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Compact Light-Field Camera with Extended Depth-of-Field Using Electrically Depth-Switchable Geometric Phase Lens

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Abstract

We propose a geometric phase lens-based light field (GPL-LF) system that provides extended depth of field (DoF) and enhanced LF resolution by utilizing the polarization-dependent depth-switching operation with the geometric phase lens (GPL). The GPL-LF system enables user's selective directional view or depth-reconstructed images with overcoming the traditional trade-off relationship between the achievable LF resolution and DoF in conventional LF imaging systems operated with passive lenses.

Author Keywords

light field camera; extended depth of field; polarization-dependent lens; geometric phase lens; vari-focal lens.

1. Introduction

Light field (LF) systems enable effective three-dimensional (3D) image reconstruction by simultaneously acquiring spatial and angular information of volume objects. The key optical component facilitating the implementation of such LF systems is the micro lens array (MLA), which functions like multi-camera array, providing angular image sampling of LF data that can be utilized for depth estimation, multi-view image generation, digital re-focus adjustment, and 3D image reconstruction.

However, conventional LF systems suffer from limited depth ranges (or depth of field: DoF) or LF resolution of elemental image sets. These two characteristics have optically trade-off relationships between each other because they are determined by an employed MLA and an objective lens condition [1]. To address this limitation, tunable optics can be employed at either MLA or objective lens parts [2]. In the former case of using a focus-tunable MLA, image degradation issues by overlapped LF image sets cannot be avoided without re-adjusting optical distance condition between the MLA plane and the image sensor plane at focal length switching, which is hard to construct in a compact module form-factor [3]. On the contrary, since the 3D elemental image sets by the MLA can be obtained by imaging not the objects directly but volume imaging results that are floated by the object lens, thus, the DoF condition of the LF imaging optics can be extended by adopting the tunable optics at the objective lens part [4]. Previously, it has been reported that the implementation of focus-tunable zoom lens can effectively improve the achievable DoF condition without sacrificing spatial resolution in the LF imaging system [5]. However, adopting a considerably heavy and bulky zoom lens significantly undermines, probably, the greatest advantageous point of the LF imaging optics—the ability to obtain 3D image information with a compact module form-factor configuration [6].

In this study, we propose a geometric phase lens (GPL)-LF system that utilizes a GPL as the main objective lens, where the GPL is employed for focus-tunable lens for enhancing the DoF in

LF imaging. On the contrary with the previous zoom lens module, the DoF enhancement can be provided at a thin, lightweight, and small volume of form-factor [7]. The GPL can function in two distinct focusing states at a single lens module: polarization-dependent convex and concave lens by the geometric phase modulation effects. By stacking the polarization-dependent focus-switchable GPL and the LC-based polarization switching unit, multi-focusing steps can be obtained at the objective lens part [8]. This approach enables LF data acquisition for 3D image reconstruction across a wide depth range without spatial resolution degradation, while simultaneously achieving an enhanced form factor.

2. Proposed method

The geometric phase (GP) effect is phenomenon in which a spatial relative phase difference occurs at the exit plane of geometric optics compared to the incident wavefront, resulting in modulation of the output wavefront due to the spatially distributed optic axis of the anisotropic material like liquid crystals or reactive mesogens. The GP component enables the implementation of optical elements with various functionalities of wavefront modulations according to the optic axis distribution of the anisotropic material. When the thickness of the anisotropic material satisfies the half-waveplate (HWP) condition, it achieves a wavefront modulation efficiency of 100% ideally at the designed wavelength. This allows for the creation of thin, lightweight, and flat optical elements. Additionally, by switching the handedness of the incident circular polarization state, an opposite phase difference can be induced at the output of the GP device, ultimately enabling its operation as switchable wavefront modulation optics. Among these, the GPL, designed with an optic axis distribution that follows a lens phase profile, can function as either a concave ($-f$) or convex ($+f$) lens depending on the handedness of the incident circular polarization, as illustrated in Fig. 1(a).

This study proposes a GPL-LF system, based on the architecture of a focused plenoptic camera, which combines the advantages of GPL and LF systems as illustrated in Fig. 1(b). The proposed GPL-LF system utilizes a compact GPL with vari-focal function as the main lens, thereby simultaneously enhancing both the DoF and the spatial resolution of the reconstructed 3D image. Moreover, the significant reduction in the volume and weight of the entire optical system enables the design of a highly practical LF system. To implement the varifocal function of GPL in a stationary form-factor, a GPL module with a layered structure consisting of a linear polarizer (LP), switchable half-waveplate (S-HWP), quarter-waveplate (QWP), and GPL was utilized. Consequently, the real object forms virtual image planes at two distinct central depth planes, and the LF system can obtain a 3D image on the distinct two depth ranges.

