Depth Camera Using High-Transmittance Off-Axis Dual Electro-Optical Irises

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Abstract: A depth camera prototype with high-transmittance off-axis dual electro-optical (DEO) irises is proposed. Our DEO irises are switchable through the polymer dispersed liquid crystal, and exhibit the advantages of low cost, easy fabrication, and higher transmittance compared to the traditional liquid crystal shutters. The transmittance of our device is near 75% when the driving voltage reaches about 30 V. The principle of depth measurement of our system is based on a pair of stereo images, which are captured through the left and right irises, respectively. The depth is calculated from the shifts of features between the two images. The DEO iris design, fabrication process, and depth camera prototype are demonstrated, and experimental results using our depth camera verify reliable performance for the depth measurement. Our DEO iris system therefore provides potential applications in depth sensing.

Index Terms: Depth camera, polymer dispersed liquid crystal, electro-optical device.

1. Introduction
The depth camera is an important optical apparatus to sense the distances in environments [1], [2]. In modern days, the applications of depth cameras have been seen in daily life, such as the synthetic depth of field in mobile phones [3]–[5], 3D mapping in autonomous driving [6], [7], and face recognition [8]. Depth cameras can be classified into two categories: active and passive. In active depth cameras, “time-of-flight (ToF)” and “structured illumination (SI)” are the most popular approaches with thorough studies, and still attract the attention from research communities. ToF utilizes a laser scanner to scan the environment and infers the depth map from the phase differences between the emitted and received signals [9]. The advantage of ToF is its high speed thanks to laser scanning, whereas the limited working distance and weak detection capability over transparent objects are the major demerits [10]. In SI, analysis based on the spatially and temporally coded patterns can render the depth information [11], [12]. A specific combination of patterns can be utilized to generate a precise depth map with high resolution. However, distortion of the illumination patterns would introduce higher uncertainty so that the accuracy of depth is reduced. In addition, the exposure time is typically long. Although these active approaches show several attractive merits, they have a major disadvantage that the detection of reflected light is highly susceptible to ambient light. The high computational complexity to demultiplex the image sequence in SI and sparse-to-dense depth completion for ToF are also existing challenges [11], [13].
Among the passive sensing approaches, the most common one is to use a stereo camera [14]. A stereo camera utilizes two sub-cameras to capture a pair of stereo images, i.e., an image pair with left-right parallax. One can then infer the depth from disparity, i.e., shifts of patches/features between the image pair, based on numerical methods and geometrical optics. The distance between these two sub-cameras is the stereo baseline which determines the farthest distance a depth camera is expected to sense. One alternative to such a stereo camera is using a combination of a single image sensor and off-axis dual irises [10], [15], [16]. A triangular geometry, similar to that between the object and two sub-cameras, can be found with this combination. Using only a single image sensor and, sampling at the aperture position, i.e., where we install the dual irises, one can generate a stereo baseline, which satisfies the requirements to estimate depths with the corresponding optical design [17]–[19]. Therefore, the off-axis dual irises are the key for a depth camera with a single image sensor. In the literatures, color-filtered dual irises were introduced to capture the stereo images in one shot [15]. However, the separation of color channels may result in very different grayscale intensities between the two stereo images. The disparity error due to this effect is significant so that the estimated depth would deviate drastically [10]. An alternative approach is using a liquid crystal panel to generate stereo images with the same color response [10]. The liquid crystal panel, placed at the optical aperture, had dense grids, and was switchable by adjusting voltage to sample the light on the aperture. This method improves the robustness of depth measurements compared to the apparatus of color-filtered dual irises. However, the major demerit is that the liquid crystal panel typically has low transmittance because it is sensitive to polarization. In addition, the dense grid on the panel generates multiple images due to diffraction, resulting in degraded image quality.

In this paper, we introduce a new depth camera with off-axis dual electro-optical (DEO) irises based on the polymer dispersed liquid crystal (PDLC). PDLC is a reliable material to control the transmittance of light or illumination, and has been applied in light shutters [20], displays [20]–[22], diaphragms [23], [24], and digital photography [25]. To the best of our knowledge, this is the first stereo depth camera utilizing a PDLC component. Our module of DEO irises is compact with low cost and easy fabrication, and the irises are switchable by adjusting the driving voltage. Our device exhibits a transmittance of 75% at 30 V driving voltage amplitude and a 40 ms transition time. We embed our DEO irises into a digital single-lens reflex camera (DSLR) to build our depth camera prototype. The experimental results demonstrate that the depth camera with our DEO irises has reliable depth measurement capability. We expect our DEO irises and depth camera system has the potential to advance the field of depth sensing.

This paper is organized as follows. Section 2 introduces the design and fabrication process of the DEO irises, and Section 3 introduces the optical layout and principle of the depth camera. Section 4 presents the experimental results and our conclusion is discussed in Section 5.

