Magnification Enhanced Multi-Aperture System with Distorted Lens Design

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ABSTRACT

In recent years, some companies take a dual-camera system to improve the magnification ability and zoomed image's quality in multi-function imaging devices. The solution comprises two apertures to perform a large zooming range without any mechanism moving optical elements: one with a wide-angle lens for lower magnification and the other with a telephoto lens for higher magnification. Nevertheless, this dual-camera system still needs to interpolate the digital zoomed image between the lower and higher magnification images results in a discontinuous quality of zoomed image. We propose a distorted lens (DL) dual-camera system with varying focal length for higher magnification performance and smoother optical zoom. The proposed optical system has a greater pixel count per field angle at the center of sensor than at the periphery of sensor. Therefore, we sacrifice some resolution of the peripheral FOV to enhance the resolution of the center FOV for improving the capability of magnification. For instance, using a 20 MP sensor and displaying a Full HD zoomed image, the maximum magnification factor of 7.54 is achieved in our distorted lens system, but this factor of 3.12 in the distortionless lens system. In other words, we raise the capability of magnification up to 242%.

Keywords: Image Sensing System, Dual-Camera, Distortion, Optical Zoom

1. INTRODUCTION

With the technological advances in mobile phone and unmanned vehicle, the demands for better quality image and higher magnification performance in these multi-function imaging devices are growing up. However, these requirements are strongly limited by the size of optical system. To be more precisely, the specifications of camera, such as the total track length (TTL) and the effective focal length (EFL), are restricted by the module depth. In addition, the specifications of sensor, such as the pixel size and the sensor arear, are restricted by the module height. Nowadays, a commercial mobile camera system is usually equipped with a fixed focal length lens whose EFL is between 24mm and 30mm and a sensor whose size is between 1/2.3" and 1/3". Besides, the imaging device usually offers the digital zoom in attempt to get the additional magnification achieved through the internal cropping and enlarging ability in post-processing. For the reasons given above, the small module size constrains the overall magnification factor and results in the distorted and pixelated zoomed image.

Several approaches have been presented to improve the problems listed above for the desirable image properties and implementing the optical zoom. In this paper, "digital zoom" refer to pixel interpolation where no additional information is actually provided, whereas "optical zoom" refer to magnification of the projected partial image, providing more information, better resolution, and higher image quality [1]. Some companies take the dual-camera system to address the physical construction problem [2]. They combine two different focal length cameras to implement the two-step optical zoom: one with a wide-angle lens for the lower magnification and the other with a telephoto lens for the higher magnification. Because mounting an additional camera for extending the zooming range, the quality of the zoomed image would not be lost and degraded. Nevertheless, the level of increased magnification is not so significant or still needs to interpolate the digital zoomed images between the lower and higher magnification images. Therefore, this kind of solution

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would result in a discontinuous quality between the two-step optical zoomed images and the middle digital zoomed images.

Other companies improved the dual-camera system by replacing the fixed tele sub-camera with the periscope-style camera [3]. The focal length of the periscope-style camera is variable by moving either its lenses or mirrors inserted in the folded optical path. This solution implements the real optical zoom within a range of high magnification; therefore, the quality of the zoomed images is smoother and more continuous. Nevertheless, this kind of solution needs to remotely control the movable mechanism for shooting zoomed images with different magnification factors that contributes to a unstable system. Besides, we need to preset the system for the required zoomed image instead of post-processing that brings about the disadvantages when filming a video with a unmanned vehicle like drone.

2. DL-BASED MULTI-APERTURE SYSTEM

For the applications of the portable imaging devices and unmanned vehicles, we generally pursuit a high magnification and high resolution only in a center of the field of view. Patents [1] and [4] use a distorted lens camera to enhance the resolution of the zoomed image and increase the capability of magnification in the central portion of the FOV. In this paper, we propose a DL-based multi-aperture system to extend the entire zooming range and implement the smooth optical zoom at the same time. In the following sections, we define the parameters that characterize the DL camera, and analyze the geometrical constrains and conditions that guide the capability of magnification of the proposed optical system.

