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A camera array system based on DSLR cameras for autostereoscopic prints

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Abstract

In this paper, we present a multi-view camera-array system by using commercial DSLR cameras. In order to produce quality autostereoscopic prints, we initially calibrated the color based on X-Rite color-checker, then automatically adjust the alignment of all images by one black-white checker. In this system, we also utilized an external electronic trigger based on Arduino for synchronizing all cameras to generate bullet-time effect photos. Finally, we converted all photos into multiplexed images then printed them on a lenticular lens panel to be an autostereoscopic photo frame.

Introduction

Autostereoscopic lenticular prints and displays are widely used to provide natural 3D perception as similar as human vision for decades [1]. So far, several manufacturers have been producing glasses based stereoscopic displays by either polarized or shutter glasses. However, glasses-based stereoscopic displays suffer from the inconvenience of wearing glasses in a limited environment. Glasses-free stereoscopic displays are more convenient for audiences. Nevertheless, it suffers from limited viewing zones and the limitation of resolution of displays. To have better visual experience, autostereoscopic lenticular prints are used. Since current printers provide much higher output resolution than displays, autostereoscopic prints have advantages in providing rich contents, for example more views or more details.

In this paper, we develop a camera-array system to generate multi-view images for autostereoscopic lenticular prints. The system is considered as a photograph device in a well-controlled environment such as photo studios.

Proposed System

Camera array

We built a camera array system consisting of 7 DSLR (Digital single-lens reflex) cameras. All camera models are Nikon D5300 with a standard18-55 mm lens. The original resolution image is 24M pixels. They are arranged on an arc whose radius is approximately 3 meters. The converge angle between each pair is roughly 1.5 degrees. All images are taken as portrait photography. The working distance is considered from 2.5 to 3.5 m for capturing standing portrait photos such as wedding photos and family photos.

In order to synchronize all cameras, we utilized Arduino board and relay circuits for receiving and sending signal to each camera. During taking photos, several auto-functions such as auto-focusing and color processing should be turned off. To be more efficient in operation, we use the opensource called digiCamControl to send trigger signal and collect images from the storages of all cameras. Since the DSLR camera in our system requires reaction time to flip mirrors, the trigger signal will delay up to 0.5 second. The synchronization among camera is difficult to evaluate. Nevertheless, the differences of all timestamps are less than 0.1 second by observing the number value on a stopwatch.

In capturing a scene, the illumination to all camera is slightly different. To minimize the difference among cameras, we use aperture priority mode to reach a consistent exposure value. The difference can be suppressed by additional color calibration.

Figure 1. The proposed camera array system consists of 7 DSLR cameras and one external triggering circuit, that are connected with a computer.

Color calibration

Before color calibration, we disable auto-white-balance (AWB) function in cameras. Then, we use X-Rite 24 color-checker for regression. The color difference (ΔE^{*}_{94}) between the reference value of color checker and ground truth is around 4 based on the 2nd order polynomial regression [2]. Since the calibration-color checker is smaller than the working space, the procedure is executed in a well-controlled lighting environment. Our calibration procedure includes of the adjustment of gamma, white-balance, uniformity of brightness and color mapping. When a photo is taken, the processing will be executed to convert it into a correct color format.

Currently, many camera manufacturers would put advanced color processing functions to optimize the appearance quality of images. It should be carefully considered to be turned on or off in autostereoscopic prints and displays.

Image alignment

In dealing with image alignment, we utilize a projective transformation called homography to adjust the correct position of images [3]. Though the positions of cameras can be preciously arranged on a panel, their optical axis may not be initially to aim at the same target. This is because the pixel size of sensors is too small and sensitive to the scene. And, the cameras are fixed only by a socket screw. It is very unlikely to have a precious optical alignment after fabrication of the system. Therefore, additional alignment calibration is needed. Figure 2 shows original images taken from cameras without adjustment. In calibration, we let 4th camera aim at the target of checkerboard.

$$\begin{pmatrix} x'_1 \\ x'_2 \\ x'_3 \end{pmatrix} = \mathbf{H} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} = \begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{bmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} \tag{1}$$

$$x' = \frac{x'_1}{x'_3} = \frac{h_{11}x + h_{12}y + h_{13}}{h_{31}x + h_{32}y + h_{33}} \tag{2}$$