### 2. Device Design and Camera System

Fig. 1(a–d) illustrate the fabrication process of DEO irises. First, three rectangular 2 cm × 3 cm ITO (Indium Tin Oxide) glass substrates are arranged as shown in Fig. 1(a). Next, we insert eight spacers (Polyethylene Terephthalate: PET) between the ITO glass substrates to create a space for PDLC. The thickness of each spacer is 12 μm. The positions of the eight spacers are illustrated in Fig. 1(a). After we mix the E7 liquid crystal and NOA65 (Norland optical adhesive 65, UV curable) with a weight ratio of 6:4 to form a liquid mixture, the mixture is injected into and fill up the gap between the ITO glass substrates. UV light is then shined to cure NOA65 with an exposure time of 300 seconds. After the curing process, the three ITO substrates and PDLC are integrated into a single electro-optical device. Last, a light blocking layer with two off-axis 2-mm holes is attached to the device.

The working principle of PDLC is based on the reaction of the liquid crystal molecules to the electric field. The molecule orientation of a liquid crystal sphere within the PDLC is random [Fig. 1(e)] when the driving voltage is below the threshold, typically about 5 V as shown in Fig. 2. In this phase, scattering due to index mismatching between the liquid crystal and polymer (cured NOA65) suppress the light transmittance significantly. When the driving voltage is increased
The fabrication process of DEO irises is shown in (a)–(d). (a) Setting the ITO glass substrates and PET spacer. (b) Injecting the PDLC liquid mixture into the space between the ITO glass substrates. (c) Curing PDLC using UV light. (d) Attaching a light blocking layer (paper substrate) with the two transparent holes. (e) The illustration of PDLC at off state. (f) The illustration of PDLC is at on state. (g) The depth camera prototype; our DEO irises are installed at the aperture location of the optical system.

Gradually, the liquid crystal molecules become more aligned with the direction of the electrical field. This leads to index matching between the liquid crystal and polymer, and reduces the scattering strength to increase the light transmittance. Fig. 1(e, f) illustrate how the PDLC device is tuned based on the above-mentioned mechanism. The schematic of our depth camera system using DEO irises is shown in Fig. 1(g), where only the right aperture is open. We install the DEO irises at the aperture location of a commercial lens assembly (Nikon: NIKKON 50 mm 1:1.4). In order to capture the pair of stereo images, the right and left iris will be switched on separately. The experimental results will be demonstrated in Section 4.
In order to measure the transmittances of the right and left irises, we use a laser with a wavelength of 633 nm and a power meter to measure the optical power. The curves of the light transmittance versus the driving voltage (1 kHz) amplitude are plotted in Fig. 2. The blue curve is the result for the left iris and the red curve is that of the right iris. One can observe that the two curves are almost identical, except for a slight difference within the transition region between 10 V and 20 V. The transmittance of each iris is saturated at about 78% after 40 V. In the following depth estimation experiments, we will fix the driving voltage amplitude at 30 V for both the right and left irises.

3. Principle of Depth Estimation

In this section, we introduce the principle of depth estimation using off-axis irises and a single image sensor. The simplified model of our off-axis imaging system is illustrated in Fig. 3. Deriving from the lens equation and triangular geometry, the object distance \( z \) can be estimated as:

\[
z = f \frac{f z_0 \Delta c_y - \alpha c_z (z_0 - f) \Delta y}{f^2 \Delta c_y + \alpha (z_0 - f) (f - c_z) \Delta y},
\]

where \( f \) is the focal length of lens assembly, \( \Delta c_y \) is the distance between the centers of left and right irises, and \( z_0 \) is the distance of the focal plane of the optical system determined by the sensor position [15]. \( c_z \) is the distance between the optical aperture position of the camera system and the place where we put the DEO irises. If there is a misalignment, \( c_z \) would be nonzero and can be estimated by fitting the measured data with Eq. (1). \( \Delta y \) is the distance (on the sensor plane) between the images of a certain point object at \( z \) captured through the left and right irises. The \( \Delta y \) in Eq. (1) is a distance. However, since the disparity is measured based on the disparity, i.e., shifts expressed by the numbers of pixels, we can transform \( \Delta y \) to “number of pixels” by introducing a scaling factor [15]:

\[
\alpha = \sqrt{WH/N_1 N_2}.
\]

\( W \) and \( H \) denotes the width and height of the effective sensing area of the camera sensor, respectively. \( N_1 \) and \( N_2 \) are the pixel number in the vertical and horizontal directions of the camera sensor, respectively. These four parameters are fixed by the vendor.

