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Aperture access and manipulation for computational imaging

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ABSTRACT

Many computational imaging applications involve manipulating the incoming light beam in the aperture and image planes. However, accessing the aperture, which conventionally stands inside the imaging lens, is still challenging. In this paper, we present an approach that allows access to the aperture plane and enables dynamic control of its transmissivity, position, and orientation. Specifically, we present two kinds of compound imaging systems (CIS), CIS1 and CIS2, to reposition the aperture in front of and behind the imaging lens respectively. CIS1 repositions the aperture plane in front of the imaging lens and enables the dynamic control of the light beam coming to the lens. This control is quite useful in panoramic imaging at the single viewpoint. CIS2 uses a rear-attached relay system (lens) to replace the aperture plane behind the imaging lens, and enables the dynamic control of the imaging light jointly formed by the imaging lens and the relay lens. In this way, the common imaging beam can be coded or split in the aperture plane to achieve many imaging functions, such as coded aperture imaging, high dynamic range (HDR) imaging and light field sampling. In addition, CIS2 repositions the aperture behind, instead of inside, the relay lens, which allows the employment of the optimized relay lens to preserve the high imaging quality. Finally, we present the physical implementations of CIS1 and CIS2, to demonstrate (1) their effectiveness in providing access to the aperture and (2) the advantages of aperture manipulation in computational imaging applications.

1. Introduction

Many computational imaging applications require capabilities beyond those offered by normal cameras, e.g., larger field-of-view (FOV), resolution, dynamic range, depth of field (DOF) or frame rate. A variety of methods proposed to meet this need involve accessing and controlling the lens aperture (Fig. 1b). Manipulating the shape, size, structure, position and orientation of the aperture makes it possible to modify the viewing axis, control the amount of incoming light, and encode the depth information. For instance, coded aperture imaging mounts a mirror array [8] or coding patterns [24,13,12] at the aperture to obtain one or multiple images that encode the scene depth. A mirror array is employed to partition the aperture into several sub-apertures, through which multiple images of the same scene are captured for high speed imaging [9] and high dynamic range (HDR) imaging [4]. Light field photography varies the aperture position by filters or lens arrays to acquire images from different viewpoints [2,7,24,22]. Omni-directional imaging [6,18] controls the orientation of the aperture to capture panoramic images using a planar or convex mirror. Lensless imaging [25] modulates the direction and amount of the incoming light by employing a set of parallel transmittance patterns at the aperture. All these methods of improving imaging capabilities of normal cameras involve the interception and processing of the incoming light, e.g., by placing filters, beam splitters or mirror arrays in the aperture plane.

Although many other methods can be used to achieve the advanced imaging functions above, the aperture-manipulating method holds several unique advantages. For instance, compared to conventional HDR imaging using a transmission-variant mask [19–21] or a beam-splitter, the aperture-splitting method [4] has two advantages: (1) it makes best use of the incoming light, almost without blocking any light, and (2) the percentages of the incoming light received by multiple cameras can be flexibly adjusted and optimized. Panoramic imaging by rotating a camera on its optical center [3] assumes the static scene, while panoramic imaging using multiple cameras that point in different directions from the common optical center (entrance aperture) [6], can be used in the dynamic scene.

It is not easy to access the aperture of a conventional imaging lens, since it is located within the lens housing. A typical imaging lens consists of a front lens group, a rear lens group and a physical aperture, called aperture stop or simply aperture (Fig. 1b). The virtual image of the physical aperture in the front lens is defined as the primary aperture (or entrance pupil) and its virtual image in the rear lens is defined as the secondary aperture. These three

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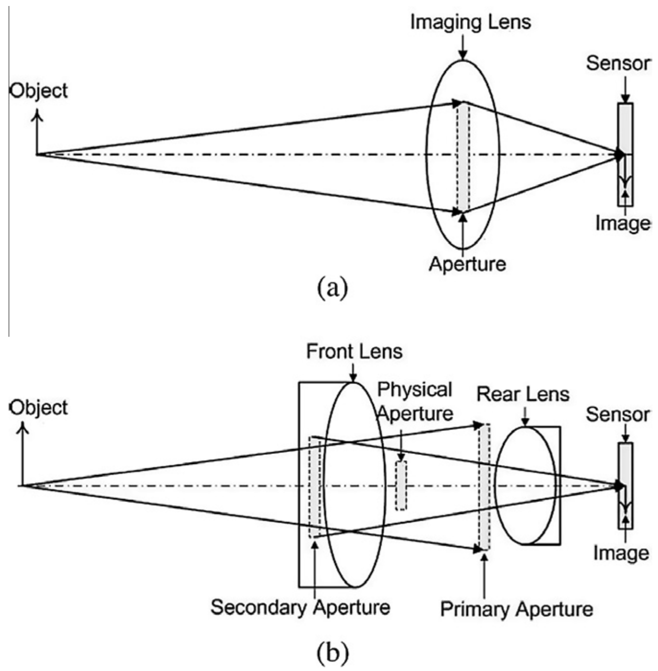

Fig. 1. (a) A conventional imaging lens showing the (b) physical aperture, primary aperture, and secondary aperture.

apertures are optically equivalent. The aperture determines which rays can pass through the lens to reach the sensor, and plays a central role in controlling image brightness, image quality and visual direction. Since the physical aperture is typically located inside the lens and the other two apertures are virtual, none of which is easily accessible, opening or closing the physical aperture is the only external aperture control available.

Accessing the aperture of an imaging lens usually requires either machining the lens housing or redesigning the lens to bring the aperture out of the lens housing. But, neither method provides easy external access to the aperture of a given lens. This paper proposes two compound imaging systems (CIS), CIS1 and CIS2, which provide external access to the lens aperture without any structural modification of the lens. As shown in Fig. 2a and b, CIS1 and CIS2 are constructed by attaching an optical relay system, either in front of or behind the imaging lens. Following are some similarities and differences between these two systems.

1. *Optical structure.* Both CIS systems consist of an imaging lens and a relay lens, but how these two lenses are used together is different.
2. *Aperture access and manipulation.* Each CIS can provide external access to the aperture of the imaging lens (Fig. 2a and b). Because the aperture is relocated at different positions, these systems are better suited for different applications. By mounting a rotatable mirror at the accessible aperture in front of the imaging lens, CIS1 is capable of controlling the visual direction to achieve single-viewpoint panoramic imaging, but CIS2 is not. CIS2 has advantages over CIS1 in applications involving aperture modulation or aperture splitting. This is because CIS2 repositions the aperture behind the imaging lens, which protects it from extraneous environmental light as well as making the system compact.
3. *Image access and manipulation.* Each CIS forms an intermediate image which is optically conjugate to the image in the sensor plane (Fig. 2a and b). By mounting a transmission pattern in the image plane, we can dynamically control the brightness of each pixel which is used in some computational imaging applications, e.g., HDR imaging [19–21,15]. CIS1 requires that transmission patterns be inserted in the intermediate image plane inside the relay lens, which limits the choices available for the relay lens. By relocating the image and aperture planes outside the relay lens, CIS2 allows the employment of the best available relay lens, which has a complicated and optimized structure.

Although many advanced imaging functions are facilitated by providing external access to both aperture and image planes in CIS1 and CIS2, our major contribution is the external accessible

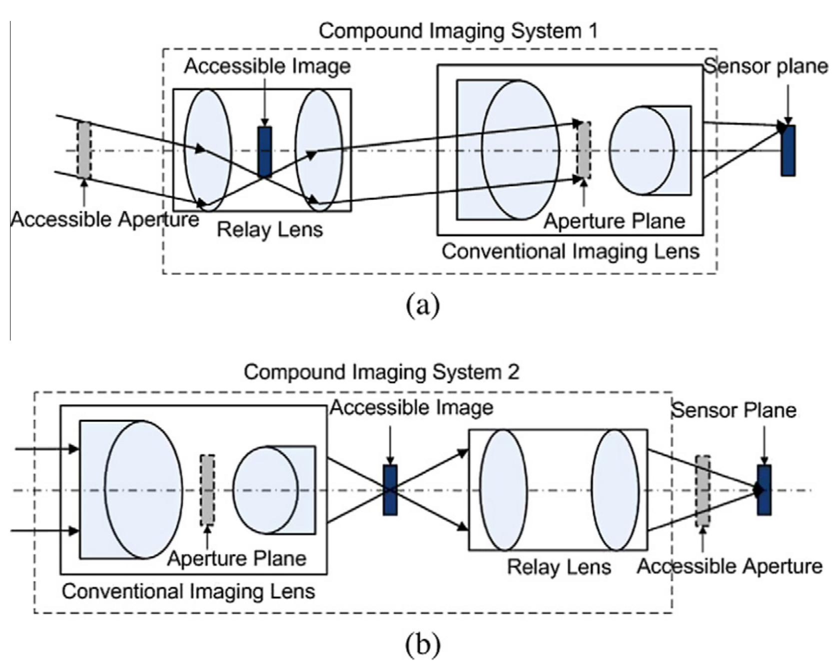

Fig. 2. Our compound imaging systems (CIS) with new relay systems. (a) CIS1, with fore-attached relay system. (b) CIS2, with rear-attached relay system. Both provide accessible apertures as well as accessible image planes for computational imaging.

apertures, for the way the intermediate image planes are formed is similar to previous work [19–21,15]. Thus, we mainly focus on aperture access and manipulation in this paper. Specifically, we discuss controlling the position, area, orientation or transmissivity of the aperture by inserting a mirror or a coded mask. We present one aperture manipulation application of each CIS, i.e., panoramic imaging using CIS1 and high dynamic range imaging using CIS2. As a minor work, we also present an image manipulation application of CIS1, which shows the feasibility of modulating the intermediate images to achieve advanced imaging functions in our CIS.