The depth estimation algorithm determines the appropriate patch size for a specific depth to render clear images at various depths. This involves calculating the shift of characteristic points in adjacent elemental images and using this information to estimate the depth, which subsequently guides the selection of the optimal patch size for the given depth.

For objects within the DoF, smaller patch sizes are selected as the object distance increases, resulting in accurately focused rendered images. However, for objects outside the defined depth range, the rendered images can become significantly blurred, even if the patch size is chosen correctly.

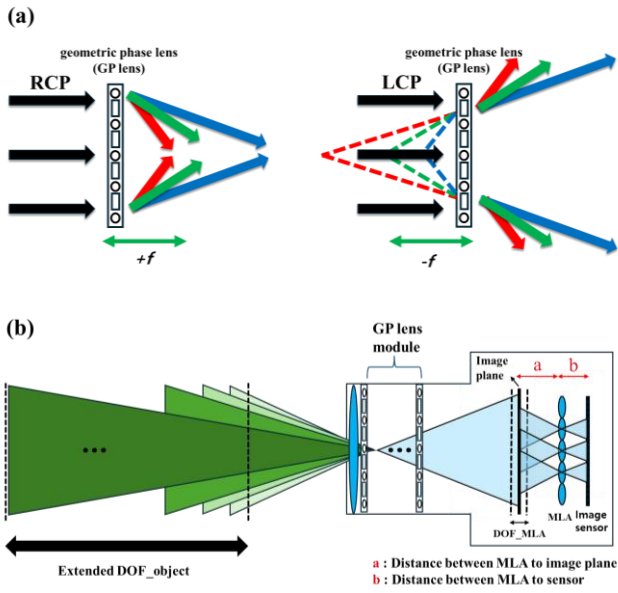


Fig 1. Schematic diagram of depth-enhanced light field imaging optics, operated by geometric phase lens (GPL) module: (a) the polarization-dependent chromatic focusing or defocusing properties of a GPL and (b) the proposed GPL-based LF imaging construction and optic design parameters.

3. Experimental results

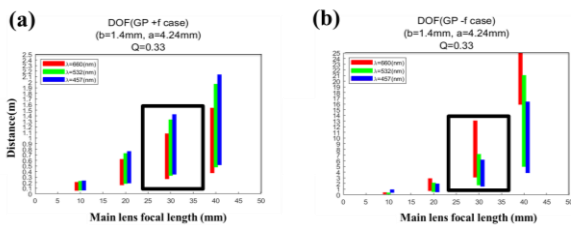


Fig 2. (a) Simulation analysis on depth of field (DOF) conditions according to focal lens designs of employed GPL as switchable objective lens: GPL operation as (a) convex lens (+f) and (b) concave lens (-f) modes.

When constructing the GPL-LF optic system and performing LF image analysis for 3D depth reconstruction, the wavelength-dependent focusing properties of the GPL should be properly considered. As shown in Fig. 1(a), the focal length condition of the GPL becomes shorter as the wavelength increases like diffractive optical elements or holographic optical elements. However, differently with conventional 2D imaging system that

cannot avoid the image blurring effects when optics with chromatic aberration is adopted, the focused plenoptic imaging system can render full color LF images when the volume images by the chromatic objective lens are floated within the depth ranges within the MLA for elemental image capturing. By using the depth-refocusing capability of the focused LF optics and post-imaging processing, the color-dependently different R/G/B elemental image sets can be rescaled and re-adjusted. By carefully overlapping these wavelength-specific images formed at different DoF conditions, it is feasible to design an objective lens condition exhibiting optimal depth ranges that support full-color LF imaging, as presented in Fig. 2. In this work, the focal length condition of the GPL used for the main lens was selectively designed and made as $f = \pm 30$ mm. In the image processing, chromatic aberration effects in the GPL are addressed by adjusting the patch size of the restored images from the R/G/B channels using a scaling factor derived from the wavelength-dependent GPL focal conditions. This adjustment significantly enhances color uniformity of reconstructed LF images [3].

Experimental setup of the implemented GPL-LF imaging optics following the focused plenoptic scheme is shown in Fig. 3(a). For proof of operation of full color LF imaging for an enhanced depth range, the imaging target condition of the object arrangements and relative distance conditions are presented in Fig. 3(b).