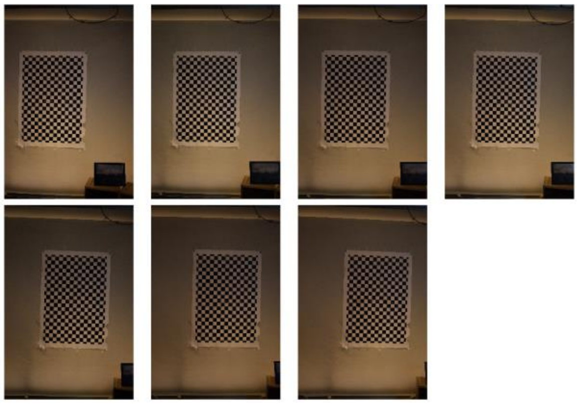


Figure 2. Several raw images of a check-board which are not well-aligned due to the manually assembly.

The projective transformation can be modeled as a 3 by 3 matrix as **H** in Equation (1). Their transformation from dataset (*x*, *y*) to (*x*', *y*') can be rewritten as Equation (2) and (3). To solve **H**, their sub-items will be the formulation as Equation (4). Therefore, we need at least four points to determine **H**. In practice, we consider the 4th image as the destination image, and the rest images will be converted to align the destination image.

$$y' = \frac{x'_2}{x'_3} = \frac{h_{21}x + h_{22}y + h_{23}}{h_{31}x + h_{32}y + h_{33}} \tag{3}$$

$$\begin{bmatrix} x & y & 1 & 0 & 0 & 0 & -x'x & -x'y \\ 0 & 0 & 0 & x & y & 1 & -y'x & -y'y \end{bmatrix} \begin{bmatrix} h_{11} \\ h_{12} \\ h_{13} \\ h_{21} \\ h_{22} \\ h_{23} \\ h_{31} \\ h_{32} \end{bmatrix} = \begin{bmatrix} x' \\ y' \end{bmatrix} \tag{4}$$

After obtaining homography **H** of each camera, we need to decompose the matrix and retrieve the perspective and affine transformation terms. In this procedure, the image can be applied affine transformation to make a good alignment. In addition, an extra horizontal shift should be considered to adjust the depth perception effect. Figure 3 illustrates the transformed images from original data. In practice, converted images may induce black boundaries. This is because overlapped space of all camera is smaller than each of them. Therefore, additional cropping operation is needed after conversion. Figure 4 is the flowchart of our procedure.

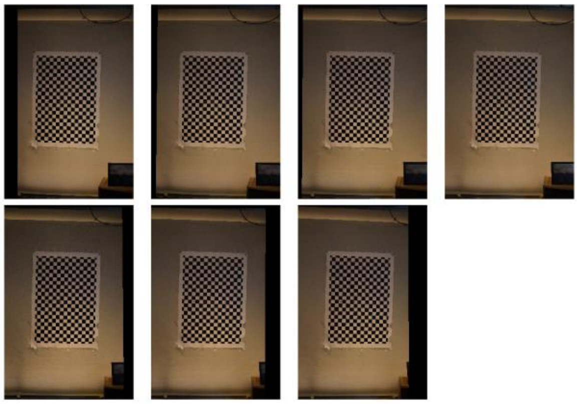


Figure 3. Converted images which are well-aligned will induce blank boundaries

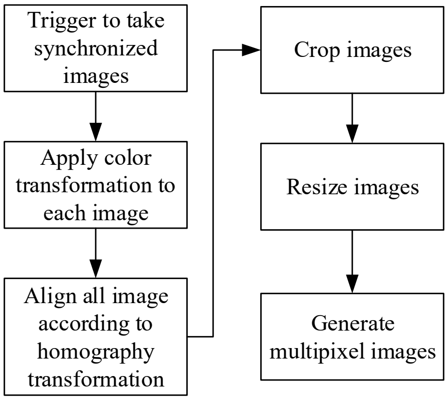


Figure 4. Flowchart of proposed method for generating an autostereoscopic image

Autostereoscopic lenticular prints

The lenticular lens panel in our system is made of PMMA. The size of portrait photo frame is 60 cm in width and 80 cm in height. To reach such a size, the thickness of the panel will be up to 4.0 mm to keep it firm and flat. Due to the thickness and refraction of ray path, the configuration of image sequence is in inversed order as shown in Figure 5. For current commercial printer, the resolution is up to 9600 dpi (dot per inch). In our application, the resolution of our lenticular lens panel is around 24.15 lpi (line per inch) which is much smaller the printer. To embed 7 views in one lenticular stripe, the printed resolution will be 168.7 dpi. However, in most situations, the value of 9600 is not dividable by 168. It is likely that the visual defect occurs. To overcome this problem, a simulation for ray path may be required.