This paper is organized as follows. Section 2 describes previous approaches to accessing the aperture, Sections 3 and 4 present the design of two relay systems used to construct CIS1 and CIS2, Section 5 describes the applications of CIS1 and CIS2, Section 6 presents simulation and experimental results, and Section 7 presents concluding remarks.

2. Background

In this section, we review some previously used optical relay systems and how they have been used to provide access to aperture.

2.1. Optical relay system and afocal system

An optical relay system is a group of lenses that relocates an image or aperture from one plane to another. The most widely used realization of a relay lens is a pair of mounted achromatic lenses or its optimized versions. By placing an aperture at the focus point of its frontal lens (Fig. 3b), the achromatic pair forms an equivalent aperture at the focus point of its rear lens. Ordinarily, a relay system is used to invert an image or increase the distance between the primary aperture and the image plane [23]. In this paper, we employ the relay system to reposition the aperture out of the imaging lens. A basic design requirement of the relay lens is that it does not alter the optical parameters (e.g. focus distance and image size) of the imaging lens with which it is used. This means that if the incoming rays to CIS1 are parallel, so should be the rays going out of the fore-attached relay lens (Fig. 3a). Similarly, in CIS2, the accessible image in front of the rear-attached relay lens should be of the same size as the actual image formed on the sensor (Fig. 3b).

Afocal optics is a good candidate for designing the relay system in our CIS1 with focal points located at infinity [23]. A pencil of parallel rays passing through an afocal system remains parallel. There are two kinds of afocal systems, Galilean and Keplerian, which are widely used in telescopes. As shown in Fig. 3a and b, both afocal systems can preserve the parallelism of incident parallel rays as they pass through them. The major difference between these two systems is that the Keplerian system is capable of repositioning the aperture plane from one side to another, making the aperture externally accessible (Fig. 3b). The Keplerian system forms an intermediate image plane between its two lenses, which is useful for image modulation. The Keplerian afocal system is thus a good option for the relay lens in both CIS1 and CIS2.

2.2. Previous methods for aperture access

Below we summarize previous approaches to accessing the aperture of an imaging lens, and present the application and performance of each approach.

1. *Modified or customized lenses*. [24,13] cut the lens barrel to place a coded mask at the aperture located inside the imaging lens (Fig. 4a). However, this method is impractical and infeasible when inserting a large-size aperture filter. [9,4] employ custom imaging lenses (Fig. 4b) with the aperture outside the lens housing, but custom lenses are very expensive.
2. *Rear-attached relay systems*. Fig. 4c shows an rear-attached relay system that repositions the aperture from inside the imaging lens to inside the relay system [15,8]. This method is widely applied to aperture manipulation (Fig. 4d) and image modulation (Fig. 4e). For aperture manipulation, the aperture splitter is placed behind one achromatic lens to partition the parallel rays into multiple beams, and correspondingly multiple achromatic lenses are required for forming images on sensors. This method has two disadvantages, both of which accrue from the fact that the accessible aperture stands inside the relay system. First, mounting and calibrating these achromatic lenses and the imaging lens is quite complicated [8]. Second, a splitter needs to be mounted inside the relay lens, which restricts the choice of the relay system to an achromatic pair, which is simple but provides low-quality images.

In the following two sections, we present two relay systems that provide external access to the aperture without requiring any modification of the lens structure, and two applications of the external aperture to adding new imaging capabilities to a given imaging system.

3. Proposed fore-attached relay system in CIS1

This section presents one of our relay systems, the fore-attached relay system used to build our CIS1. It provides the desired external access to the image and aperture planes using an afocal relay system in front of the imaging lens. Specifically, CIS1 (1) repositions the camera aperture from within to the front of the lens, (2) provides an intermediate image plane which is optically conjugate to the camera sensor, and (3) preserves the imaging properties of the imaging lens.

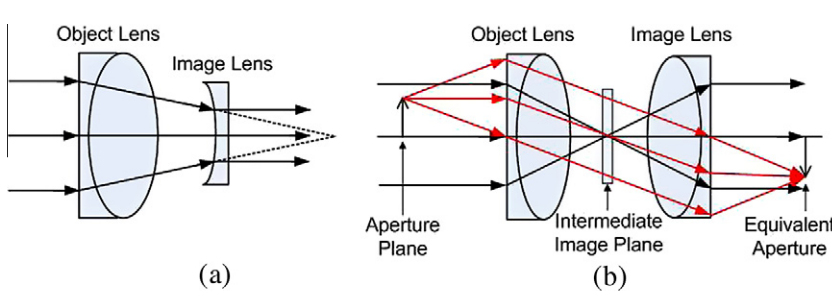

Fig. 3. (a) A Galilean afocal system consists of a positive object lens and a negative image lens. (b) A Keplerian afocal system (or mounted achromatic pair) employs two positive lenses as the object and image lenses. In both systems, the back focal points of the object lens and the image lens are located at the same position.

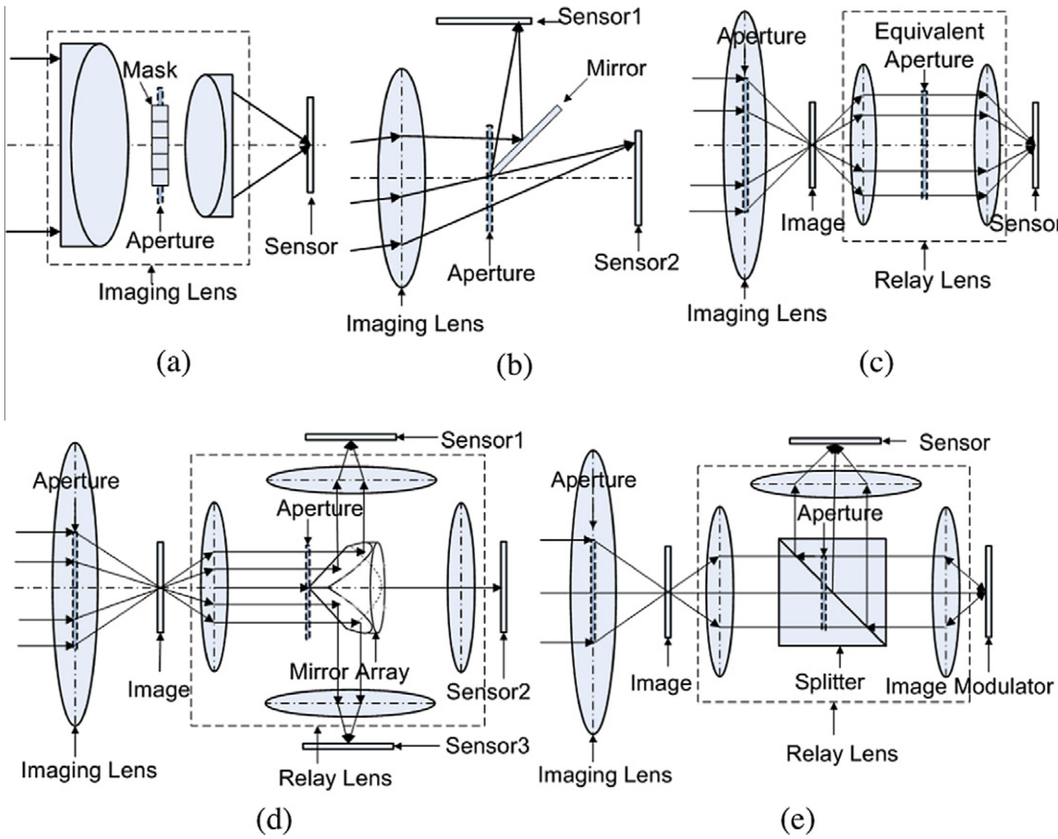

Fig. 4. (a) Modified lens for placing a mask on the aperture. (b) Custom imaging lens with its aperture outside lens housing. (c) Rear-attached relay lens and two of its applications: (d) aperture splitting by mounting a mirror array on the equivalent aperture plane and (e) image modulation by placing a modulator on the intermediate image plane.

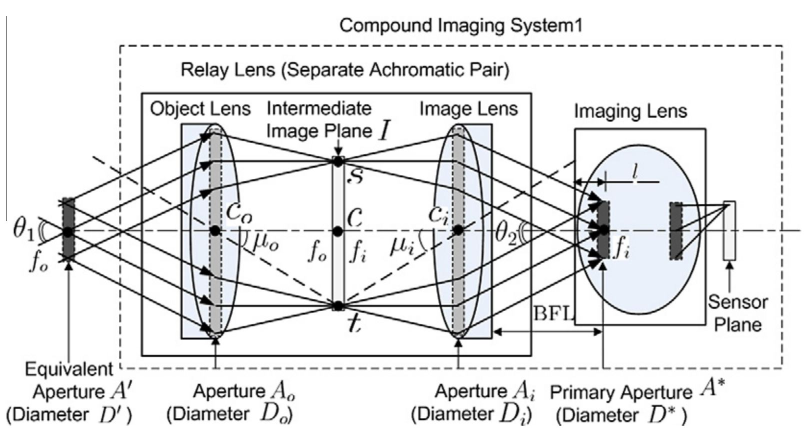

Fig. 5. The optical layout of the proposed compound imaging system CIS1. By mounting a relay lens in front of an imaging lens with the primary aperture A^* at the rear focus plane of its image lens, CIS1 provides an equivalent aperture A' in front of the relay lens and an intermediate image I inside the relay lens. BFL denotes back-focal-length.

