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Three-dimensional visualization of objects in scattering medium using integral imaging and spectral analysis

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ABSTRACT

This paper presents a three-dimensional visualization method of 3D objects in a scattering medium. The proposed method employs integral imaging and spectral analysis to improve the visual quality of 3D images. The images observed from 3D objects in the scattering medium such as turbid water suffer from image degradation due to scattering. The main reason is that the observed image signal is very weak compared with the scattering signal. Common image enhancement techniques including histogram equalization and contrast enhancement works improperly to overcome the problem. Thus, integral imaging that enables to integrate the weak signals from multiple images was discussed to improve image quality. In this paper, we apply spectral analysis to an integral imaging system such as the computational integral imaging reconstruction. Also, we introduce a signal model with a visibility parameter to analyze the scattering signal. The proposed method based on spectral analysis efficiently estimates the original signal and it is applied to elemental images. The visibility-enhanced elemental images are then used to reconstruct 3D images using a computational integral imaging reconstruction algorithm. To evaluate the proposed method, we perform the optical experiments for 3D objects in turbid water. The experimental results indicate that the proposed method outperforms the existing methods.

1. Introduction

Integral imaging introduced by G. Lippman in 1908 is one of the auto-stereoscopic 3D imaging techniques. Integral imaging records the information of 3D objects through a lens array and also can display 3D objects. As shown in Fig. 1, elemental images are acquired through a 2D lens array in the pickup process. The recorded elemental images, called as elemental image array (EIA), are utilized to display 3D images in the reconstruction process [1–6]. The advantages of integral imaging include the use of white light source for color images, providing continuous perspective images, and full-parallax 3D display. Thus, integral imaging has many attentions in the area of the next-generation 3D image display.

Recently, 3D space sensing and visualization have been actively studied for various applications [7–13,23]. Among them, many researchers have studied the problem of scattering noise to effectively visualize 3D objects under scattering environments [7–8]. Attenuation of light by scattering reduces the image quality such as image contrast and brightness. Thus visibility enhancement under the scattering environment is required in various fields including underwater imaging, security, and medical diagnostics.

In fact, integral imaging has been considered as one of the interesting solutions for 3D visualization under scattering environments [9–13]. Several methods have been proposed to improve the image quality by removing scattering objects in computational integral imaging reconstruction. Among them, one method is to use the interference phenomenon between the ballistic photons getting through the scattering medium and the scattered photons. The 3D information of the scattered objects is recovered by superimposing a set of images using synthetic aperture integral imaging [9]. Another method is to use statistical image processing and computational integral imaging reconstruction algorithm to remedy the effect of scattering noises [10].

In this paper, we propose an image enhancement method based on spectral characteristics of a scattering medium for visualization of the degraded 3D images. To obtain high-resolution elemental images, we employ synthetics aperture integral imaging (SAII) that uses a camera array or a moving camera in the pickup process [13]. The proposed spectral analysis method analyzes the recorded elemental images to determine the degree of scattering. Our adaptive reconstruction

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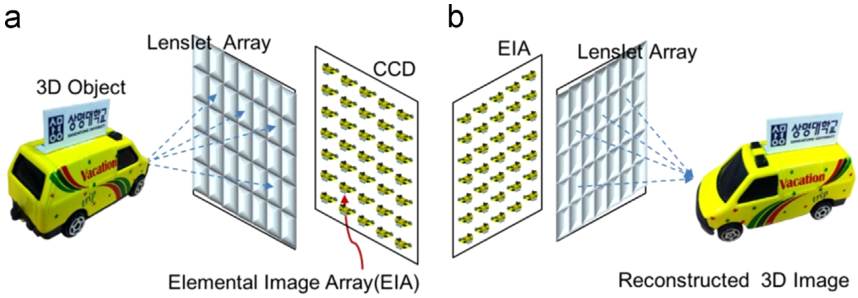

Fig. 1. Pickup and display/reconstruction of integral imaging.