2.1 Distorted lens camera

A distorted lens camera which projects a distorted image of an object onto the sensor expands the image in the center region of the FOV and compresses the image in the periphery region of the FOV. This optical system exploits barrel distortion to produce a variable pixel count per field angle across the image sensor, i.e., having a significantly greater pixel count per field angle at the center portion of the given distorted image than one at the periphery portion. A distorted lens camera has a better zoom capability than a conventional distortionless-lens camera, because the DL camera system sacrifices some resolution of the peripheral FOV to enhance the resolution of the on-axis FOV. Furthermore, a distorted lens camera realizes the smooth optical zoom by simply cropping, correcting, and rescaling the distorted image in post-processing. Therefore, the distorted-based image capturing system could overcome the problems due to the limitations and disadvantages of the miniature module size in a compact and inexpensive way.

2.2 Characterization of DL camera

In order to display a target image with a required magnification factor, we need to crop and resample a source image from the sensor. In other words, the FOV of the cropped source image is equivalent to the FOV of the required target image and the resolution of the cropped source image is higher or same as the resolution of the target image to avoid information loss. In this section, we assume the aspect ratios are the same between the target image and the sensor, and then in the next section we would generalize it to different aspect ratio and optimize it for the DL camera system. If the total number of pixels are N_T and N_S in the target image and the source image respectively, the highest magnification factor is N_S/N_T in a conventional distortionless-lens system. However, the capability of magnification in distorted lens camera would better by the variable effective focal length (EFL) of the distortion lens which is a function of incident angle.

Shabtay et al. [1] explain how to calculate the maximal zoom magnification from discrete magnifications to continuous magnifications. The magnification factor is given as

$$\frac{N_S}{N_T} = (Z^C_{max})^2 = 2\,ln(Z^D_{max}) + 1, \tag{1}$$

where Z^C_{max} and Z^{D}_{max} are the maximal zoom magnifications in conventional camera and in DL camera respectively, and Z^{D}_{max} is bigger than Z^C_{max} when N_S is bigger than N_T as desired. Nevertheless, the ideal rectangular-distorted image instead of the standard circular-distorted image is considered. Their calculated formula is not practical and unrealistic, because it is hardly to produce a rectangular-distorted lens system. We use this conception and extend it to a circular-distorted image for the practical DL camera; moreover, we also calculate and design an appropriate distortion curve for an information-lossless DL camera.

The barrel-distortion image capturing system is assumed. The maximal magnification factor Z^D_{max} and the distortion curve of lens are the functions of the sensor's resolution and the target image's resolution. The number of horizontal and vertical pixels in the sensor are H_S and V_S, and the number of horizontal and vertical pixels in the target image are H_T

and V_T. In this section only considering the same aspect ratios between the sensor and the target image, that is to say, H_S/V_S is equivalent to H_T/V_T.

Distortion arises because different areas of the lens have different focal lengths and different magnifications. The definition of distortion is given as

$$\mathcal{D} = \frac{d_D - d_{source}}{d_{source}}, \tag{2}$$

where d_D is the real ray height in the image place or the distance from the center to any point on a distorted image, and d_{source} is the paraxial ray height or the distance from the center to any point on a source image. The source image could be regarded as the projected image covering the whole FOV with sufficient resolution as same as the sensor of a conventional camera required. In other words, if the resolution of the target image is $(H_T \times V_T)$ and the maximal zoom magnification is Z_{max}^{D} in DL camera system, then the number of horizontal and vertical pixels in the source image should be H_{source}(=$H_T \times Z_{max}^{\mathrm{D}}$) and V_{source}(=$V_T \times Z_{max}^{\mathrm{D}}$).

We generalize the Equation (1) for the rectangular-distorted image to the Equation (3) for the circular-distorted image by introduce a new parameter, distortion factor Z_d, which is related to the level of distortion in different part of the distorted image on the sensor. The new maximal magnification is given by