3.1. Design

Fig. 5 shows a schematic of CIS1 wherein an afocal relay system is attached in front of an imaging lens [6]. Our relay system consists of the object lens (focal length f_o and aperture A_o with diameter D_o) and the image lens (focal length f_i and aperture A_i with diameter D_i). We achieve afocal imaging by cascading these two achromatic lenses, with their focal points colocated at C. By mounting this relay system such that its rear focal plane coincides with aperture A^*, we relocate the primal aperture A^* to the equivalent aperture A' which is external and accessible (Fig. 5). Since this collocation ensures that $C_oC_i = f_i + f_o$, a pencil of parallel imaging beams passing through an afocal system remains parallel, thus forming an image at the infinite-distance plane where its object stands. Thus, we preserve the imaging properties of the imaging lens. In addition, an intermediate image plane I is formed inside the afocal relay system which is also accessible for image modulation.

3.2. Imaging properties

3.2.1. Angular magnification and transverse magnification

To describe the object-to-image relations, we introduce the angular magnification Γ and the transverse magnification M. Γ is the ratio of the angle μ_i subtended at the imaging lens by the image

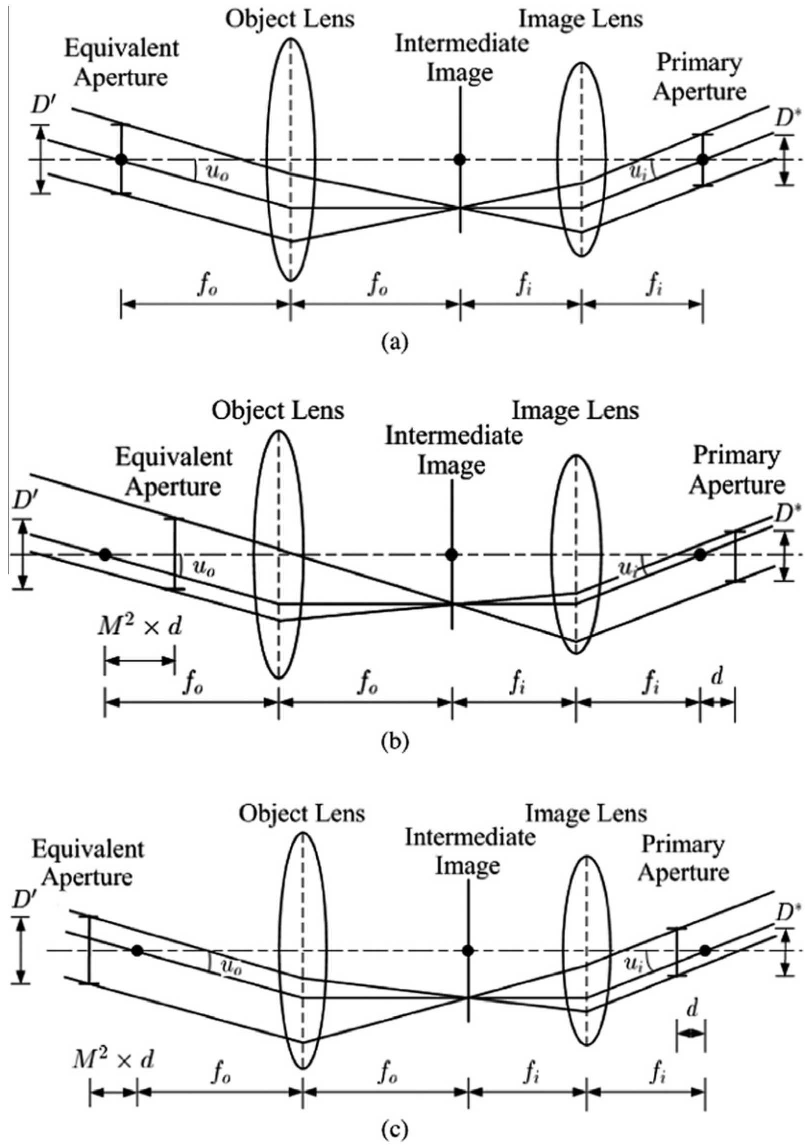

Fig. 6. Illustrations of the position and size of the equivalent aperture as the position of the primary aperture changes relative to the rear focal plane. The primary aperture stands (a) on, (b) closer than, and (c) farther than the focal plane.

to the angle μ_o subtended at the imaging lens by the object. M is the ratio of the size D' of the equivalent aperture A' to the size D^* of the aperture A^*, as shown in Fig. 5. In our afocal relay system, Γ and M are equal and, ideally, unity.

$$\Gamma = \frac{\tan \mu_i}{\tan \mu_o} = -\frac{f_o}{f_i} = -\frac{D'}{D^*} = M \tag{1}$$

The minus sign indicates the image formed after our relay system is inverted vertically.

3.2.2. Position and size of the equivalent aperture

As mentioned above, the external aperture A' is conjugate to the primary aperture A^* of the imaging lens. In this section, we discuss how positioning of the relay lens affects the position and size of the equivalent aperture A'.

1. *Case 1: A^* is placed on the rear focal plane of the image lens.* When the primary aperture A^* of the camera lens is placed exactly on the rear focal point of the image lens, the equivalent aperture A' is imaged at the front focal point of the object lens, as shown in Fig. 6a. According to the Lagrange invariance constraint [23], the size of the equivalent aperture A' is M times the size of the primary aperture A^*, denoted as $D' = -M \times D^*$, while the CIS1 FOV is $-1/M$ of the FOV of the camera itself.
2. *Case 2: A^* is placed within or beyond the rear focal plane of the image lens.* When the primary aperture A^* is located within or beyond the focal distance of the image lens, the equivalent aperture A' is located beyond or within the focal distance of the object lens, as illustrated in Fig. 6b and c respectively. If the distance between the primary aperture and the rear focal point of the image lens is d, then the secondary aperture is shifted away from the front focal point of the object lens by a distance of $M^2 \times d$. Given d is small, the longitudinal magnification is constant and equal to M^2. Let define the sign of d as positive if A^* is placed beyond the rear focal plane and negative if it is within the rear focal plane, the size of the equivalent aperture is independent of d, denoted as $D' = -M \times D^*$. When aperture A^* moves farther from the rear focal point of the image lens by a distance equal to or larger than f_o/M^2, the equivalent aperture A' overlaps with the object lens or lies within the relay system.

Thus, the maximal distance l of the aperture A^* from the rear vertex of the image lens should be f_o/M^2 + BFL, where BFL is the back focal length of the image lens.

It should be noted that shifting the relay system away from the imaging lens has no effect on FOV and DOF of the host camera (consisting of the imaging lens and the sensor), which depends only on the angular magnification Γ of the afocal relay system (1). Thus, the distance between the afocal relay system and the imaging lens (or exactly A^*) can be flexible, except for the constraint ($l \leqslant f_o/M^2$ + BFL). However, placing A^* at the rear focal point of the image lens with $f_o = f_i$ will result in a symmetric relay system. Obviously, the symmetric structure will simplify the optical lens design, as some of the lens aberrations can be canceled out. There is no need for scaling the aperture size, DOF or FOV of the host camera. Therefore, a symmetric afocal relay system with A^* at its rear focal point is preferred.

3.2.3. Field-of-view and aperture of relay system

The key task for constructing our compound imaging system CIS1 is to design an afocal relay system, whose FOV and aperture match very well with those of the host camera. The conditions on BFL, FOV, and aperture of our relay system are as follows:

1. *Field-of-view.* According to (1), the FOV of the relay system is given by:

$$\tan\theta_1 = -\tan\theta_2 \frac{f_i}{f_o} \tag{2}$$

   where θ_1 and θ_2 are the FOV of the relay system and the host camera respectively. Specifically, the afocal relay system should support the intermediate image I of diameter larger than $2f_i \tan\frac{\theta_2}{2}$.
2. *Aperture.* According to reversibility of optical path, every light beam through the primary aperture A^* (Diameter D^*) within the FOV (θ_2) should pass through the fore-attached relay system. For simplicity, we can denote the aperture of our afocal relay system as two separate apertures—the aperture (Diameter D_o) of the object lens and the aperture (Diameter D_i) of the image lens. The geometrical conditions on the apertures of the relay system are as follows.

$$\begin{aligned} D_i &\geqslant D^* + 2f_i \tan\frac{\theta_2}{2} \\ D_o &\geqslant M \times \left(D^* + 2f_i \tan\frac{\theta_2}{2}\right) \end{aligned} \tag{3}$$

4. Proposed rear-attached relay system in CIS2

This section presents our second relay system, the rear-attached relay system, used to build the CIS2. As we mentioned above, by attaching the relay system behind the imaging lens, CIS2 provides a rear access to the aperture for aperture manipulation applications.

As shown in the Fig. 7, the rear-attached relay system is mounted with its frontal $2f$ plane at the image plane of the imaging lens. Thus, it repositions the image plane to the sensor plane, which is located at its rear $2f$ plane. In addition, our relay system relocates aperture A_1 at the equivalent aperture A_1' between the relay lens and the sensor.

The aim of this proposed relay system is to gain external access to aperture A_1 behind the imaging lens and relay lens (Fig. 7) without altering the imaging properties. To achieve this goal, our design of this relay system must meet three major conditions: (1) reform an image at the sensor plane with unit magnification ratio, (2) provide an equivalent aperture A_1' (an optical conjugate to aperture A_1) behind the relay lens, and (3) allow relay lens optimization, which is independent of aperture manipulation.

4.1. Equivalent image with unit magnification

As mentioned in Section 3.2.2, the symmetric relay system is preferred in the optical design. We wish to concatenate the relay system and the imaging lens, with the image plane on the frontal $2f$ plane of the relay system. This would then form an equivalent image on the sensor with unit magnification ratio, without modifying the imaging properties of the host camera. However, in practice, it is difficult to control the distance between the relay system and the imaging lens precisely so as to achieve unit magnification. So, we will study how positioning affects the position and size of the equivalent image. This is similar to the analysis (Section 3.2.2) of how the position of the relay lens affects the position and size of the equivalent aperture. For instance, if the image plane is displaced by d from the $2f$ focal plane, then the equivalent image is shifted away from the rear $2f$ focal plane by a distance of M^2d, given that the transverse magnification M is constant and equals $M = -\frac{f_o}{f_i}$, where f_o and f_i are respectively the focal lengths of the object and image lenses. Accordingly, the magnification ratio of the equivalent aperture is equal to the magnitude of the transverse magnification $-M$.