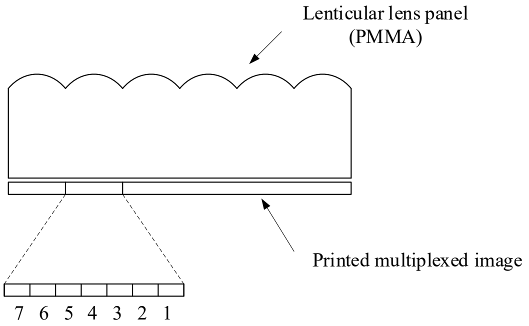


Figure 5. The lenticular lens panel is made of PMMA and its thickness is up to 4mm

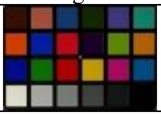
The misalignment between the lenticular lens panel and the printed sheet may induce Moire effect. To minimize the defect caused by un-expected effect such as the production quality of large-sized PMMA, we also took a preliminary experiment to adjust a proper printing resolution as shown in Figure 6. It is a practical solution to verify its printing resolution.

Figure 6. Black-white stripes printed with several lpi are used to verify the proper printing resolution

Result and Discussion

In color calibration, the color difference (ΔE^{*}_{94}) after calibration is as small as 4. The experiment environment is considered as a photo studio. That means illumination in the environment is uniform. Table 1 shows the results of before and after color calibration. The reason we choose 2nd order regression is based on preliminary experiences. And technology of color calibration of camera is getting mature. In practice, we can store the calibration parameters for every lighting scenario.

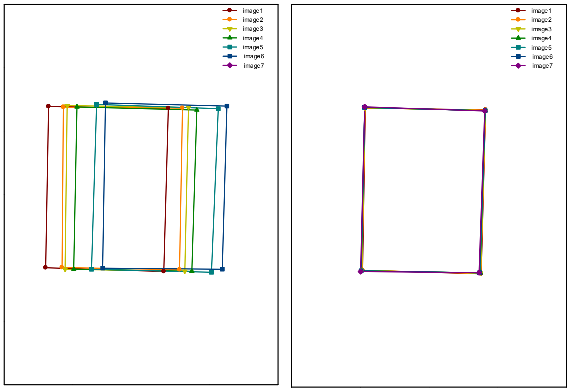
Table 1 Color calibration result

	Original	2nd order regression
Color Checker		
ΔE	21	4

In image alignment, we implemented the homography operation for all images. For most modern DSLR cameras, the lens distortion effect can be corrected by manufactures' build-in software. In our application, it is not necessary to have distortion-free images. This is because our configuration does not cover a wide range. In stead, the total converge angle is 9 degrees. For each stereo pair image, the angle is as small as 1.5 degrees. Therefore, the keystone effect does not appear. Table 2 shows the transformation matrixes of all images. It can be noted that the transformation only guarantees the distance at calibration plane is parallax-free. As a result, if a target is close to the cameras, it will have a pop-up perception effect. Figure 7 shows the relative positions of checker-board in all images. For original images, the fabrication of a camera-array system can not make a proper alignment.

Table 2 The parameters of transformation matrixes for all image

	h_{11}	h_{12}	h_{13}	h_{21}	h_{22}	h_{23}	h_{31}	h_{32}	h_{33}
Image1	0.999	0.001	419.8	-0.001	0.999	15.47	0.0	0.0	1.0
Image2	1.006	-0.009	213.5	0.009	1.006	-14.13	0.0	0.0	1.0
Image3	0.989	-0.006	164.7	0.006	0.989	37.75	0.0	0.0	1.0
Image4	1.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	1.0
Image5	0.984	0.008	-281.4	-0.008	0.984	74.51	0.0	0.0	1.0
Image6	0.986	-0.005	-390.4	0.005	0.986	69.31	0.0	0.0	1.0
Image7	0.995	0.005	-563.6	-0.005	0.995	41.12	0.0	0.0	1.0



(a) Before alignment (b) After alignment

Figure 7. The four corns of all checkerboard are superimposed to show the misalignment of original images and alignment of converted images.

For capturing bullet time scenes, we verified the synchronization. In Figure 8, a jumping girl is captured to illustrate the difference of time-stamps among all cameras are small enough. And its autostereoscopic lenticular print is shown in Figure 9.

