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Computer-generated hologram calculation for real scenes using a commercial portable plenoptic camera

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ABSTRACT

This paper shows the process used to calculate a computer-generated hologram (CGH) for real scenes under natural light using a commercial portable plenoptic camera. In the CGH calculation, a light field captured with the commercial plenoptic camera is converted into a complex amplitude distribution. Then the converted complex amplitude is propagated to a CGH plane. We tested both numerical and optical reconstructions of the CGH and showed that the CGH calculation from captured data with the commercial plenoptic camera was successful.

1. Introduction

Holographic three-dimensional (3D) display is an attractive 3D display technique, because it does not require any glass and satisfies all depth perceptions in human visual systems. In those display systems, a computer-generated hologram (CGH) is calculated from 3D models and displayed on a spatial light modulator (SLM). If we want to calculate a CGH of real scenes under natural light, we have to capture 3D information of the scenes such as a depth map or multi-perspective images. Many studies have proposed techniques for achieving this purpose.

Integral imaging is a 3D imaging technique that records multi-perspective images of a scene by a lens array [1–3], and could be used to calculate CGHs for real scenes under natural light [4–12]. Recently, a system that captures 3D live scenes by integral imaging and reconstructs the live scenes by holography has been proposed [10]. In addition, an approach in which a CGH is calculated from dense sampled rays captured by integral imaging has been proposed [8,9,12]. This approach overcomes the resolution limitation of a 3D display based on typical integral imaging. Thus integral imaging is effective in CGH calculation for real scenes under natural light, although conventional integral imaging systems are relatively large and cumbersome because they often use a large lens array and a large field lens, and require precise alignment between the lens array, the field lens and a CCD/CMOS sensor.

In this study, we demonstrate a method to calculate a CGH for real scenes using a commercial portable plenoptic camera to achieve a compact and easy-to-use capture system. A plenoptic camera consists of a main lens, a micro-lens array and an image sensor, and can capture a set of multi-perspective images of a target scene [13–15]. This capture is based on integral imaging and the set of captured multi-perspective images is called the light field. A plenoptic camera can be constructed compactly compared to conventional integral imaging systems because the main lens de-magnifies a target scene on the micro-lens array. Additionally, plenoptic cameras have become popular and some products are inexpensive and commercially available, for example the Lytro [16] and R series produced by Raytrix GmbH [17]. They are small enough to be portable and require little care to calibrate themselves because alignment between the main lens, the micro-lens array and the image sensor in commercial plenoptic cameras is already performed. Therefore, by using the commercial plenoptic cameras we can easily construct a portable capture system to obtain light fields for CGH calculation. In our system, we use a first generation Lytro camera with size of $41(\mathrm{H}) \times 41(\mathrm{W}) \times 112(\mathrm{D})$ mm for CGH calculation.

Lee et al. have been proposed an approach for CGH calculation using a plenoptic camera [11]. Since this study uses a lab-made optical system as a plenoptic camera system, our study expands Ref. [11] and shows that not only a lab-made system but also common commercial products can be used for CGH calculation for real scenes under natural light.

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2. CGH calculation using a plenoptic camera

2.1. Overview of the CGH calculation

Fig. 1 shows an overview of the CGH calculation from a light field captured with a plenoptic camera. The plenoptic camera forms the intermediate image, which is a de-magnified image of the target object on the micro-lens array by the main lens, and captures the light field by sampling the intermediate image spatially and axially with the micro-lens array. In the CGH calculation from the light field, we used an approach using the ray-sampling (RS) plane [8,9]. An RS plane is a plane virtually set near a target object on which the rays from the object are sampled spatially and angularly. Since the sampled ray information is identical to a light field, we can apply light fields captured with a plenoptic camera to the approach using the RS plane.

The CGH calculation based on ray information has the problem that reconstructed images are degraded when an RS plane is not placed near a target object [9]. In a plenoptic camera, since the intermediate image is formed on the micro-lens array as shown in Fig. 1, the RS plane is located on the intermediate image. Thus we can obtain the dense ray information of the intermediate image, which results in preventing the degradation of the reconstructed image. However, it should be noted that since the intermediate image is the de-magnified target object by the main lens axially and laterally, the reconstructed image of the CGH is also de-magnified.