4.2. Effective aperture behind relay system

To relocate an effective aperture A_1' behind the relay system, the design of our relay system involves two requirements: forming an

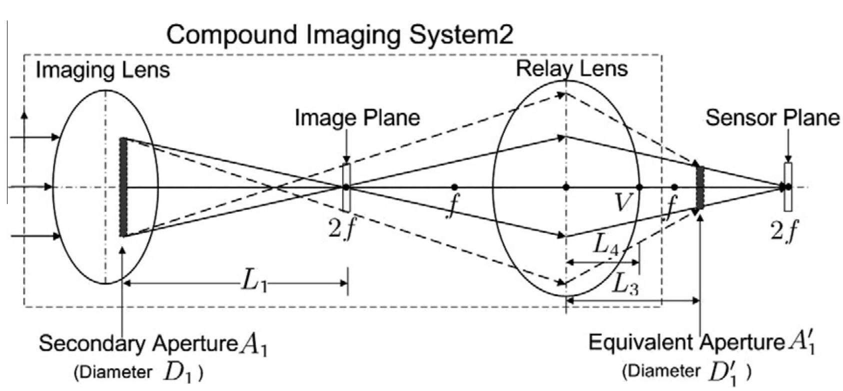

Fig. 7. The optical layout of the proposed compound imaging system CIS2. By mounting a relay lens behind the imaging lens with the image plane at the $2f$ point of the relay lens, CIS2 provides the equivalent aperture D_1' behind the imaging and relay lenses.

image A_1' of A_1 behind the relay lens and making sure that any imaging beam passing through A_1 will not be blocked by the relay system.

First, to form an image A_1' of A_1 behind the relay lens, we need to determine the focal length f and the structural parameter L_4 for the relay system, where L_4 denotes the distance between the rear vertex V and the center of the relay lens. Suppose that the distance between A_1 and the image plane is L_1 and the distance between A_1' and the optical center of the relay lens is L_3. According to the object-to-image relationship [23], i.e., $\frac{1}{f} = \frac{1}{L_1+2f} + \frac{1}{L_3}$, the image distance L_3 is determined as follows:

$$L_3 = f + \frac{f^2}{f + L_1} \tag{4}$$

Below, we describe two designs of the relay lens that can provide rear accessible apertures.

1. *Design 1: the rear focus point is selected to be outside the relay lens* ($L_4 \leqslant f$). From (4), we have $L_3 > f \geqslant L_4$, and thus A_1' is formed behind the relay lens. This kind of relay lens can be employed for gaining external access to the aperture of any imaging lens.
2. *Design 2: the rear focus point is selected to be inside the relay lens* ($L_4 > f$). In this case, the image distance L_3 of A_1' must be larger than L_4. According to (4), given that an imaging lens with L_1, the focal lens and structural parameters of the relay lens must satisfy the condition, i.e., $\frac{f^2}{L_4-f} - f > L1$.

Second, we must ensure that any imaging beam passing through A_1 is not blocked by the rear-attached relay lens. In the compound imaging system, there are always two apertures—aperture A_1 (relative aperture: D_1/L_1) in the imaging lens and aperture A_2 (relative aperture: D_2/L_2), the secondary aperture of relay lens. The one with smaller relative aperture controls the imaging beam and hence is called the effective aperture. Since it is not desirable to relocate the effective aperture inside the relay lens, similar to the previous method (Fig. 4c), we design our relay system with a larger relative aperture than that of the imaging lens. In this case, our proposed relay system repositions the effective aperture A_1 to A_1' outside the relay lens. As shown in Fig. 8, the equivalent aperture A_1' is conjugate to the aperture A_1, and thus their relative apertures should be equivalent ($D_1'/L_1' = D_1/L_1$). In the following, we present two conditions on the relative aperture $\frac{D_2}{L_2}$ of the relay lens.

1. *The condition for the aperture to be effective.* For the aperture A_1 and its image A_1' to be effective, any imaging beam originating from point O within the cone angle $\angle GOH$ must be allowed to pass through the aperture A_2. Thus, it is required that $D_2/L_2 \geqslant D_1'/L_1' = D_1/L_1$.

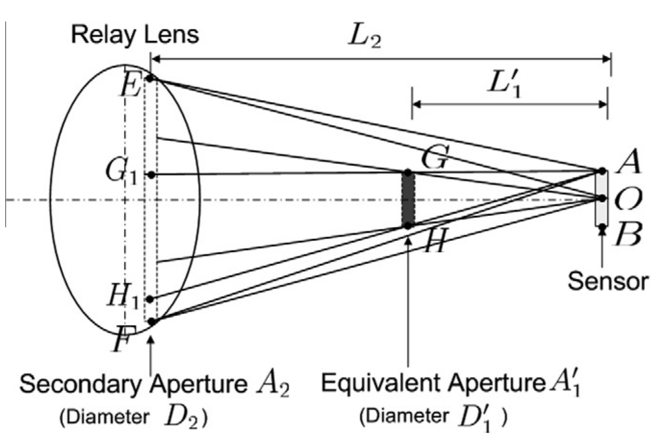

Fig. 8. Relationship between the image lens aperture A_1 (or equivalently A_1') and the relay lens aperture A_2.

2. *The condition for avoiding vignetting.* To suppress optical vignetting, every point on the sensor should receive the same amount of irradiance, given the radiances of outside scene points are the same. Since A_1' (Dia: GH) is the effective aperture, any imaging beam passing through A_1' is able to go through A_2 without being blocked. To satisfy this condition, specific ray (AHH_1) should go though A_2. We hence derive the relationship of A_1 and A_2, which is the prerequisite to avoid any vignetting effect.

$$\frac{D_2}{L_2} \geqslant \frac{D_1}{L_1} + |AB| \cdot \frac{L_2 - L_1'}{L_1' \cdot L_2} \tag{5}$$

4.3. Imaging quality

It is required that attaching a relay system not degrade the quality of the image formed by the imaging lens. In general, there is no ideal lens that forms a point image of a point object. By attaching a relay lens, the imaging quality of the host camera will decrease to some extent. To the best possible quality, we need to improve the point spread function of the relay lens, which depends on the material, shape, and positions of individual lenses constituting the relay lens. The previous relay system (Fig. 4c) requires that a modulator be mounted on the equivalent aperture inside the relay lens, which limits the selection of relay lens to simple achromatic pairs and thus decreases the imaging quality. By repositioning the accessible aperture outside the relay lens, our CIS enables us to optimize the relay lens and manipulate the aperture simultaneously. Thus, we can preserve the quality of the image provided by the optimized relay lens (Fig. 9a).

Using the optical design software ZMAX, we simulate the imaging quality of achromatic pairs and our optimized relay lens, both of which are available from Edmund Optics. Modulation transfer function (MTF) is the most widely used method of describing lens performance. MTF is defined as the response of an optical system to an image decomposed into sine waves. It measures how faithfully the lens reproduces detail from the object to the image. In general, the imaging quality of a lens can be represented by the 0.5 cut-off frequency of MTF [23]. According to Fig. 9b, the cut-off frequency of the optimized relay lens is up to 90 lines/mm, which is much higher than that of the achromatic pairs (<10 lines/mm).

5. Applications of aperture manipulation with our CIS

In this section, we present some applications of aperture manipulation that are made easier by our CIS systems. As mentioned in Section 1, CIS1 enables single-viewpoint panoramic imaging by controlling the aperture orientation in front of the imaging lens. CIS2 makes it more practical to split the aperture for HDR imaging, requiring just one off-the-shelf imaging lens and one relay lens.

5.1. Panoramic imaging with fore-attached relay system

In comparison with a pin-hole camera, optical lens has the advantage of gathering a large amount of incoming light using a large aperture. However, optical lenses restrict access and control of the geometric and photometric properties of the aperture [25]. Our fore-attached relay system offers the possibility to regain this access and control. Below, we present one of the applications of CIS1—controlling the aperture orientation for panoramic imaging.

A camera that can capture a large FOV from a single viewpoint is highly desired in many applications. However, with a regular imaging lens, it is impossible to place multiple cameras at a viewpoint due to physical conflict. Many efforts have been made to solve this problem. For example, planar mirrors are used to virtually co-locate

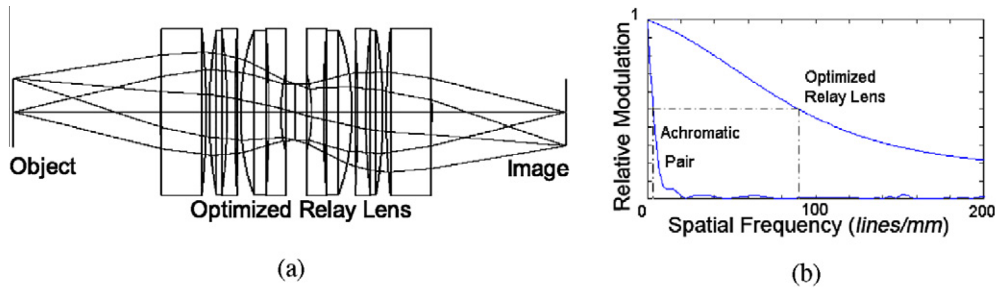

Fig. 9. (a) Optical structure of the optimized relay lens. (b) MTFs of the mounted achromatic pair and the optimized relay lens.