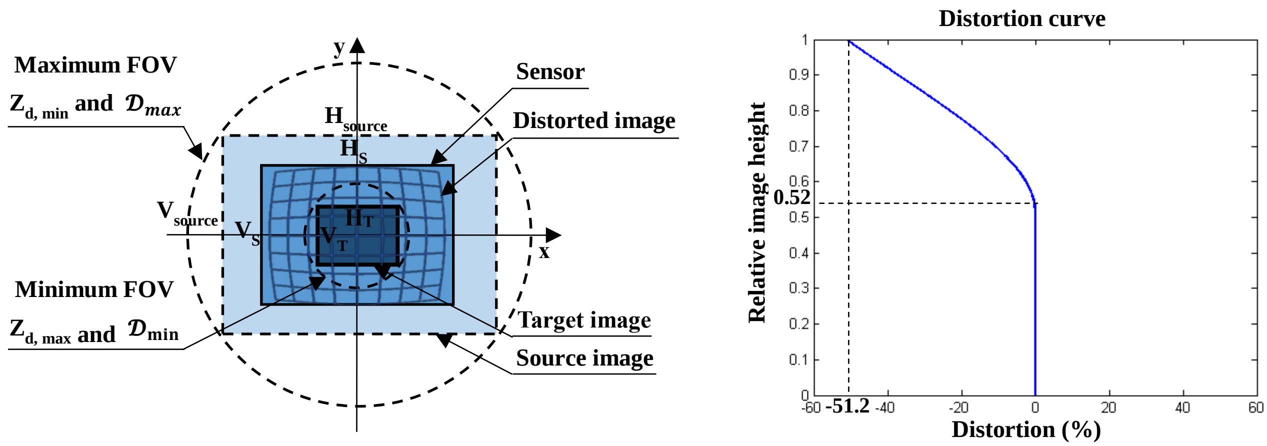
$$\frac{d_D}{D_T} = \sqrt{2\,ln\left(\frac{Z_{max}^{D}}{Z_d}\right) + 1}, \tag{3}$$

where D_T is the half diagonal length of the target image. The distortion factors with different magnifications are the functions of the distances between the source image's center and the focused points or pixels, so we replace the total number of pixels in Equation (1) with the relative distances on the distorted image. In order for the DL camera system to be able to implement the optical zoom without any information loss, the center part of the distorted image should be distortionless and have the highest resolution between the whole FOV. The central part of the FOV with the maximal zooming magnification as the inner circle with dashed line just covering the target image is illustrated in Figure 1(a). The center FOV covered by the inner dashed-line circle has the highest resolution and maximal distortion factor $Z_{d,max}$ with lowest distortion degree $\mathcal{D}_{min}$, the peripheral FOV covered by the outer dashed-line circle has the lowest resolution and minimal distortion factor $Z_{d,min}$ with highest distortion degree $\mathcal{D}_{max}$, and the distortion factors are gradually changed in the FOVs between these two circles.

Figure 1(a) illustrates the relative area size and FOV between sensor, target image, and source image. The distorted image is a projected source image as barrel-distorted in accordance with a DL camera. The maximal magnification of a DL camera system is limited by the relative size between target image and sensor. Considering the aspect ratio of target image in practical is usually 16:9 or 4:3, thus the maximal zoom magnification is dominated by the shortest side, i.e. the vertical resolution of target image and sensor. We could calculate the maximal magnification and distortion factor on different part of distorted image by combining the Equation (3) and the following condition:

$$d_{source} = d_T \times \frac{Z_{max}^{D}}{Z} = D_T \times \frac{Z_{max}^{D}}{Z_d}, \tag{4}$$

where d_T is the distance from the center to any point on a target image, and Z is the zooming factor determined by a user. We could get a zoom-in image by cropping a part of source image based on the zooming factor and correct the distorted image according to the distortion factor. Equation (4) connects the distorted image and the user-choosing zooming image by the corresponded region of the source image. The effective area of distorted image is restricted to the shortest side of the target image, because the border of the distorted image is coincidently on the outermost pixel of the sensor. Therefore, we could calculate the corresponded distortion factor on the periphery of target image which covers the whole FOV from Equation (4) when the zooming factor is equal to 1, and then we could substitute it into the Equation (3) to calculate the maximal zooming magnification which is equal to $Z_{d,max}$. For example, if we use a 16:9 sensor with 20 mega pixels (MP) and a Full FD target image, we could display a lossless zoomed image with the maximal magnification factor of 3.98 in the DL camera, but the maximal magnification is only 3.12 in the conventional camera. Figure 1(b) shows the distortion curve defined by Equation (2) in this instance DL camera. The distortion is 0% if the relative image height in distorted image is smaller than 0.52, but the distortion is dramatically decrease until reaching the maximal distortion which is -51.2%. Figure 1 illustrates how the DL camera system efficiently distributes the pixel utilization in different part of FOV to implement the smooth optical zoom and increase the maximal magnification.



(a) (b)

Figure 1. Projection of the field of views with different distortion factors. (a) Illustration of the relative area size between sensor, distorted image, target image, and source image. (b) A demonstrated distortion curve for an information-lossless DL camera.

