporarily mount a mirror on the unused side of the beamsplitter B1, focus the camera at infinity, and close the aperture of the first $4f$ system to the smallest. The small aperture enables us to send narrow beams toward the beamsplitter. When the phase SLM and the mirror have different tilting angles, the camera will see two copies of the beam (one from the mirror and the other from the SLM), and we adjust the tilt of phase SLM to overlap the two copies.

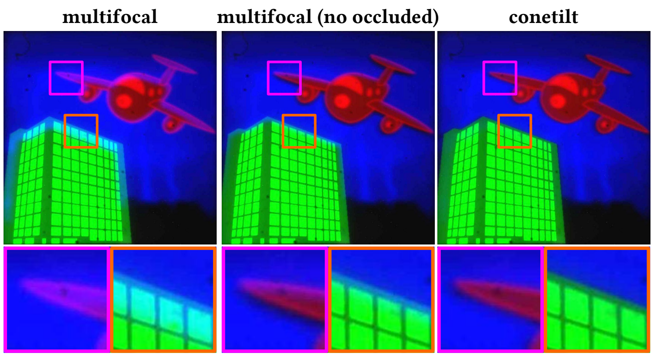
(3) *Aperture of the first $4f$ System.* We use the calibration camera focusing at infinity to adjust the aperture size of the first $4f$ system (i.e., the size of the light cone). Since the size of the light cone is limited by the capability of the phase SLM to tilt light, we show the phase SLM to help the calibration. We display an all white image on the DMD and tilt all pixels by $2u_m$ in the same direction. With the second aperture open, by changing the tilting direction, we adjust the aperture location and size till the tilted light cones touch the boundary of the original light cone in every direction.

(4) *Aperture of the second $4f$ System.* After finishing the last step, we adjust the location and the size of the aperture so that the entire cone is cropped when tilted by $2u_m$ toward every direction.

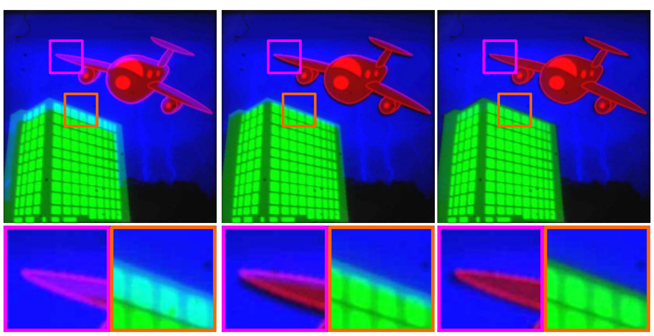
(5) *Placing the Field Lens.* Since the DMD is virtually relayed by the $4f$ relays, it makes adjusting the position of the field lens slightly trickier. We put a camera at the output side and focus the camera on the virtual copy of the DMD before placing the field lens. The



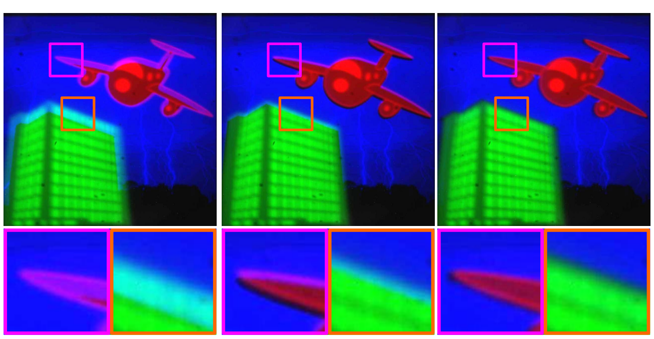
(a) Scene and tilting vectors



(b) Camera centered, focused on the building



(c) Camera centered, focused on the airplane



(d) Camera centered, focused on the background

Fig. 21. **Lightning (RGB).** The figure shows the captured results of the lightning scene (Fig. 13 in the paper) with the fore-, middle, and background displayed in different color channel. Note that while each color channel is captured separately, they share the same phase function.

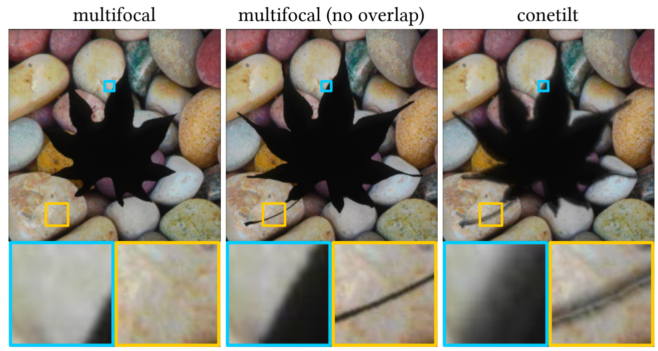


Fig. 20. **Leaf (background)** The figure shows the captured results of the leaf scene (Fig. 16 in the paper) when the leaf in the foreground is colored in black. The camera focuses on the background.

position of the field lens is chosen to maximize the sharpness of DMD. The focal length of the field lens is 60 mm.
(6) *Adjust the Position of the Tunable Lens.* The distance between the focus tunable lens and the field lens is determined by the focal length of the field lens and is very important. Since the default tilt implemented by the field lens makes light cones of all pixels to overlap at the focal plane, we first focus a camera on the output side on the focal plane where we see a sharp cone. We then place the tunable lens at the location where the cone is sharpest.
(7) *Find Pixel Correspondence between DMD and Phase SLM.* To find the pixel correspondence between the DMD and the phase SLM, we focus the camera on the phase SLM (and the DMD, since they are colocated.) We label the patterns shown on the phase SLM and the DMD and use the results to calculate the pixel mapping. We then resample the phase function according to the correspondence to display on the phase SLM.

Note that the spatial resolution is preserved only when the phase SLM is perfectly colocated with the DMD and is optically thin. In our prototype, we observe a small loss ($\sim 1.5\times$) in spatial resolution.

B MORE RESULTS

Fig. 20 shows the captured results of the leaf scene when we color the leaf in the foreground with black and focus the camera on the background. This enables us to examine the contribution from the background. As can be seen, the multifocal display is unable to prevent the content behind the leaf to be seen. This results in an illusion of a smaller foreground leaf. When we remove the directly-occluded regions, since the camera focuses on the background, the occluding boundaries are in sharp focus. This creates a false illusion that there is a black leaf on the background. In comparison, ConeTilt is able to blend the occluded regions automatically, which is closer to what we see in reality.

Finally, Fig. **??** shows the lightning scene in three colors — where we display the airplane, the building, and the background entirely in the red, green, and blue channel, respectively. This enables us to examine the light leakage from each focal plane more easily.