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A Study on Camera Array and Its Applications ⋆

Dong Wang * Quan Pan * Chunhui Zhao * Jinwen Hu *
Zhao Xu ** Feng Yang * Yihui Zhou *

* *School of Automation, Northwestern Polytechnical University, Xi'an, Shaanxi, China (e-mail: wangdongwarden@mail.nwpu.edu.cn, {quanpan,zhaochunhui,hujinwen,yangfeng}@nwpu.edu.cn).*
** *School of Electronics and Information, Northwestern Polytechnical University, Xi'an, Shaanxi, China (e-mail: zhaoxu@nwpu.edu.cn).*

Abstract: The reduced cost of cameras and the complex scenes make it possible and necessary to replace the monocular camera with camera array under certain situations. In this paper, we first provide a review on the existing camera arrays and sort them according to the array arrangement, and then give an overview of the imaging properties that are benefited from the camera array including dynamic range, resolution, seeing through occlusions and depth estimation. At last, a novel camera array-based airborne optical system is proposed to meet the intelligence, surveillance and reconnaissance (ISR) requirements for large field of view (FOV), high dynamic range and resolution, multi-view and multiple dimensions imaging. For the sake of onboard application of this system in practice, some key technologies are highlighted that need to be developed in the future research, such as the self-calibration and the synthetic aperture imaging by camera arrays on mobile platforms.

Keywords: Camera Array; Array Arrangement; Imaging Properties; Airborne Optical System; Synthetic Aperture Imaging

1. INTRODUCTION

There is an ongoing and rapid growth in the attention for cameras, both in research, such as Stanford Vision Lab (Alahi et al. (2015)) and MIT Computer Vision Lab (Nussberger et al. (2016)), and commercial domain, such as IMPERX and PointGrey, because they are lightweight, low-cost, easily controllable, energy-efficient and can provide a large amount of feature information.

As the application fields of cameras become extensive, such as aerial ISR, target tracking, contactless measurement and 3D reconstruction, monocular camera can not meet the task requirements. In addition, as the scene becomes more and more complex, although multiple images of a static scene can be used to expand the performance envelope of the monocular camera, it is still hard for dynamic scene. Camera array is a system generated using a lot of the image sensors and lenses with the same characteristics, which provides the researchers with a new solution to the above issue because of its multiple viewpoints and multiple parallaxes.

Compared to the monocular camera, camera array can generate some special advantages: (1) Researchers could change their arrangement and control parameters of each camera, like frame rate and exposure time, to achieve large FOV, high resolution and dynamic range. Finally, they can better improve imaging effects or meet the special requirements of photography. (2) Since there are multiple viewpoints in a camera array, it can generate multiple parallaxes which create the potential properties that almost belong to the camera array, such as accurate depth estimation and synthetic aperture imaging.

Camera array is firstly made famous in cinematography called "bullet time", orbiting around a scene that has been frozen in time. At Super Bowl 2001, an array of 30 synchronized video cameras from different viewpoints gave viewers a sense of flying through the scene. Then, researchers built camera arrays for virtualized reality (Kanade and Narayanan (2007); Joo et al. (2015)), depth recovery (Si et al. (2014); Fehrman and Mcgough (2014)), image-based rendering (Zhang and Chen (2004)), high performance imaging (Bennett et al. (2005); Carles et al. (2014)), synthetic aperture imaging (Levoy et al. (2004); Vaish et al. (2004); Yang et al. (2016)), stereo imaging (Maitre et al. (2008) and panoramic imaging (Hossein et al. (2013); Dueholm et al. (2016)).

The purpose of this paper is to provide a brief review on latest application and development of camera array and an overview of a novel camera array-based airborne optical system. We firstly discuss the existing camera array arrangements, and then briefly analyse the imaging prop-

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Corresponding author: Chunhui Zhao (e-mail: zhaochunhui@nwpu.edu.cn)

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erties benefited from the camera array of corresponding arrangements. At last, we describe an ideal of a novel camera array-based airborne optical system proposed, and for the sake of onboard application, we also highlight some key technologies to be addressed about the future development of this airborne optical system. The remainder of this paper is organized as follows. The existing diverse arrangements of camera array are presented and classified in Section 2. An overview of imaging properties benefited from camera array is provided in Section 3, which is followed by an introduction of a novel airborne optical detection platform in Section 4. Conclusions are drawn in Section 5.

2. CAMERA ARRAY ARRANGEMENT

The cameras in the array should be aligned in a certain pattern with an equal baseline and angel between optical axis of each camera. Based on the geometric pattern, the camera array can be classified into the parallel arrangement (as shown in Fig. 1) and radial arrangement (as shown in Fig. 2).