In the CGH calculation using the RS plane from a light field, the light field is converted into a complex amplitude distribution on the RS plane. This conversion is performed by 2D Fourier transform of each sub-image (i.e. an area under each micro-lens) of the light field, which is based on angular spectrum theory [18]. The light field has only intensity distribution and does not have phase distribution. Therefore, before Fourier transform, we multiply each of the sub-images by random phase distribution to equalize the power spectrum. This converted complex amplitude is propagated to a CGH plane based on wave optics to calculate the complex amplitude distribution on the CGH plane. Finally the complex amplitude on the CGH plane is superposed by a reference light so as to produce an interference pattern.

2.2. Lytro camera

Next we describe the process to apply data captured with Lytro to the CGH calculation discussed above. We used a first generation Lytro camera that has a 3280 × 3280 image sensor with 1.4 μm pixel pitch and 12-bit depth. The shape of the micro-lenses is hexagonal and its diameter is about 10 pixels (i.e. 14 μm). The sensor is covered with about 330 × 380 micro-lenses. In Lytro, the captured data are stored in an LFP or LFR file that has a raw image and JSON files. This LFP file can be parsed by tools [19]. We used *lfptools* [20] for extracting raw images from LFP files. Fig. 2b shows a raw image obtained by *lfptools*. As shown in Fig. 2b, the raw image consists of sub-images. In order to use the raw image as a light field, we must divide the raw image into a set of the sub-images. There are methods to divide the raw image including advanced calibration steps [19,21,22], but we divided the raw image by using manually estimated center points of each micro-lens. Finally we obtained a set of 10 × 10 pixels sub-images, the number of which is 330 × 380. As pixels at the edge of a sub-image are degraded by vignetting of a micro-lens, we used only the center 8 × 8 pixels in the sub-image.

As shown in Fig. 2b, the shape of the micro-lenses of Lytro is hexagonal, which means that the spatial sampling pattern of the light field is also hexagonal. In order to apply the light field to the CGH calculation easily, we converted the hexagonal spatial sampling pattern into an orthogonal one. In our system, this conversion was performed by resampling rays from a captured light field, which is based on light field rendering [23]. Although we converted the spatial sampling pattern, the resolution of the hologram reconstruction based on integral imaging with a hexagonal lens array is higher than the case using a rectangular lens array [24]. Thus our future work is to optimize the ray sampling pattern and ray resampling method.

3. Experimental results

3.1. Experimental setup

To verify the CGH calculation discussed above, we calculated CGHs from data obtained with Lytro and performed numerical and optical reconstructions of the CGHs.

Fig. 2a shows the experimental setup of capturing a real scene with Lytro. As shown in Fig. 2a, the captured scene consists of multiple planer objects placed at different distances. Object 1 and Object 2 are located at 100 mm and 500 mm from Lytro, respectively. We captured the scene by focusing on Object 1 using autofocus, which is a packaged function of Lytro. In the CGH calculation using the RS plane, when a target scene consists of multiple objects located at different distances, we need to capture multiple light fields by focusing on each of the objects to sample the dense rays and encode those light fields into a single CGH [9]. However, we used a single light field captured by focusing on Object 1 for the CGH calculation, because the plenoptic camera de-magnifies the scene by the main lens such that the axial magnification is

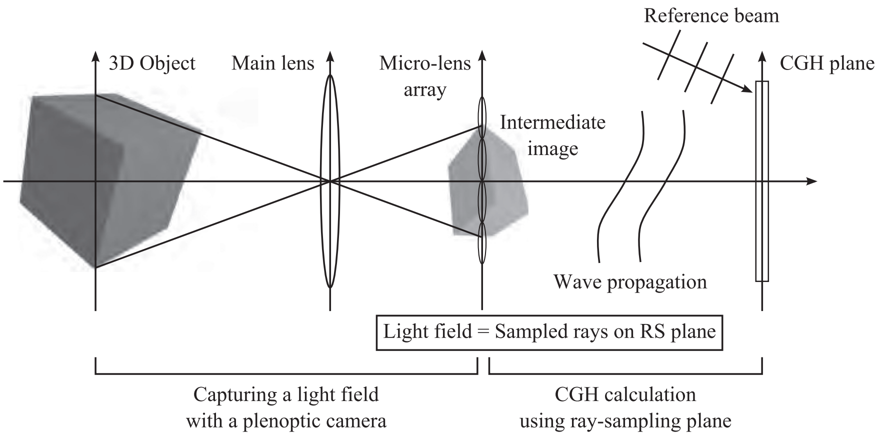

Fig. 1. Overview of the CGH calculation using the ray-sampling plane from a light field captured with a plenoptic camera.