2.3 DL-based dual-camera system

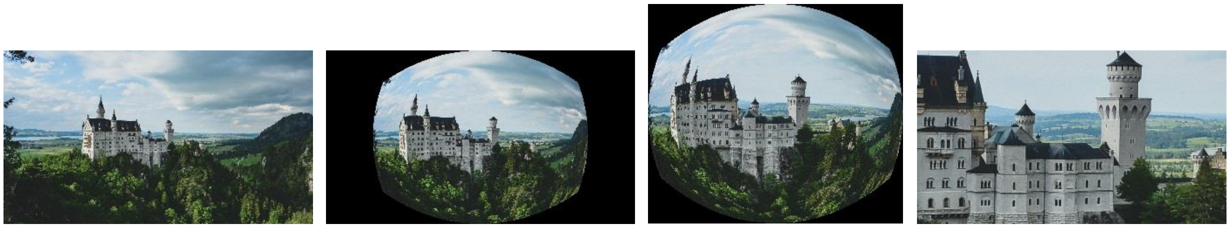
A DL-based multi-aperture system consists of a set of DL cameras with different FOVs to improve the entire magnification ability. The optical axis of each DL camera is at the same position and the FOV of each DL camera is decreasing for covering the different zooming range following each other continuously. In this paper, we use a DL-based dual-camera as an example of the proposed optical system. A DL-based dual-camera comprises a wide-angle DL camera for lower magnification and a telephoto DL-camera for higher magnification. The central FOV of the wide-angle DL camera with distortionless is equal to the whole FOV of the telephoto DL-camera that implements the continuous and smooth optical zoom. However, in order to make the maximal magnification of the conventional distortionless dual-camera be the same as the DL-based dual-camera, we need to interpolate the digital zoomed images between two optical zooming ranges results in the quality of zoom-in images discontinuously changed. The quality of zoomed images will be quantified and the maximal zoom magnification will be optimized in Section 3.

3. DIGITAL SIMULATION RESULT

In this section, we digitally simulate the performance of ideal DL camera with desired distortion curve. We use dozens of high-resolution images as ground truth images to simulate the incident rays transmitting distorted lens and projected on sensor. Given the resolution of sensor and target image, we could crop, rescale, and distort the ground truth image to get the source and distorted image as illustrated in Figure 2. Figure 2(b) illustrates large area of sensor is wasted if the aspect ratios of sensor and target image is the same as conventional camera designed, but we could increase the sensor utilization by optimizing the aspect ratio of sensor as illustrated in Figure 2(c). Figure 2(d) shows a zoom-in image with user-choosing zooming factor which is obtained from the distorted image by easily cropping, resampling, and distortion correcting. To understand how to select appropriate specifications of DL-based dual-camera for optimal magnification ability, image quality, and sensor utilization, we figure out the relationship between maximal magnification and aspect ratio, and analyze the quality of zoomed images with different resolution ratios for practical application.

3.1 Optimizing aspect ratio and resolution ratio

Considering the aspect ratio of target image in practical is usually bigger than one, therefore, the maximal magnification and sensor utilization are constrained by the vertical side of sensor which is related to the effective area of distorted image. If the aspect ratio of target image (R_{asp}^{T}) is determined, the aspect ratio of sensor (R_{asp}^{S}) should not be the same as the target image as used in a conventional distortionless-lens camera. Instead, the aspect ratio of sensor should be less than the aspect ratio of target image for improving the sensor efficiency and extending the total zooming range.



(a) (b) (c) (d)

Figure 2. Digital simulated images: (a) source image, (b) distorted image with conventional sensor, (c) distorted image with optimized sensor, and (d) zoom-in image from distorted image.