2.1 Parallel Arrangement

By parallel arrangement, cameras in the array are aligned such that optical axes of cameras are parallel to each other. It includes linear array (1D) and area array (2D) for multi-view images acquisitions as shown in Fig. 1. A camera array in the parallel arrangement presents rich overlapping FOV and multiple parallaxes generated by baselines between each optical axis, which generates the corresponding depth maps. According to different range of the baseline between each camera, the parallel camera array can be classified as the single center of projection and multiple centers of projection.

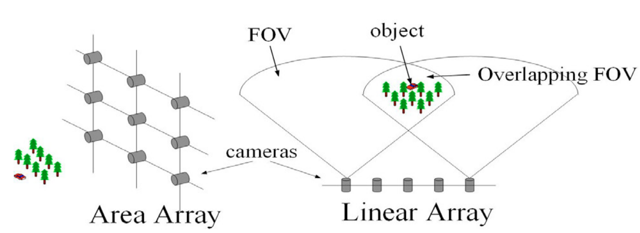

Fig. 1. The parallel arrangement of camera array

A. Single center of projection The single center of projection denotes that cameras are patched together tightly to approximate that they are aligned to a common perspective. On one hand, the goal is to acquire improved imagery with high resolution, high signal-noise ratio (SNR) and high dynamic range rendering in the large overlapping FOV. On the other hand, this form is for synthetic aperture imaging.

For high performance imaging, Baker and Tanguay (2005) have developed a system of up to 24 cameras with abutting FOV whose images are mosaicked yielding video with higher pixel resolution than the individual camera. Similarly, Daiki and Hitoshi (2015) proposed a prototype of super-resolution camera array system comprising 12 low-cost Web camera devices to achieve approximately a 2 dB higher S/N ratio. A larger scale implementation of array was developed by Bennett et al. (2005) using 96 cameras to acquire the 7 megapixel video, they also increased the dynamic range by trading off the field of view and using different exposures across their cameras. Next, they used 52 wide-angel cameras with full overlapping FOV with 30 staggered frames per second to achieve a high speed video with 1560fps (Bennett et al. (2004)). However, their system used multiple workstations and its infrastructure such as the camera grid, interconnects, and workstations were bulky, making them less suitable for onsite tasks. Ding et al. (2011) firstly presented a portable 3x3 camera array system of Pointgrey Flea2 cameras for acquiring the dynamic fluid surfaces and used high speed imaging scheme that was similar with Bennett et al. (2004)'s idea that he interleaved the exposure time at each camera. The system was able to perform at 60fps under the condition that the maximum frame rate of each camera was 30fps. For synthetic aperture imaging which receives great attention from researchers during the last two decades, its pioneer works were proposed by Levoy et al in the Stanford, e.g. Levoy et al. (2004); Vaish et al. (2006). They set up a two-dimensional camera array and aligned multiple cameras to a focus plane to simulate a giant virtual lens, enabling us to synthesize images which would be impossible for an ordinary camera len. Based on this technology, camera array experiences the transformation from area array e.g. Vaish et al. (2004, 2006)to linear array e.g. Yang et al. (2016); Zhao et al. (2013); Joshi et al. (2007).

B. Multiple centers of projection Multiple centers of projection denotes that cameras are spread over a wide baseline to capture the scene from many different points of view to provide the multi-view information for stitching a large FOV (with small overlapping FOV of camera array), e.g. Baker and Tanguay (2005); Najeem et al. (2016) or three-dimensional imaging (with large overlapping FOV of camera array), e.g. Tobias and Hanno (2010); Xie et al. (2016). In spite of this, the distinguishing properties of multiple centers of projection can be obvious in the radial arrangement in Section 2.2 A.

2.2 Radial Arrangement

By radial arrangement, cameras in the array are aligned to form a circle (2D) or hemisphere (3D) for multi-view image acquisitions. According to the directions of optical axes of cameras, radial arrangement can be further classified into two forms: toed-in camera array and toed-out camera array as shown in Fig. 2.

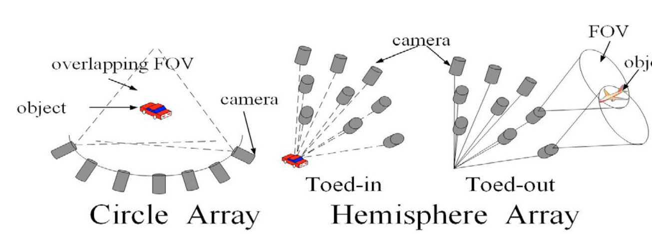

Fig. 2. The radial arrangement of camera array

A. Toed-in camera array The optical axis of each camera in the toed-in camera array converges to a common