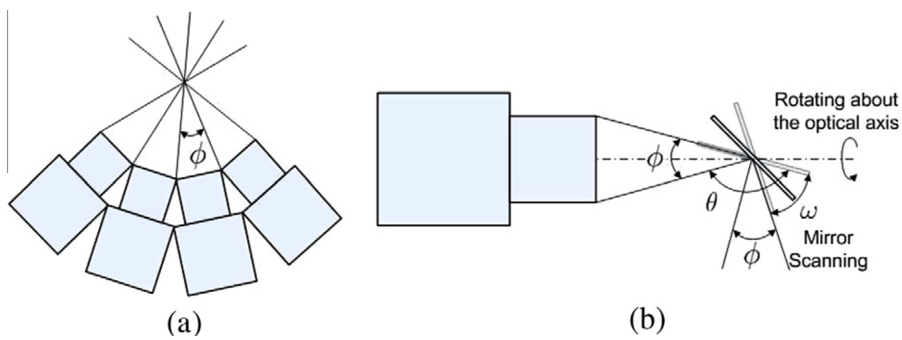

Fig. 10. Panoramic imaging systems enabled by our CIS1. (a) The optical centers of the cameras are co-located at the single viewpoint. (b) The mirror located at the viewpoint rotates about the optical axis of the camera while panning in the vertical direction to acquire images that are merged to construct a panoramic image. The resulting FOV has cylindrical shape, ψ in vertical by $360 - 2\phi$ in horizontal, where (ψ, ϕ) are vertical and horizontal FOV of the still camera. The half FOV of the scanning camera is $\theta = 180 - \phi$. The maximum mirror scanning angle is ω where $\omega = 90° - \phi$.

the cameras [10,17] or curved mirrors are used to increase the camera FOV while preserving a single viewpoint [14,18]. By bringing the optical center out in front of the lens housing, our fore-attached optical system is capable of co-locating multiple cameras with a common viewpoint and allowing single-viewpoint omni-directional imaging, as shown in Fig. 10a. However, the apex angle of the FOV cone for this system is less than the hemispherical angle 180°, because the FOV of some camera might partly be blocked by other camera bodies. Furthermore, the front surface of the lens cannot be round, since a round lens will result in FOV gaps.

An alternative to the camera cluster solution is to use a mirror to control the orientation of the equivalent aperture, as shown in Fig. 10b. When a rotating planar mirror is placed at the secondary aperture with its rotation axis passing through the center of the secondary aperture, the mirror rotates around the optical center of the camera; a large FOV can be scanned as a result of the rotation. The resulting FOV has cylindrical shape, ψ in vertical by $360 - 2\phi$ in horizontal, where (ψ, ϕ) are vertical and horizontal FOV of the still camera. The maximum mirror scanning angle is ω where $\omega = 90° - \phi$. Compared with methods that rotate the entire camera [11] and the existing rotating mirror system [16], a camera based on this rotation scheme offers the advantages of higher scanning speed, due to the considerably low torque required for rotating the lightweight mirror, while maintaining the capability of single-viewpoint imaging.

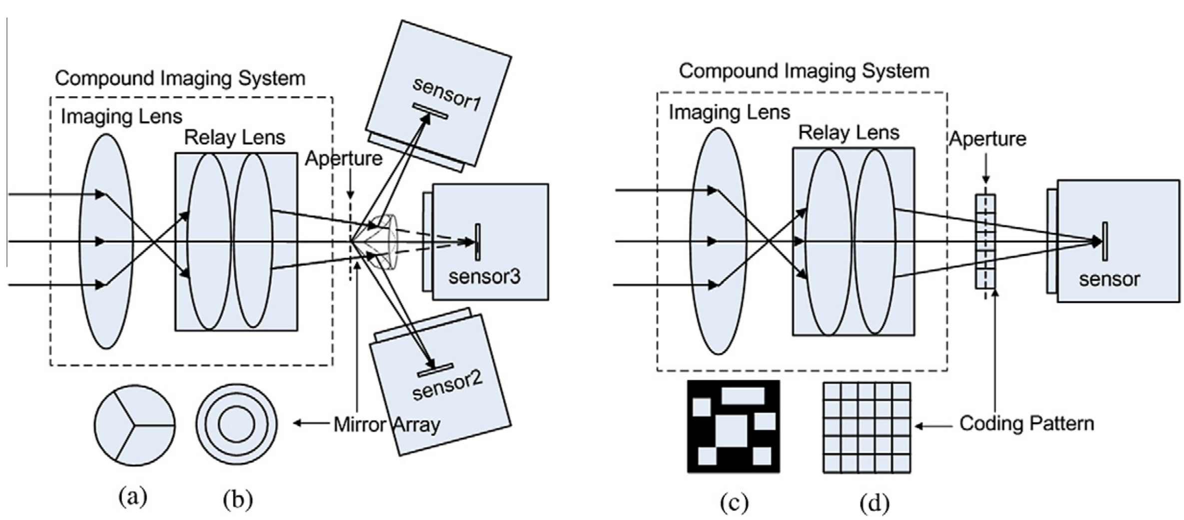

Fig. 11. Aperture manipulation with our CIS2. (1) Aperture splitting: (a) HDR imaging using fan-shape mirror array and (b) multi-aperture photography using circular mirror array. (2) Aperture coding using (c) coding pattern and (d) spatial light modulator (SLM).

5.2. HDR imaging with a rear-attached relay system

In this section, we present two applications of CIS2—aperture splitting (Fig. 11a and b) and aperture coding (Fig. 11c and d). For aperture splitting, previous methods (Fig. 4d) require one achromatic lens to be mounted in front of each sensor and thus necessitate calibrating multiple lenses and sensors. For splitting the aperture for HDR imaging [13] and multi-aperture photography [8], our CIS just needs to mount the mirror array on the outer aperture, and sensors on the equivalent image planes (Fig. 11a and b). For aperture coding [24,13], our CIS allows inserting complex aperture filters and replacing the aperture modulators (Fig. 11c and d), much more easily than previous methods (Fig. 4a).

We demonstrate the performance of CIS2 by splitting its external aperture for real-time HDR imaging. We replace the costly customized lenses [9,4] with two off-the-shelf lenses (an imaging lens and a relay lens).

5.2.1. Necessity of mounting splitter on aperture

As shown in the Fig. 11a, by mounting a mirror array and multiple sensors behind the compound imaging system, we can split the aperture for HDR imaging [4] and multi-aperture photography [8]. Now, we try to explain the necessity of placing the mirror array at the aperture plane, along with the optical axis. As shown in Fig. 12, suppose the distance between the aperture and the sensor is L, we place the mirror pyramid at the distance of D from the aperture plane, with an offset (s,t) from the optical axis. Along the rays coming from any pixel (x,y) on the sensor, we can project the mirror onto the aperture. The projection of the mirror center is (u,v).

$$\begin{cases} u = s + (s - x)\frac{D}{L-D} \\ v = t + (t - y)\frac{D}{L-D} \end{cases} \tag{6}$$

We partition the aperture plane into three sub-apertures (S_1, S_2, and S_3). If D is non-zero, the coordinates (u,v) of the mirror center and the size of sub-apertures depends on the location of the corresponding pixel (x,y) on the sensor. In this case, the size of the sub-aperture (S_i, i = 1, 2, or 3) varies as the pixel (x,y) moves from the sensor center to its edge, which causes the vignetting effect (the intensity variation across sensor). Therefore, to suppress the vignetting effect, we should mount the mirror array with its vertex on the aperture ($D = 0$). This ensures that every pixel on the same sensor is identically exposed. Furthermore, for HDR imaging, each sensor should be under varying exposure. Thus, we mount the splitter on the aperture with non-zero offset (s,t) from the optical axis and capture images through sub-apertures of various sizes.

5.2.2. Splitting aperture for extending HDR

As shown in Fig. 11, we place a mirror array on the aperture and shift it in the aperture plane to split the aperture asymmetrically. Through sub-apertures of various sizes, we can capture multi-exposure images. The dynamic range of the CCD detector can be defined as the ratio of the maximum to the minimum electron charge measurable by the potential wells, or as the ratio of the maximal ($I_{\max}$) to the minimal ($I_{\min}$) detectable radiances [20], as shown in (7). This HDR imaging system enhances the normal dynamic range by the area ratio of the maximal to minimal sub-apertures, as shown in (7). In addition, we can choose a mirror array with 6 or more facets to widen the dynamic range.

$$\begin{aligned} DR &= 20\log\frac{I_{\max}}{I_{\min}} \\ HDR &= 20\log\left(\frac{I_{\max}}{I_{\min}}\frac{\max_i S_i}{\min_i S_i}\right) \end{aligned} \tag{7}$$

6. Simulation and experimental results

In this section, we will show some experimental results obtained from our compound imaging systems consisting of a conventional imaging lens and an off-the-shelf relay lens. We also verify that both CIS1 and CIS2 are practical solutions for aperture manipulation. In the following subsections, we will describe CIS1 and CIS2 prototypes, as well as their calibration, evaluation, and application.

