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Design of microcamera for field curvature and distortion correction in monocentric multiscale foveated imaging system

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ABSTRACT

To realize large field of view (FOV) and high-resolution dynamic gaze of the moving target, this paper proposes the monocentric multiscale foveated (MMF) imaging system based on monocentric multiscale design and foveated imaging. First we present the MMF imaging system concept. Then we analyze large field curvature and distortion of the secondary image when the spherical intermediate image produced by the primary monocentric objective lens is relayed by the microcameras. Further a type of zoom endoscope objective lens is selected as the initial structure and optimized to minimize the field curvature and distortion with ZEMAX optical design software. The simulation results show that the maximum field curvature in full field of view is below 0.25 mm and the maximum distortion in full field of view is below 0.6%, which can meet the requirements of the microcamera in the proposed MMF imaging system. In addition, a simple doublet is used to design the foveated imaging system. Results of the microcamera together with the foveated imager compose the results of the whole MMF imaging system.

1. Introduction

Imaging systems that simultaneously achieve both large field of view (FOV) and high-resolution are necessary in many vision-based applications such as wide-area surveillance and astrophotography [1–3], since large FOV images can cover wide area to observe more targets and high-resolution images can see more details of the targets. But as discussed in a pioneering study by Lohmann, lenses obey certain scaling laws that determine large FOV and high-resolution imaging can hardly simultaneously achieve [4]. Therefore, it is of great significance to study the joint design of large FOV and high-resolution imaging system.

Various methods have been proposed to realize large FOV and high-resolution imaging. A straightforward alternative for very large FOV, high-resolution imaging is the angle scanning of a conventional high-resolution camera to sequentially form a composite image of the large FOV scene, but this approach is only practical for stationary objects [5]. Tiling smaller sensor die into a larger contiguous defect-free chip can also acquire desired images, but there exists splicing gap between sensors and the images have blind area [6]. It is possible to use the multicamera array, where images are simultaneously composited from an array of independent cameras, but this approach is difficult, costly and the entire physical size of the optics is too large [7]. The use of computational imaging, such as applying a postcapture deblurring step, is another method to achieve high-resolution in the case of a small camera size. It is advocated that the computational camera design consists of a spherical lens shared by several small planar sensors [8,9]. This does not mean that physical resolution of the detected image is unimportant, because some conventional aberrations cannot be completely removed in computation. Using object lens and lens array can capture the light field [10,11]. Brady and Hagen propose to use the field processing capabilities of small-scale secondary lens arrays to correct aberrations due to larger scale objective lenses, with an ultimate goal of achieving diffraction-limited imaging. They design the multiscale lens system, including a single primary large objective lens and multi-aperture secondary small lens array [12]. Then by use of the method of image mosaicking, the multiscale lens system achieves the large FOV and high-resolution imaging. The use of multi-aperture secondary optics is the defining feature of multiscale design, but multiple sets of secondary optics are different because each individual secondary optic needs to correct aberrations of their corresponding off-axis perspective of the primary lens. Therefore, the multiscale lens system has no rotational symmetry and it is difficult to fabricate and align. In order to realize the rotational symmetry structure, monocentric [13] multiscale imaging system is proposed which consists of a single monocentric objective lens and many microcameras [14–16]. In monocentric multiscale imaging system, the objective lens is a monocentric design with all spherical surfaces sharing a common center of curvature, and

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all the microcameras are the same. According to the design of monocentric multiscale imaging system, the completed camera AWARE-2 [17,18], achieves a 120°-by-50° FOV and 38 μrad instantaneous FOV (IFOV), and the recently completed camera, the AWARE-10 [19,20], achieves a 25 μrad IFOV over a 100°-by-60° FOV. However, these two cameras cannot dynamically gaze the moving target and too many mircocameras cause big sampling data, inevitably leading to the difficulty of the follow-up image processing and transmission.

In order to simultaneously realize large FOV and high-resolution dynamic gaze of the moving target, in this paper, we combine monocentric multiscale design with foveated imaging [21–23] and propose the monocentric multiscale foveated (MMF) imaging system. The MMF imaging system consists of a primary monocentric objective lens and a few secondary subimaging systems, which avoid the high-density microcameras and big sampling data. The individual microcamera of the proposed imaging system relays a relatively large portion of the intermediate image, which lead to large field curvature and distortion of the secondary image. Note that large field curvature and distortion cause low quality of the image and positional error of the moving target, and also they are bad for smooth image mosaicking of the component images. Therefore, it is essential for the correction of field curvature and distortion in the MMF imaging system. We have organized this paper as follows. In Section 2, the MMF imaging system concept is presented. In Section 3, the field curvature and distortion of secondary image is analyzed theoretically. Section 4 is mainly about the correction of the two aberrations of the secondary image. Finally, we summarize the main achievements in Section 5.

