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# Depth-tunable three-dimensional display with interactive light field control

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ABSTRACT

A software-defined depth-tunable three-dimensional (3D) display with interactive 3D depth control is presented. With the proposed post-processing system, the disparity of the multi-view media can be freely adjusted. Benefiting from a wealth of information inherently contains in dense multi-view images captured with parallel arrangement camera array, the 3D light field is built and the light field structure is controlled to adjust the disparity without additional acquired depth information since the light field structure itself contains depth information. A statistical analysis based on the least square is carried out to extract the depth information inherently exists in the light field structure and the accurate depth information can be used to re-parameterize light fields for the autostereoscopic display, and a smooth motion parallax can be guaranteed. Experimental results show that the system is convenient and effective to adjust the 3D scene performance in the 3D display.

## 1. Introduction

With the development of 3D display, glasses-free 3D displays have attracted much more attentions. The 3D display with large size, high resolution and dense viewpoints were demonstrated [1–4]. However, it is difficult to present a perceptually pleasing 3D experience by directly displaying the multi-view content on the 3D display, because the acquired depth of the 3D scene does not fit well with the display capacity of display devices and the 3D salient regions in the reconstructed light field differ from one individual to another.

As the main depth cue for 3D scene perception is binocular parallax, the post-process to process the disparity information of multi-view contents is indispensable. However, the disparity compatibility problem is not fully considered in the 3D display and it is still underdeveloped for adjusting disparity structure for multi-view contents. Lei et al. extended the disparity handling method for two-view or stereoscopic display [5,6] to deal with the multi-view situation, which controlled the disparity of corresponding points in each view [7]. However, it is unpractical for the dense multi-view 3D display which contains tens of viewpoints. The disparity of each view is computed separately and it is hard to maintain a smooth motion parallax after the disparity control due to the error of disparity acquisition. Recently, a depth map assisted disparity control method for the multi-view content was presented, and the projection relationship between views was taken into consideration to decide the disparity between views [8]. Selected region was projected to other views to find its corresponding regions, and the disparity information of the region was obtained. The accurate disparity adjustment was done by shifting the image of each view respectively. However, it suffers from the same problem with [7] because the shift value for each view is also separately acquired and the reference region is only adjusted to the zero disparity plane (ZDP) in both works. Masia et al. proposed a 3D depth remapping method which took the depth reconstruction capability of display device into consideration [9]. The depth map was remapped to adapt the display device, but a side-effect of depth remapping was the virtual viewpoint distortion since the depth map was altered before DIBR [10]. Moreover, the most serious weakness in all the above previous works is that the knowledge of per pixel depth is indispensable when adjusting the disparity, and the knowledge is difficult and inconvenient to obtain, especially for real scene. The characteristics of the inherently structure of multi-view contents with the depth information are not fully considered in previous works.

Inspired by the analysis of light field [11,12], the depth-tunable 3D display is presented by controlling the dense light field. Benefiting from a wealth of scene information of the dense light field, the 3D display disparity control is possible without priori depth information of the scene, which eases the priori demand of multi-

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view content for disparity adjustment [8,9]. Different from previous works which shift the multi-view images according to the priori depth information, the proposed method handles the disparity by shifting multi-view images according to light field structure: EPI-strip introduced in the next section. With different image shift values, light field structures are different, which correspond to different disparities. Therefore, the proposed disparity adjustment method is not limited to adjust the reference region to ZDP. As the light field structure is formed by all the multi-view images, the depth information is estimated by statistically analyzing the linear pattern of the light field structure, which considers all the multi-view images as a whole and leads to a more accurate disparity estimation. The previous point pattern based methods not only estimate the disparity information separately: stereo-matching [5–7] or depth map [8,9], but also deal each image separately with the disparity adjustment. To break this independence, a linear regression disparity line is further proposed to represent the global depth information of the light field, and the disparity control process becomes a global operation, which improves the accuracy of disparity control and maintains robustness in the presence of disparity noise. Moreover, a smooth motion parallax is maintained with the disparity adjustment if the original multi-view content exhibits a smooth motion parallax. The rest of the paper is organized as follows, in Section 2 the concept of light field is briefly introduced, and then the depth expression in the light field structure and the basic light field structure control idea are explained. In Section 3 the detailed processes of the depth-tunable system are shown. In the experiment and discussion section, the effectiveness of the proposed method is verified and a depth-tunable 3D exhibition system is carried out to show the freedom of the disparity adjustment with the dense light field.