6.1. CIS1 prototype and calibration

We build the CIS1 prototype using an afocal system, similar to that in [6]. Typical afocal systems have very limited FOV (i.e., only a few degrees), which is too small for many vision applications. For CIS1, a pair of eyepiece lenses, mounted back to back, is used to form an afocal system. The lens pair is designed for Virtual Research V8 HMD (Head Mounted Display), which has a 60° FOV (diagonal) for a 1.3-inch micro-display and an equivalent focal length of 28.6 mm. We choose the eyepiece lens because it has a

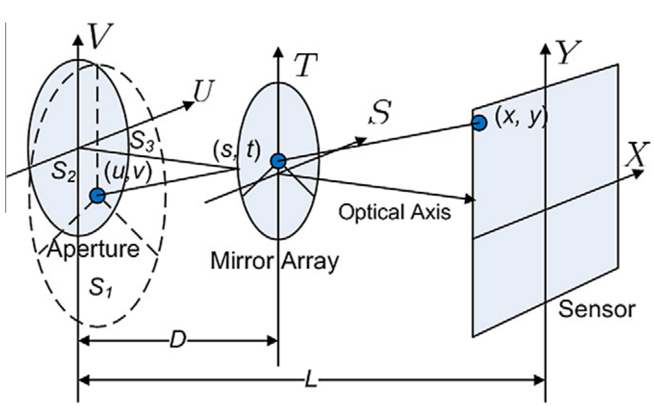

Fig. 12. Vignetting in images captured through sub-apertures. Each facet of the mirror array reflects part of the incoming rays and forms an image on its corresponding sensor plane $X-Y$. By projecting the mirror array onto the aperture plane $U-V$ from pixel (x,y), the aperture is partitioned into three sub-apertures (S_1, S_2, and S_3, depicted by dashed lines). The lightness of pixel (x,y) is proportional to the area of the corresponding sub-aperture.

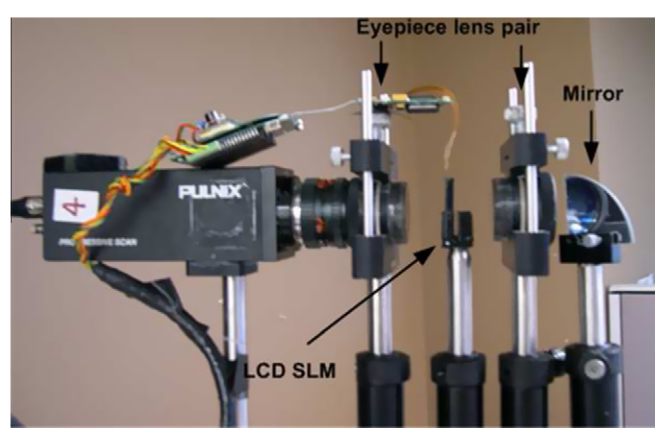

Fig. 13. Experimental setup of CIS1. The fore-attached relay system consists of two eyepiece lenses. This relay system is positioned with the primary aperture on the rear focal point of one eyepiece lens. Between the two eyepiece lenses, a LCD spatial light modulator is mounted on the intermediate image plane for image modulation applications. A mirror mounted on the accessible aperture can be rotated on the axis, which is aligned with respect to the equivalent aperture plane.

long eye relief (10–30 mm), wide FOV, and large aperture. In this way, the primary aperture of the imaging lens and its equivalent aperture help control the incoming beam in CIS1. Fig. 13 shows the experimental setup. The host camera is a B/W analog camera with a 2/3″ CCD sensor (640×480 pixels), equipped with a 16 mm CCTV lens. The diagonal FOV of the camera is around 38°. The primary aperture of the imaging lens is manually adjustable in the range 0–14 mm. Table 1 shows the intrinsic parameters of the CCTV imaging lens and CIS1 with relay lens. The parameters are estimated using the Camera Calibration Toolbox [1]. The focal length of CIS1 is close to that of the original imaging lens, which indicates that the magnification of the relay system is very close to 1. The principal point of CIS1 shifts from that of the imaging lens due to misalignment of the relay system with the imaging lens. The misalignment was captured by the calibration and can be compensated in image post-processing step. Also notice that the distortion of CIS1, is more than twice that seen with only the imaging lens, which implies the large distortion of the relay system.

6.2. Evaluation and application of CIS1

Two experiments were designed to verify that the primary aperture A^* is indeed imaged out and the equivalent aperture A' is indeed the optical center of the composite system after adding the relay system. In the first experiment, we replace the camera CCD sensor with a flat-panel light source to illuminate the lens pupil. At the object side, a white paper is used as a diffusion screen. If the lens pupil is relayed to outside the camera, a real image of primary aperture A^* should be expected on the equivalent aperture plane. Fig. 14 shows the experimental setup and the images on the white paper as the paper moves along the optical axis away from the relay lens. It clearly shows that a real image of aperture A^* is formed (Fig. 14c) on the equivalent aperture plane. The second experiment is conducted to verify that the optical center of the composite system is indeed the secondary aperture. We place a checker board in front of the camera and estimated the distance from the board to the camera based on calibrated intrinsic parameters of the composite system. The estimated distance is 303 mm, the measured distance from the board to the secondary aperture is around 300 mm, and the distance from the board to the primary aperture of the camera is around 440 mm. This shows that the optical center of the composite system is the equivalent aperture, not the original camera lens center.

To demonstrate geometric control of the aperture, we place a planar mirror on a rotation stage with its rotational axis aligned with the vertical axis of the camera. Since the rotational axis passes through the optical center, the images captured must be from a single viewpoint. Therefore, the image mosaic becomes very simple: the images can be simply overlaid to form a panoramic image, and no geometric warping is necessary. Fig. 15a shows a set of input images; Fig. 15b shows the corresponding panoramic image.

By mounting a spatial light modulator (SLM) on the equivalent image plane, we can use the CIS1 prototype for image modulation. A color LCD spatial light modulator (SLM) is placed at the shared focal point of the eyepiece lenses, for high dynamic range imaging. The mapping from the SLM and the CCD sensor is pre-calibrated using a checker board pattern displayed on the SLM. There are two ways to capture HDR images with the SLM [19–21]. The first method captures HDR images by sacrificing the spatial resolution, where a fixed pattern is displayed on the SLM to vary the exposure of pixels in a neighborhood, and the HDR image is constructed by selecting the "right" response from among the neighbors, thereby

Table 1
CIS1 intrinsic parameters of the imaging system with or without relay lens.

Name	Focal length (pixels)	Principal point (pixels)	Distortion
CCTV Imaging lens	$f_x = 1242.62$ $f_y = 1236.67$	$cc(1) = 329.71$ $cc(2) = 247.30$	$kc(1) = -0.2322$ $kc(2) = -0.3914$
Compound Imaging System1	$f_x = 1277.19$ $f_y = 1270.25$	$cc(1) = 282.28$ $cc(2) = 217.76$	$kc(1) = -0.6198$ $kc(2) = 1.3513$

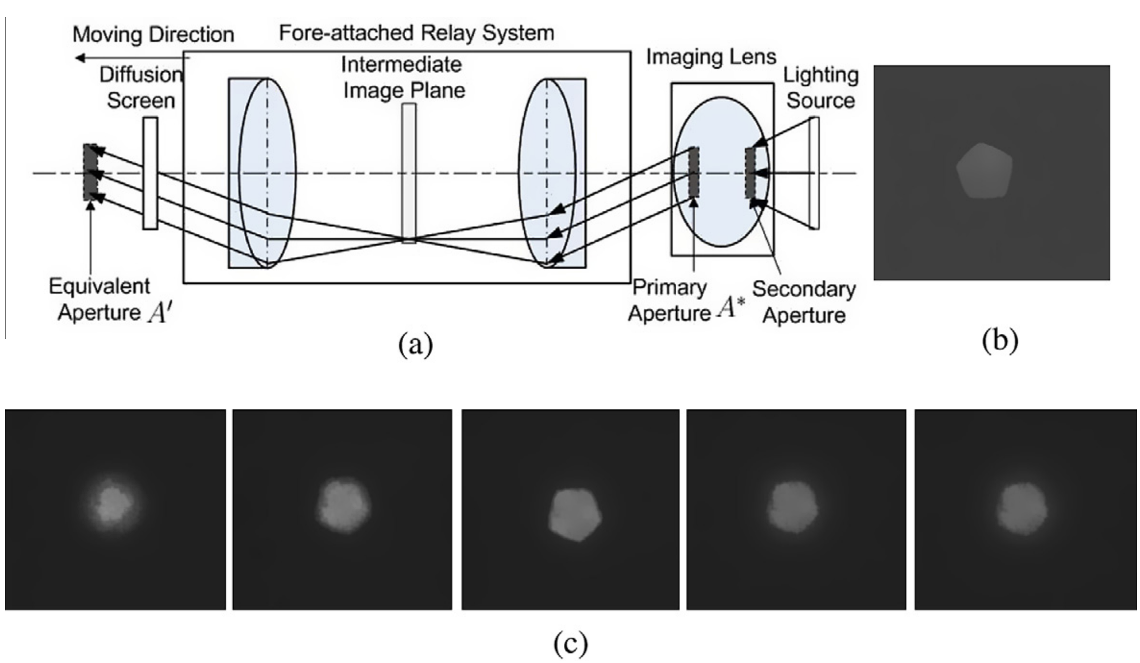

Fig. 14. The experiment on the formation of the secondary aperture. (a) Experimental setup. (b) The image of the primary aperture A^* of the imaging lens. (c) The images of the equivalent aperture on the diffusion screen as the screen moves away from the relay lens along the optical axis. The third sharp image is the one formed on the equivalent aperture A' plane.