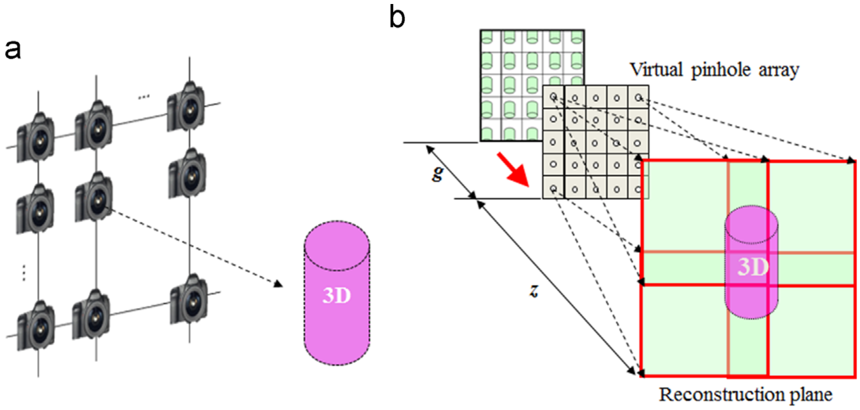

Fig. 2. (a) Synthetic aperture integral imaging (b) computational integral imaging reconstruction.

method removes the scattering signal from each elemental image according to the degree of scattering. Computational integral imaging reconstruction with the proposed method reconstructs improved 3D images due to reducing the effect of the scattering noises. To show the feasibility of the proposed method, optical experiments with turbid water are conducted and compared with existing methods.

2. Synthetic aperture integral imaging and computational integral imaging reconstruction

Integral imaging is a useful technique for 3D imaging and visualization. It consists of two processes: pickup and reconstruction. The pickup process of integral imaging can record 3D objects as elemental images by using a lenslet array or a camera array system [14–19,22–23]. The lenslet array provides a lot of low-resolution elemental images with single shot. On the other hand, the camera array provides small group of high-resolution elemental images, as depicted in Fig. 2(a). This is called as the synthetic aperture integral imaging (SAII) [14,22–23].

After recording the elemental images in the pickup process, a computational integral imaging reconstruction (CIIR) process is applied to the recorded elemental images in order to reconstruct 3D images volumetrically. The principle of CIIR is a reverse of the pickup process. In other words, a plane image at some fixed distance is reconstructed by the back-projection of elemental images through virtual pinhole array, as shown in Fig. 2(b). According to the distance of the reconstruction plane, the different plane images are generated.

3. Proposed method

This section describes the proposed reconstruction method based on integral imaging for improving the visual quality of 3D images under scattering. The method employs a pickup system with SAII to obtain high-resolution elemental images. It is assumed that the recorded elemental images suffer from scattering. Thus, those images need to be analyzed to eliminate the scattering medium. To do so, we introduce signal characteristics formulation based on the spectral analysis. The defined formulation enables an efficient method using the spectral analysis to reduce the scattering effect.

3.1. Formulations

The observed images for 3D objects under a scattering environment are seriously degraded due to the scattering noise. In this paper, we consider the spectral analysis based on signal model to remove the effect of scattering noise in the scattering medium. To do so, we introduce a signal model between scattering medium and the observed image. Let us consider the observed image signal $g(x)$ for 3D objects as a weighted linear combination of scattering medium $t(x)$ and original signal $f(x)$, which can be then represented by

$$g(x) = \alpha f(x) + (1-\alpha)t(x) \tag{1}$$

here, α is a scalar in the linear combination and we call it the visibility parameter α. This parameter depends on the scattering degree of the scattering medium. If $\alpha = 1$, $g(x)$ becomes original signal $f(x)$. This means that the object is not affected by scattering. On the other hand, it becomes the scattering signal $t(x)$ when $\alpha = 0$. Using the Fourier transform, Eq. (1) can be represented by

$$G(\omega) = \alpha F(\omega) + (1-\alpha)T(\omega) \tag{2}$$

where $G(\omega)$, $F(\omega)$, and $T(\omega)$ are the Fourier transformed signals of $g(x)$, $f(x)$, and $t(x)$, respectively. In order to reconstruct the signal $F(\omega)$ from $G(\omega)$, we need the estimation for both $T(\omega)$ and α. To do so, in this paper, we employ the spectral characteristic of the scattering medium for effective estimation.

Fig. 3(a) and (b) shows the examples for the typical image and the scattered image in a scattering medium. Their Fourier spectrums are