Fig. 4(a) presents the experimental results of the near-depth refocused view. In this configuration, objects within the near DoF range, from 0.34 m to 1.08 m, are refocused, while objects outside this range, particularly in the background, remain blurred. Fig. 4(b) shows the experimental results of the far-depth refocused view. In this configuration, objects within the far DoF range, from 3.07 m to 6.19 m, are refocused, while objects outside this range, especially in the foreground, remain blurred. Both results mean that the DoF range for the depth refocusing is highly limited at the single focusing condition of the objective lens. However, by applying the presented depth-switchable GPL as the objective lens, the synthetic image volume at the image plane can be extended and the DoF range for the 3D real object is also effectively extended. By applying multi-depth switching GPL module operatable over two depth planes, it is expected that extremely large DoF condition can be provided.

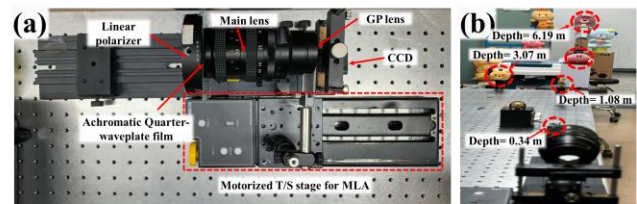


Fig 3. (a) Experimental setup of GPL-LF system. (b) The specific depth positions of the objects within the scene.

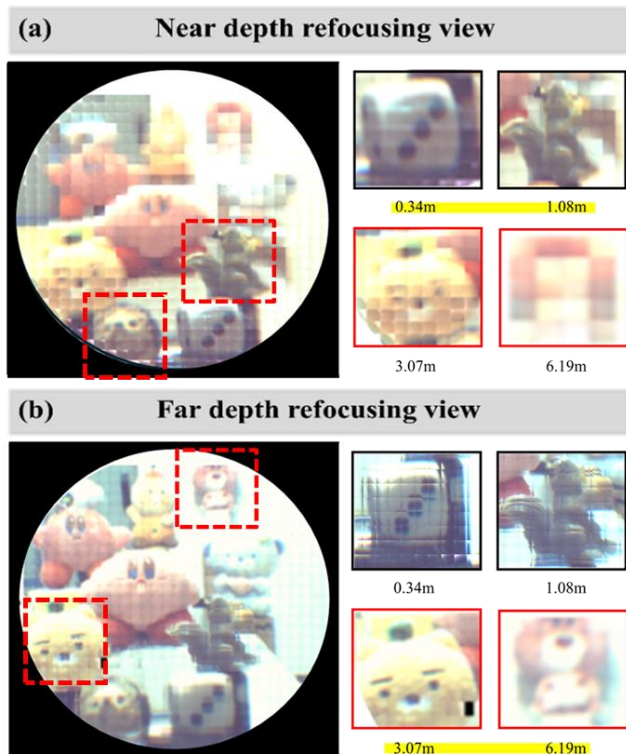


Fig 4. Depth-refocused images, reconstructed from the elemental image array sets with the implemented GP-LF optics: (a) near-depth refocusing results within a DoF range of 0.34 m to 1.08 m, (b) far-depth refocusing results within a DoF range of 3.07 m to 6.19 m.

4. Conclusion

In this study, we propose a GPL-LF system that addresses the challenges of limited DoF and resolution degradation by leveraging the lightweight, thin structure, and polarization-dependent depth-switching capabilities of the GPL. The GPL operates in two distinct lens modes of convex and concave wavefront modulations, depending on the polarization state of the incident light. The polarization-switching functionality of the voltage-driven LC cells and their stacking with the GPL module allows the DoF-extended focused plenoptic imaging system. In particular, to improve full color LF imaging results and achievable DoF ranges, the chromatic property of the GPL needs to be properly determined in switchable central depth plane design and applied in LF imaging processing steps.

5. Impact of Your Research

The typical trade-off relationship between the DoF and reconstructed image resolution in conventional LF imaging optics has been overcome by the presented multi-depth-switchable GPL-LF imaging system. Without compromising the form-factor, by adopting the ultra-thin and lightweight GPL as the objective lens unit, the proposed system significantly extends the depth range from 0.34m to 6.19 m for LF imaging data acquisition. In the future, the depth range can be further improved when considering the achievable depth number is exponentially increased with the 2^n relationship as the GPL stack is increasing with the n -layers. Among various LF design scheme, the focused plenoptic imaging design is most proper considering the color-dependent focusing properties of the employed GPL units. In

addition, to correct the chromatic aberration behaviors in the GPL, an optimal design of the central depth planes and an additional post-processing method are necessarily needed, but after these steps, the GPL-based focused plenoptic imaging optics can successfully full color LF results, featuring good color uniformity and depth-adjusted high-resolution LF images for a wide range of DoF condition. The detailed design rules will be discussed in the presentation.

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8-3 / H. Jeong • Distinguished Student Paper

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