2. MMF imaging system concept

Aiming to simultaneously realize large FOV and high-resolution dynamic gaze of the moving target, we put forward the MMF imaging system. The MMF imaging system is composed of a primary monocentric objective lens and 3×3 secondary subimaging systems. Fig. 1 shows the schematic design of the MMF imaging system with one secondary subimaging system. The spherical intermediate image is produced by the primary monocentric objective lens and the system uses 3×3 microcameras to relay the spherical intermediate image. Thus the entire visual field is divided into 3×3 sub-FOVs, and then all the secondary images acquired by the microcameras synthesize a mosaic image, which achieves the large FOV image. In addition, to achieve the high-resolution dynamic gaze of the moving target, a foveated imager is designed in each sub-FOV based on foveated imaging.

The foveated imager and the microcamera share the same objective lens, which produces the spherical intermediate image. Thus the whole system becomes compact. A beam splitter behind the spherical intermediate image splits the rays coming from one point of the intermediate image into two beam segments by 50/50 and separates the optic paths: one path, reflected to the microcamera; the other path, straight forward to the foveated imager. The microcamera is placed on the reflected path of the beam splitter to form the image of the sub-FOV of the entire visual field. A collimation lens collects the light transmitted through the beam splitter to the two-axis micro-electro-mechanical system (MEMS) mirror. By tilting the MEMS mirror instantaneously toward the direction of the moving target, rays of light reflected by the MEMS mirror are redirected toward the optical axis. The same collimation lens collects the rays of light reflected by the MEMS mirror and forms the image of the target.

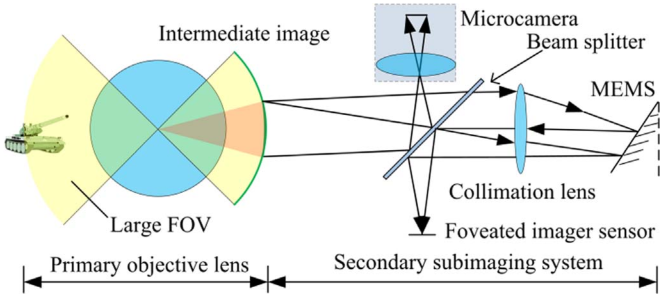

Fig. 1. Schematic design of the MMF imaging system with one secondary subimaging system.

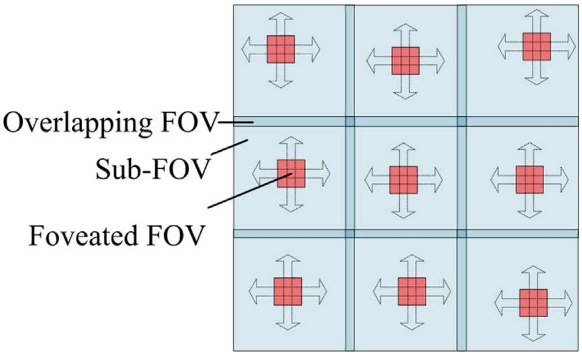

Fig. 2. Image fields of the MMF imaging system.

Fig. 2 shows the image fields of the MMF imaging system. The foveated imager provides a long focal length and a narrow FOV, which is similar with the fovea pit of the eye. The foveated imager can scan the foveated FOV across the microcamera FOV (sub-FOV) by tilting the MEMS mirror, which mimics the human eye movements. Therefore, the foveated imager has the dynamic capability for high-resolution target tracking. The microcamera captures the peripheral scene with relatively low resolution. It is used to acquire the image of peripheral scene for stimulus detection. In order to provide sufficient information for post image mosaicking, a small overlapping FOV is needed between adjacent sub-FOVs. The proposed MMF imaging system can be used in wide-area warning. When the target is founded in one of the nine sub-FOVs, the corresponding foveated imager will dynamically gaze the target by tilting the MEMS mirror instantaneously toward the direction of the target. Thus it is important for the microcamera to get the target's accurate position instantaneously, and only by knowing the accurate target location can the foveated imager obtain the gaze direction. Getting the target's accurate position instantaneously needs optical correction of the distortion and field curvature. In addition, using digital image processing to correct distortion may lose the position information of the target. Therefore, the distortion and field curvature should be corrected by designing the microcamera instead of using digital image processing. From Fig. 2, it can be seen that the large FOV and high-resolution dynamic gaze of the moving target are realized by combining the microcameras and foveated imagers in MMF imaging system.

3. Analysis of field curvature and distortion of the secondary image

In monocentric multiscale imaging system [24], there are lots of microcameras to relay the spherical intermediate image produced by the primary monocentric objective lens, e.g., the completed camera AWARE-2 involves 98 microcameras and AWARE-10 involves 382 microcameras. Hence, each individual microcamera covers a very small portion of the curved intermediate image and the small curved intermediate image can be approximately treated as a plane in monocentric multiscale imaging system, shown in Fig. 3(a).

In our proposed MMF imaging system, because the foveated imager that provides high-resolution dynamic gaze of the moving target is added in each sub-FOV, there is no need to use so many microcameras to acquire the high-resolution image. In this paper, we design and use 3×3 microcameras as the secondary optics to relay the spherical intermediate image in the MMF imaging system, shown in Fig. 3(b). Compare to Fig. 3(a), an individual microcamera of Fig. 3(b) covers a