Using Eqs. (1) and (2), we can estimate the distance of the object by finding the shifts of certain features and then calculating the depth of each feature. In previous work using dual color filters [15] or a liquid crystal aperture [10], only one target is used at a time and its depth is calculated. Moreover, these approaches might fail to generate the disparity map because the color filtering may result in missing features in the images and the liquid crystal panel produces ghost images due to diffraction from the dense grid. In our work, we generate the disparity map from a pair of stereo
images. The image quality using PDLC is sufficient to render the disparity map. To generate a disparity map, we apply the algorithm in [26]; disparity is searched between a pair of stereo images under a optimization framework, and a non-local weighted median is applied as a regularization to remove the outlier disparity value. This process is executed under an image pyramid from coarse to fine scale, and only disparity in the stereo baseline direction, i.e., horizontal direction (y-axis), is considered. We will show the quantitative experimental results in next section.

4. Experiments
In this section, we demonstrate the experimental results of our depth camera using the DEO irises. The schematic of the system setup is shown as Fig. 1(g) and the system parameters are listed at Table 1. We capture the images of a scene consisting of plastic bottles lined up so that each is a different distance away from the depth camera. The depth of each plastic bottle is known in advance as the ground truth. The pair of stereo images are shown in Fig. 4(a) and 4(b). According to Fig. 2, there will be light leakage from the off iris; however, the transmittance at the off state (0 V) is only about 1.5%, which is a small amount. Since the main factors to influence the accuracy of depth sensing are the focal length, distance between dual irises, and system alignment, the influence of such light leakage can be ignored. In addition, one can observe that the images in Fig. 4(a, b) have color distortion and dark corners. The dark corners are due to vignetting. Vignetting arises

### Table 1
System Parameters of the Depth Camera Using DEO Irises

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>$f$ (mm)</td>
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<tr>
<td>$\Delta c$ (mm)</td>
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<td>$c_z$ (mm)</td>
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<td>$H$ (mm)</td>
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<tr>
<td>$N_2$</td>
<td>2848</td>
</tr>
<tr>
<td>$a$</td>
<td>0.0055</td>
</tr>
</tbody>
</table>
from the light blocking, aberrations and failure of cosine-fourth law, and leads to non-uniform light transmittance (to the sensor) across the entire scene [27]; the corners usually exhibit the lowest transmittance. The color distortion could be due to the wavelength dependence of the transmittance of the PDLC device and insufficient exposure time. However, since the color distortion is not serious, and the degrees of distortion in the two stereo images are comparable, the images still meet the requirements for computing the disparity map.

Since the gray plastic bottle (number 5) in Fig. 4(a) and (b) is near the focal plane, its disparity is only a few pixels. By contrast, the red plastic bottle (number 1) is farther away from the focal plane; therefore, we can observe that the shift of the red plastic bottle is much more prominent. Two yellow dashed reference lines are added in the figures for easier observation. In Fig. 4(b), the red bottle cap obviously shifts away from the reference line. The disparity map obtained using the algorithm in [26] is shown in Fig. 4(c), which is related to the depth map through Eq. (1). A darker blue denotes a nearer depth, whereas a farther distance is represented by a lighter blue. In addition, one can observe that each plastic bottle has a different disparity color. In Fig. 4(d), we plot the curve of the disparity versus depth according to Eq. (1). The red triangles show the measured disparities of all the bottle caps from disparity map in Fig. 4(c), with their distances known (measured by a ruler) as the ground truth. The red triangles are situated tightly along the curve calculated from Eq. (1), verifying the accuracy of our depth measurement approach using our DEO iris depth camera.

The range of depths that a depth camera can detect is also a concern. A depth can be determined only when the disparity of an object at the depth can be observed. The relationship between the object distance \( z \) and disparity \( \Delta y \) is nonlinear according to Eq. (1), as shown in Fig. 5. When an object gets too close to the camera, the disparity between the stereo images increases dramatically with decreasing the distance; this implies that an object may not be captured in both stereo images (occlusion) and the depth cannot be calculated. On the other end of the curve, the disparity changes only slightly with the distance, making it difficult for the camera to keep its depth resolution. With the system parameters listed in Table 1, when the distance of an object goes beyond \( \sim 100 \) cm, the change of disparity is less than a pixel with a depth change of 1 cm so that the depth resolution becomes poor. If the distance goes below 10 cm, serious occlusion occurs. Modifying the system parameters, such as the focal length, distance between dual irises, and pixel size, can change the working depth range.

5. Conclusion
In this paper, we present a depth camera using off-axis DEO irises. The DEO irises are switchable and designed for capturing stereo images. Compared with the approach using simply the liquid crystal, our irises are fabricated with PDLC to offer higher transmittance (75% at 30 V voltage amplitude). While the liquid-crystal-based device used a display panel and introduced ghost images
due to diffraction from the dense grid, our system with our DEO irises does not produce such an effect. Since the DEO irises can be turned open in turn, it is not necessary to separate the color channels as what was implemented in the color-filtering strategy in which a color object may not be captured completely in the stereo image(s). These advantages improve the reliability of depth measurement. Our system has demonstrated reliable depth estimation performance and sufficient image quality to generate the disparity map. Our future work includes a portable version of our DEO iris depth camera to provide more flexibility.

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References