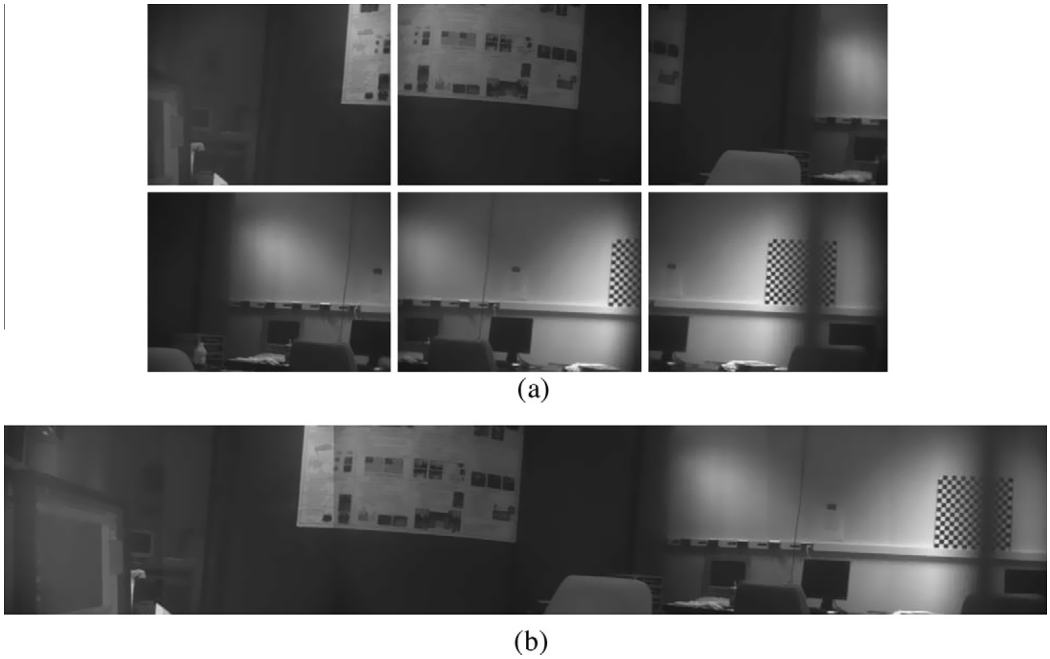

Fig. 15. The application of CIS1 for panoramic imaging. (a) Six input images captured as the mirror rotates; (b) Mosaic panoramic image. In the panoramic image, there are seams between images which are mainly caused by vignetting and cosine-4th effect of the camera lens and added relay system. Since our goal is to show panoramic imaging with the single viewpoint by using CIS1, the intensity difference between input images was not compensated. *Note*: the vertical dark bar is caused by the lens holder of the eyepiece lens close to the mirror.

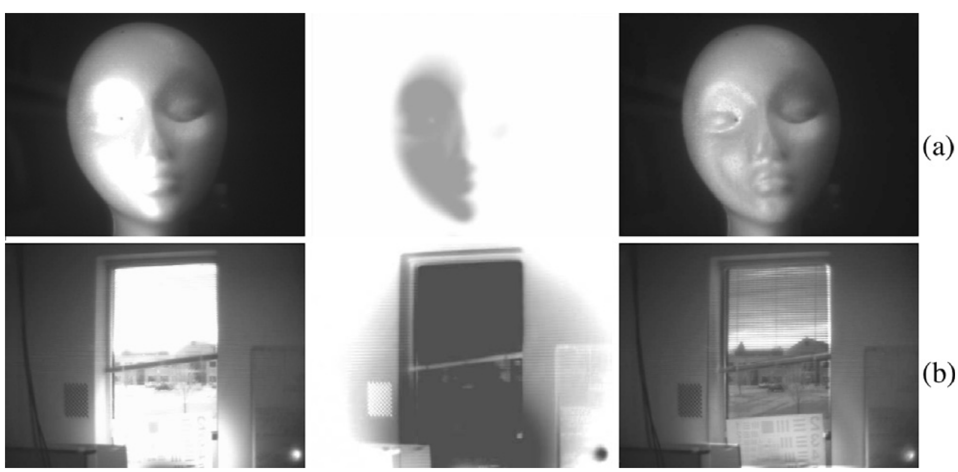

Fig. 16. Sensor modulation for high dynamic range imaging. (a) Foam head scene. (b) Window scene. The first column shows the images captured with a white (full transmittance) pattern displayed on the SLM. The second column shows the feedback masks displayed on the SLM to attenuate the bright pixels present in the captured images. The third column shows the resulting images.

obtaining image samples along a sparser grid and reducing the resolution. The second method is an ''adaptive'' approach which iteratively modifies the display pattern of the SLM until all pixels are properly exposed as seen from the captured image. The bright or saturated pixels on the CCD sensor are reimaged after the input light is attenuated by the corresponding pixels on the SLM. In our experiments, we tested the second approach in two static scenes: foam head scene and window scene. The experimental results are shown in Fig. 16. In the figure, the first column shows the images captured with a white (full transmittance) pattern displayed on the SLM. The second column shows the feedback masks displayed on the SLM to attenuate the responses at the bright pixels present in the captured images. The third column shows the resulting high dynamic range images. The saturated areas near the left eye (the first row) and the saturated window (the second row) become clear after the lights are attenuated by the masks.

6.3. CIS2 prototype and calibration

Since CIS2 repositions both the aperture and image planes outside the relay system, inserting the aperture modulator does not impose any requirement on choosing relay system. Thus,we choose the TECHSPEC globally optimized (that means the object and image lenses are jointly designed to achieve the best imaging quality) relay lens to construct CIS2. Using the optical design software ZMAX, we simulate its modulation transfer function (Fig. 9b) and imaging parameters (Table 2). According to $\text{BFL} = f - L_4 = -12.5$ mm and $\text{EFL} = f = 45$ mm, the focal point should lie inside

Table 2
Parameters of COSMICAR imaging lens and TECHSPEC relay lens in CIS2, where EFL and BFL respectively stand for effective and back focal length.

Name	*EFL* (mm)	*f*/#	L_1 (mm)
COSMICAR imaging lens	25	⩾1.4	47.5
			BFL (mm)
TECHSPEC relay lens	45	4.0	−12.5

the relay lens. By the condition $L_1 < \frac{f^2}{L_4 - f} - f$ in Section 4, we conclude that TECHSPEC relay lens is only suitable for those imaging lenses with their secondary aperture $L_1 < 117$ mm. In general, since the secondary apertures of most imaging lenses satisfy $L_1 < 100$ mm, this optimized relay lens is capable of accessing the aperture of most lenses. We choose a COSMICAR imaging lens, as shown in Table 2. We refocus a LEICA microscope to get the secondary aperture in focus and then adjust the microscope to focus on the mounting plane. The adjustment in distance is an estimate of the position ($L_1 = 47.5$ mm) of the aperture. Thus, we can access the aperture of this COSMICAR lens.

The relative aperture of the relay lens is equal to the reciprocal of $f/\#\left(D_2/L_2 = \frac{1}{f/\#} = 1/4.0\right)$. As discussed in Section 4.2, it is required that the relative aperture of the imaging lens satisfies $D_1/L_1 \leqslant 1/5.6$ to avoid vignetting. In this case, the aperture of the imaging lens controls the incoming beam CIS2. Thus, CIS2 is capable of providing rear access to aperture and image plane.

We build a CIS2 prototype by mounting the imaging lens and relay lens on a optical bench (Fig. 19a). We continue adjusting their relative positions until the two lenses are concentric. The mounting and calibrating process is simpler for CIS2, compared to the previous method that uses a separate achromatic pair. Using the Camera Calibration Toolbox [1], we estimate the intrinsic parameters of the imaging lens and the CIS2 prototype, respectively (Table 3). The focal length of the CIS2 prototype is slightly different from that of the COSMICAR imaging lens, which indicates the magnification ratio of the relay lens is 1:1. The difference between the principal points of CIS2 and the imaging lens is due to the misalignment between the relay lens and the imaging lens. It should be noted that the distortion of the CIS2 prototype, which is due to both the imaging lens and the relay lens, is more than twice that of the COSMICAR imaging lens.

Table 3
Intrinsic parameters of the imaging system with or without the relay lens.

Name	Focal length (mm)	Principal point (pixels)	Distortion (*kc*)
COSMICAR Imaging lens	$f_x = 25.39$ $f_y = 26.62$	$cc(1) = 579.25$ $cc(2) = 353.31$	$kc(1) = -0.20077$ $kc(2) = -15.07476$
Compound Imaging System2	$f_x = 25.73$ $f_y = 26.97$	$cc(1) = 631.71$ $cc(2) = 380.80$	$kc(1) = -0.50684$ $kc(2) = 7.28243$

6.4. Evaluation of image quality of CIS2

In general, due to the insertion of an additional relay lens, the image quality of CIS2 can be expected to decrease to some extent compared to that of the conventional imaging lens. In this section, we test the image quality of the CIS2 prototype using simulation and experimental data.

As shown in Section 4.3, our rear-attached relay system allows the use of a globally optimized relay lens. We analyze the performance of CIS2 in terms of the imaging quality of the relay lens, specifically MTF and point spread function (PSF). The MTF of the optimized relay lens has a half-cutoff frequency up to 90 lines/mm (Fig. 9b). We also evaluate the imaging quality of the optimized relay lens in terms of the spatial domain version of MTF—PSF. PSF is the response of an imaging system to a point source. The PSF of a perfect imaging system is assumed to be one point. Using Zmax, we can simulate the PSF and the spot diagram of the optimized relay lens (Fig. 17). The diameter of the diffusion disc is roughly 10 microns, roughly the size of two pixels. From this simulation result, we conclude that the spherical aberration of this relay lens is quite small. To measure the PSF of CIS2, we place a tiny light point in front of the imaging lens and mount a digital camera (SONY DFW-sx900) at the equivalent image plane of CIS2 (Fig. 19a). To obtain a symmetrical PSF, we capture multiple images of the shifted point source. The PSF of CIS2 is obtained by normalizing the average of those images so that the sum of its elements equals one. As shown in Fig. 18, the PSF of CIS2 is very close to that of the COSMICAR imaging lens without the relay lens, and their diffusion discs only cover the 3×3 pixel patch (pixel size: 4.65×4.65 μm). The measured PSF of CIS2 is close to the simulated PSF of the optimized relay lens.