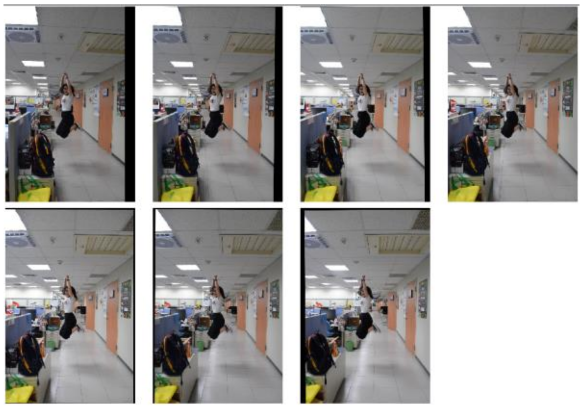


Figure 8. The experiment result shows the synchronization of camera array would make the jumping people "frozen".

Figure 9. Autostereoscopic lenticular print: Synchronization of DSLR will be capable to take a bullet-time photo

Figure 10. This example shows an autostereoscopic print with a smaller depth of field

For autostereoscopic lenticular print, the depth perception is limited due to the constrain of refraction of lenticular lens panel. Since the pitch of lenticular lens is as small as 1 mm, the target far from the camera will be very difficult for human vision system to fuse. To proof the concept, another experiment with smaller depth of field is shown in Figure 10. A humanoid hanger locating at a 40 cm distance behind the people is almost the boundary to be fused by human eye.

Conclusion

We successfully developed a camera array system to capture multi-view images for autostereoscopic prints. This system involves several issues including synchronization, color difference and alignment among cameras. The result shows the proposed system works for photo studios.

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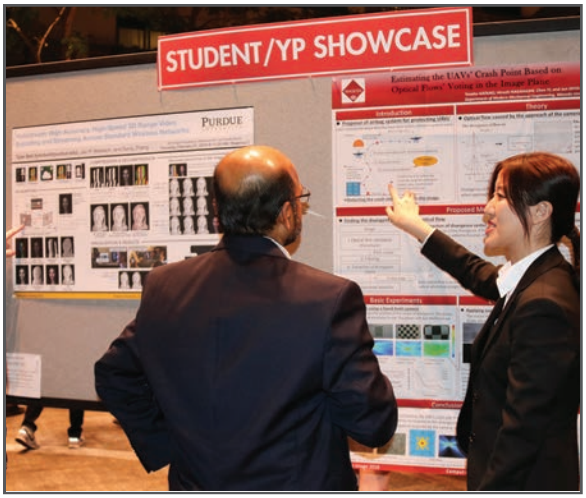
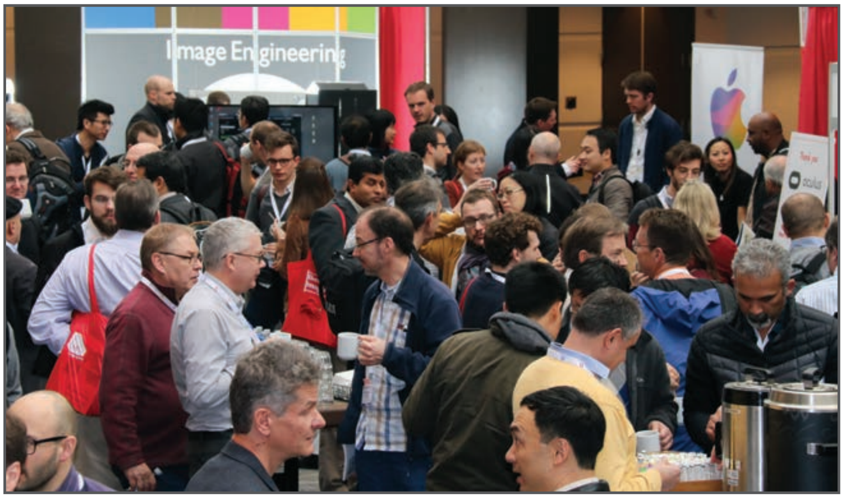
Author Biography

Tzung-Han Lin received his Ph.D. in Department of Mechanical Engineering from National Taiwan University in 2006. He joined Industrial Technology and Research Institute as a senior engineer in 2007. He is now an Associate Professor of Graduate Institute of Color and Illumination Technology at National Taiwan University of Science and Technology (NTUST). His research interests include 3D scanning, visual appearance, computer vision and computer graphics related topics.





AR is a fundamental and transformative interface and platform.

20+ years from my initial working demo to today's AR displays

Optimistic that it won't take another 20 to reach ubiquitous consumer AR!