## 2. Depth expression in the three-dimensional light field

The light field concept was firstly proposed with a 4D function called the “Lumigraph” [11] and considered as the content form of free viewpoint TV (FTV) [13]. Here, instead of processing 4D light field, the 3D light field is processed since the content for the 3D display satisfies the horizontal parallax only stereo constraint.

Fig. 1 shows the representation of 3D light field, where Fig. 1(b) is a 3D light field, created from a set of multi-view images in Fig. 1(a). Each light ray in the light field $f(x, y, V)$ is parameterized with three parameters, where parameter $V$ denotes the discrete number of views, and $V=0, 1, 2,\ldots,N$ from leftmost view to rightmost view among the multi-view images. Parameters $(x, y)$ denote the intersection of the ray with the imaging plane. Different 2D sections of the 3D light field represent different 2D views that contain different information of the 3D scene. As shown in Fig. 1(b), a planar $x$-$y$ cut at particular $V$ results in the original multi-view image at the $V$th viewpoint and the $x$-$V$ cut represents epipolar plane image (EPI) which contains the depth information in the slopes of linear structures in EPI, as show in Fig. 1(c). The feature of EPI and the linear light field structure are presented in detail in Fig. 2. The model of pinhole camera array is given in Fig. 2, to simplify the 3D scene recording process only one-dimensional camera CCD is figured out. The linear position shift of pin-hole camera leads to a linear dependency between the location of cameras and projection coordinates in their CCD planes, and the dependency leads to the linear structure of EPI. That is to say, the projection of a 3D scene point in the epipolar plane is a line whose slope is related to the depth of the 3D scene point.

In the capture process, the disparity can be computed according to similar triangles,

$$\text{DISPARITY} = \frac{f\cdot\text{baseline}}{z} \tag{1}$$

where DISPARITY denotes the disparity between adjacent images, *baseline* denotes baseline of adjacent cameras, $f$ is the imaging distance and $z$ is the object depth. In the EPI, the slope of the linear light field structure corresponding to the 3D scene point $K$ can be computed as,

$$K = \frac{\delta v}{\delta x} = \frac{1}{\text{DISPARITY}} \tag{2}$$

There are two ways for disparity adjustment. In the capture process the disparity is proportional to the camera baseline, and adjusting the camera baseline can change the disparity value of multi-view images. In the capture post-processing stage, the disparity is inversely proportional to the slope, and the disparity value can be adjusted by shifting the multi-view image to change the slope of the linear structure. Similar with previous works, the camera baseline adjustment is inconvenient and the disparity adjustment is done at the capture post-processing stage. Moreover, only when the camera array is linear arrangement and the camera baseline is constant among the whole camera array, the light field structure is linear. Our method is applied to the multi-view content with linear viewpoint arrangement and with a smooth motion parallax originally, which are common and necessary for 3D display content. In summary, our basic idea of disparity adjustment is that the slope of the linear light field structure is adjusted meanwhile the light field structure maintains linear. Thus the disparity can be controlled without priori depth information and a smooth motion parallax can be maintained.

## 3. Depth-tunable 3D display system

The depth tuning process has three detailed processes: the reference region selection, slope acquisition and ZDP refocusing. The reference region selection and the slope acquisition processes are the preliminary work for disparity adjustment, which obtain the original slope value of the reference region. Then zero disparity plane of the 3D content can be refocused and the reference

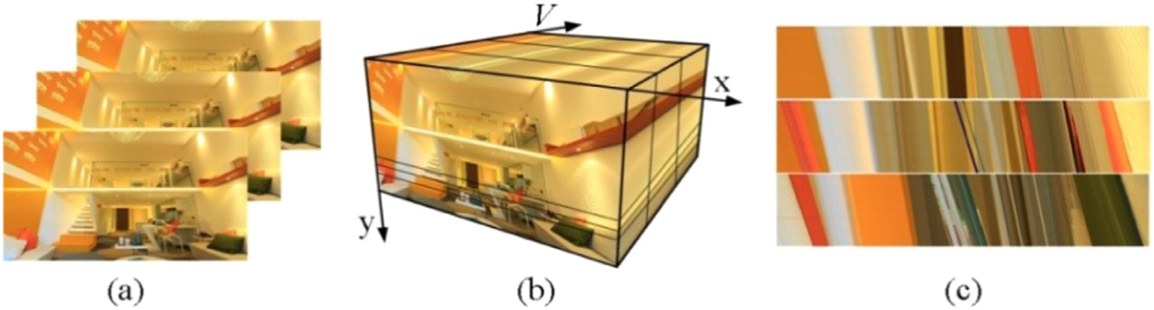

**Fig. 1.** Representation of light field (a) multi-view content, (b) 3D light field, and (c) epipolar plane images.