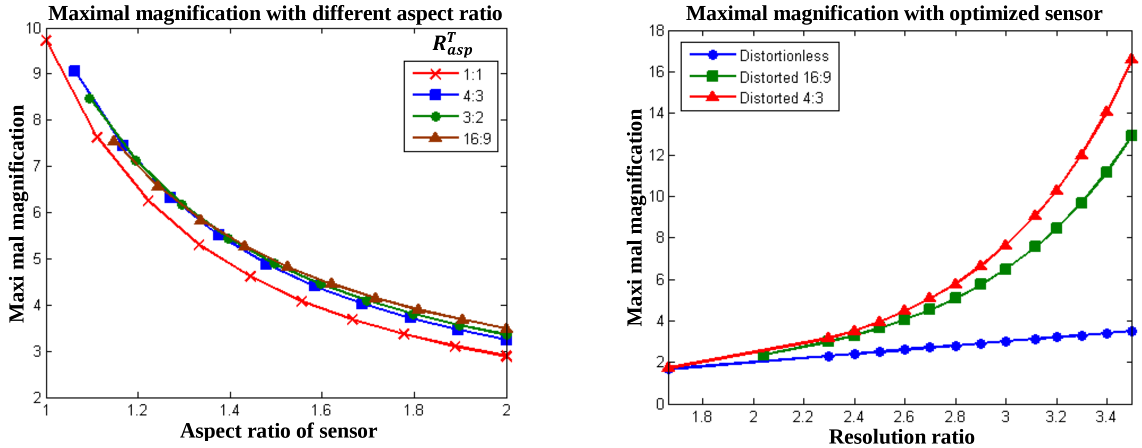
For example, the resolution of sensor is given as 20MP, but the aspect ratio of sensor is variable. Considering four standard aspect ratios of target images, the resolution of which is equal to Full HD. We could use the Equation (3) and Equation (4) to draw the trendlines to illustrate the relationship between maximal magnification and aspect ratio of sensor as showed in Figure 3(a). The maximal magnification and sensor utilization are monotonically increased with decreasing the aspect ratio of sensor until reaching the optimal magnification ability. The optimized aspect ratio of sensor is happened when the border of distorted image is coincident with vertical side and horizontal side of sensor simultaneously. Besides, if the aspect ratio of target image is more symmetrical, the optimized maximal magnification will be bigger and the optimal aspect ratio of sensor will be closer to one.

To make the DL camera enable to achieve the required maximal magnification economically, it is desirable to minimize the resolution of sensor for the given target image. Figure 3(b) illustrates the relationship between the maximal magnification and the resolution ratio in a DL camera or in a convention camera with different aspect rations of target images. The resolution ratio (R_{res}) is defined as the square root of the total pixels number of sensor divided by the total pixels number of target image (R_{res}=$\sqrt{N_S/N_T}$). The maximal magnification of the conventional camera is equivalent to the resolution ratio, but the maximal magnification of DL camera is significantly increased with increasing the resolution ratio. In addition, Z_{max}^D is much bigger than Z_{max}^C as long as the resolution ratio is big enough, and if aspect ratio of target image is closer to one, the maximal magnification of DL camera will be bigger. The minimal resolution ratio is related to the aspect ratio of target image, because the central part of FOV with distortionless should cover the whole target image for information lossless.

3.2 Constrains of the quality of zoomed image

The DL camera assigns some resolution of the peripheral FOV to the central FOV for increasing the capability of magnification in the center viewing angle. Consequently, some information in the peripheral FOV is lost results in the decreased image quality. In this paper, we use peak signal-to-noise ratio (PSNR) as the indicator to evaluate the difference of image quality between ground truth image and zoomed image. However, the value of PSNR could only be taken as a reference rating, because its value is depended on the object and size of image. The lowest quality of zoomed image is happened when the zooming factor is equal to one in DL camera, because it covers the whole FOV and loses the largest amount of information. On the other hand, the quality of zoomed image with maximal zooming factor is the worst in conventional camera, because it needs to interpolate the largest amount of pixels for compensating the missed information.

As discussed in Section 3.1, the more symmetric the target image is, the bigger the maximal magnification will be in optimized DL camera. Thus in this section, we assume the aspect ratio of target image is 4:3 for optimizing the performance of DL camera system. Due to the limitation of the resolution of ground truth image, we consider a sensor with 1.3MP and a target image whose resolution is 400×300 pixels to demonstrate the superior magnification ability of DL camera. Figure 4(a) illustrates the variation of image quality with different zooming factors in DL camera and in conventional camera. The resolution of sensor in conventional camera is 1320×990 pixels and the resolution of optimized sensor in DL camera is 1175×1112 pixels, and both the resolution ratio and Z_{max}^C are 3.3. We use the bilinear interpolation to extend the maximal zooming factor of conventional camera as the same as Z_{max}^D which is equal to 12.0. The quality of zoomed image in conventional camera is infinite if the zooming factor is smaller than Z_{max}^C, because there is no need to do interpolation. The quality of zoomed image is around 26 dB if the zooming factor is bigger then Z_{max}^C in conventional camera. Theoretically, the PSNR in conventional camera should be decreased with increasing the zooming factor due to

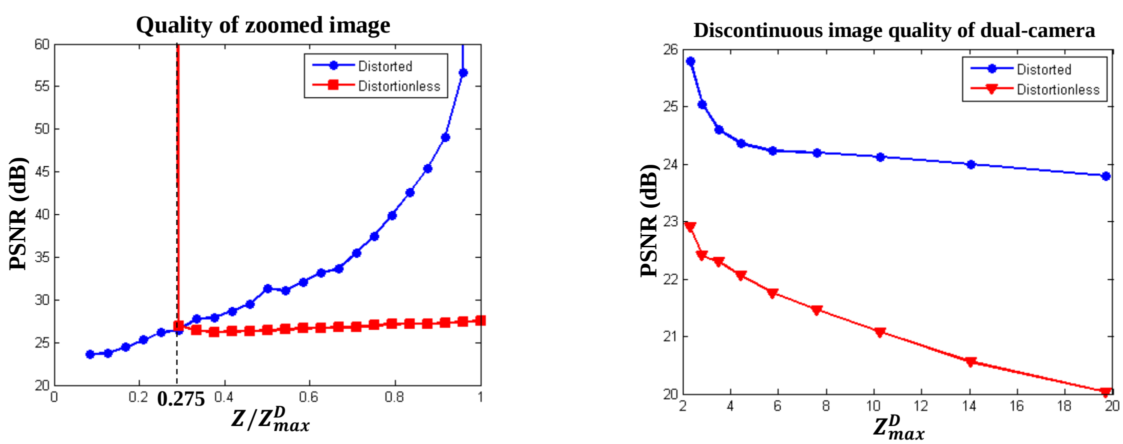


(a) (b)

Figure 3. Maximal magnification with different geometrical constrains. (a) The resolutions of sensor and target image are fixed, but the aspect ratios of both are variable. (b) The magnification ability of DL camera is rapidly raised with increasing the resolution ratio between sensor and target image.

more interpolation, but the FOV and the objects in the zoom-in image is related to the zooming factor such that the variation of PSNR is inapparent. The PSNR of zoomed image in DL camera is rapidly increased with increasing the zooming factor until raising to infinite when Z is equal to Z^D_{max} as designed.

In this paper, we assume there is no information fused between two cameras in the dual-camera system for simplifying the problem. Therefore, there is a discontinuously changed of the zoomed image quality between two-step zooming range, i.e., the quality of zoomed image is suddenly decreased in conventional camera or increased in DL camera when alternating the used camera. We still use the same specifications of target image as mentioned previously, but we change the resolution ratio and the maximal magnification synchronously to demonstrate the discontinuous qualities between zoomed images in distortionless dual-camera and in optimized DL-based dual-camera. We estimate the discontinuous quality of zoomed image by the smallest PSNR between two-step zooming range, i.e., the zoomed image with the maximal zooming factor in wide-angle camera of conventional dual-camera and the zoomed image with the minimal zooming factor in telephoto camera of DL-based dual-camera. Figure 4(b) shows the discontinuous quality of zoomed image in DL-based dual-camera



(a) (b)

Figure 4. Image quality of DL camera and conventional camera: (a) Given the resolution of sensor and target image, the quality of zoomed image is changed with zooming factor. (b) The image quality is discontinuous and varied with the maximal magnification in the dual-camera system.

is better than in conventional dual-camera, the difference of which is as least 3 dB. The discontinuous image quality is decreased significantly with increasing the maximal magnification in conventional dual-camera, but the discontinuous image quality is decreased slowly with increasing the maximal magnification in DL-based dual-camera, that means the quality of zoomed image is smoother and insensitive to the resolution ratio in DL-based dual-camera system.

4. CONCLUSIONS AND FUTURE WORK

We proposed a DL-based multi-aperture system that consists of a set of distorted lens cameras with different FOVs for increasing the capability of magnification and improving the quality of zoom-in image. According to the required zooming factor, we can obtain a high-quality zoomed image by simply cropping, rescaling, and undistorting the distorted image to achieve the smooth optical zoom. Using a DL-based dual-camera as an example, in this paper, we have investigated how the aspect ratios of sensor and target image can be optimized to maximize the magnification ability and sensor utilization efficiency. Based on the optimal design, we have calculated the relationship between maximal magnification and aspect ratio, and analyzed the quality of zoomed images with different resolution ratios. In the future work, we plan to use optical software to design a DL camera to verify our proposed optical system is practical and realistic.

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