We now describe our experiments on qualitative evaluation of the imaging quality of CIS2. Initially, we capture an image using a regular camera (Cosmicar imaging lens and SONY DFW-SX900) as the original image. As shown in Fig. 20a, we also capture an image of the same scene with CIS2. Further, we replace the optimized relay lens in CIS2 with an achromatic pair (from Edmund Optics) and recapture an image (Fig. 20b). The image captured with CIS2 (Fig. 20c and f) retains most of the contrast of the original image

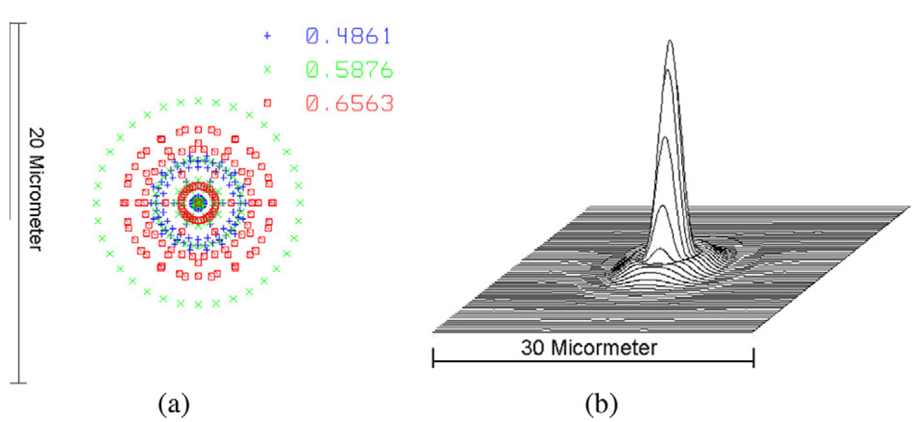

Fig. 17. Parameters of optimized relay lens from simulation. (a) Spot diagram, which is distribution of three imaging beams (red, green and blue) on the image plane from a single point source. (b) Point spread function. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

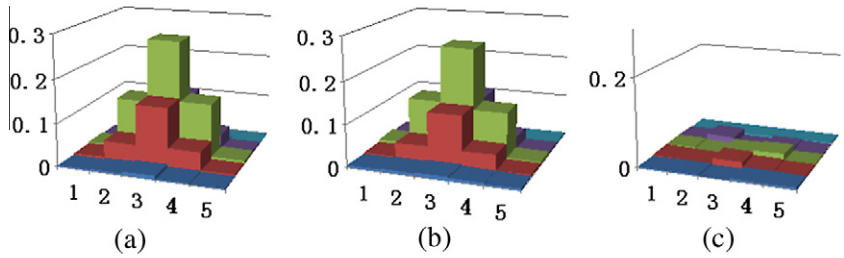

Fig. 18. (a) Measured PSF of COSMICAR imaging lens, (b) measured PSF of compound imaging lens, and (c) their difference.

Fig. 19. (a) CIS2 prototype using optimized relay lens, and (b) CIS2 prototype using achromatic pair.

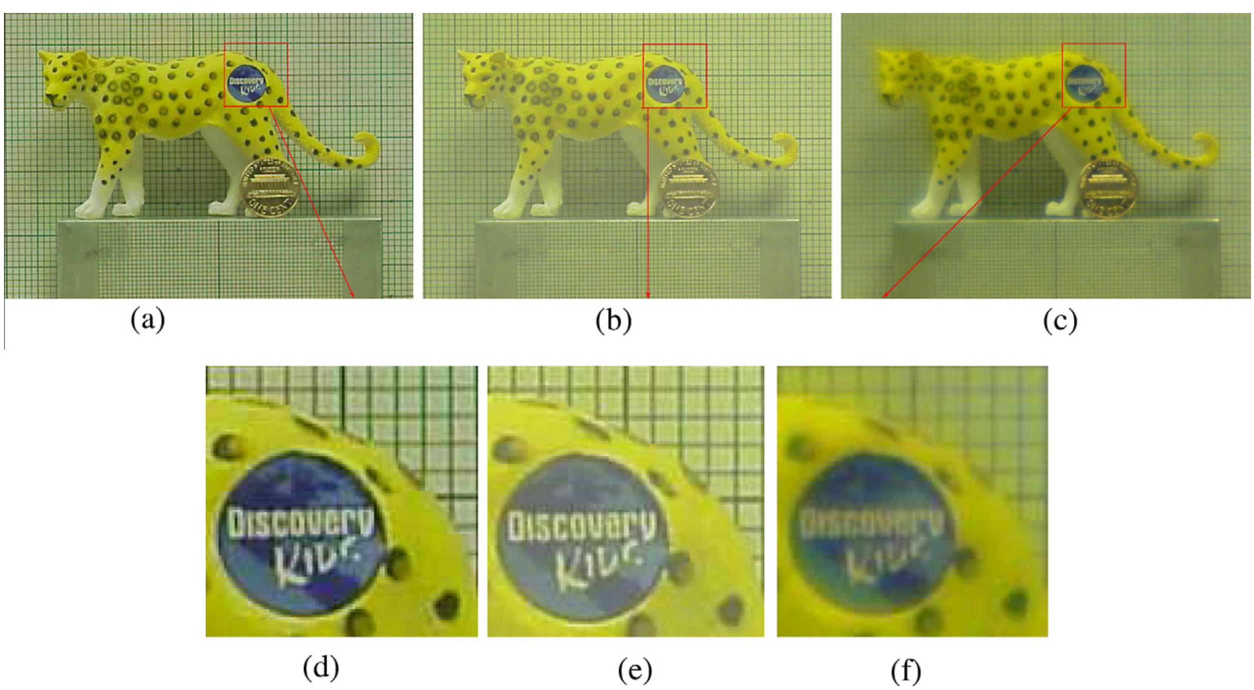

Fig. 20. (a) Original image with close-up (d), (b) image captured with optimized relay lens with close-up (e), (c) image captured with achromatic pair with close-up (f).

(Fig. 20d and g). But the image captured with the achromatic pair is significantly blurred (Fig. 20e and h). These results are consistent with the simulated MTF of the optimized relay lens and the achromatic pair (Fig. 9b).

6.5. Accessible aperture and imaging planes behind CIS2

In this section, we demonstrate that CIS2 indeed repositions the accessible aperture and image planes behind it.

According to (5), if the relative aperture (the ratio of aperture size to focal length) of COSMICAR is adjusted to below 1:5.6 such that any incoming beam passing through it will not be blocked by the relay lens, the CIS2 prototype provides the equivalent aperture and image planes without causing the vignetting effect. To detect the positions of the accessible aperture and image planes, we place a diffusive screen just behind the relay lens (Fig. 21a). While moving away from the relay lens, the screen displays different patterns (Fig. 21b–e). The position of the equivalent aperture is the one where the sharp hexagonal pattern is observed (Fig. 21c), which demonstrates that the CIS2 prototype indeed provides an external aperture behind it. On this accessible aperture plane, we can place any aperture modulator (filters, mirror arrays, or lens arrays) to access and manipulate the aperture. To show the vignetting effect, we capture the image of a uniform lighting box by

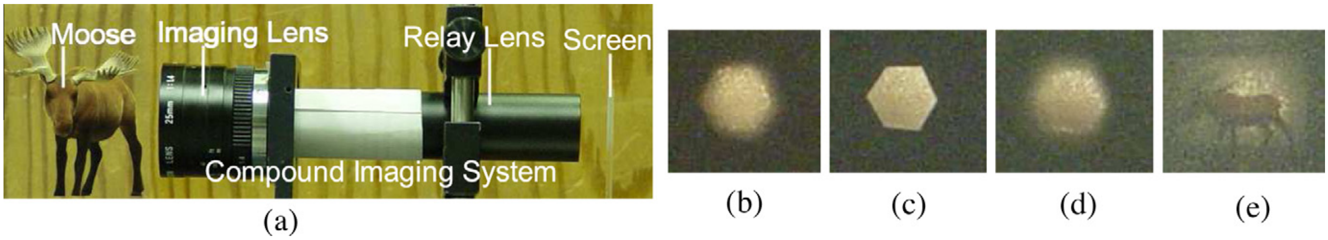

Fig. 21. Accessible aperture and image planes behind our CIS. (a) CIS prototype. The patterns on the screen when it stands (b) in front of, (c) on, (d) behind the aperture plane, and (e) on the image plane. The sharp hexagonal pattern indicates the position of the accessible aperture.

mounting a camera (AVT Guppy F-033) behind the CIS2 prototype. With the same illumination and aperture setting, we capture the image formed between the imaging lens and the relay lens. When the relative aperture of the imaging lens is adjusted to below 1:5.6, the image formed behind CIS2 has the same intensity as that formed behind the COSMICAR imaging lens in the center and decreases to 84% at the corner, as shown in Fig. 22. This kind of vignetting effect is tolerable in computational imaging and can be corrected by calibration.

6.6. Aperture-splitting based HDR imaging using CIS2

In this section, we use CIS2 for aperture-splitting based HDR imaging, similar to [4] except that we replace the costly customized lens with the proposed CIS2. As shown in Fig. 23, we use a three-facet mirror array to partition the equivalent aperture and direct the beam reaching each sub-aperture onto its corresponding sensor. For image acquisition, we choose three cameras (AVT Guppy F-033). The HDR imaging system is constructed by simply mounting the mirror on the equivalent aperture and the sensors on the image planes. By shifting the mirror array in the direction perpendicular to the optical axis, we split the aperture unevenly and capture multi-exposure images through various sub-apertures (Fig. 24a–c). Since almost no rays are blocked or absorbed by the mirror array, we can make full use of the common imaging beam provided by CIS2. For the HDR image reconstruction, we choose the gradient-domain fusion algorithm in [5], which constructs the synthetic gradient field by suppressing large gradients and then searches the optimal image intensity whose gradient field is closest to the synthetic one. From the HDR reconstruction, CIS2 captures the clear image of objects under extreme illumination conditions, such as shading and specular surfaces. The synthetic HDR image (Fig. 24d) illustrates that CIS2 provides a practical solution to aperture-splitting based HDR imaging.

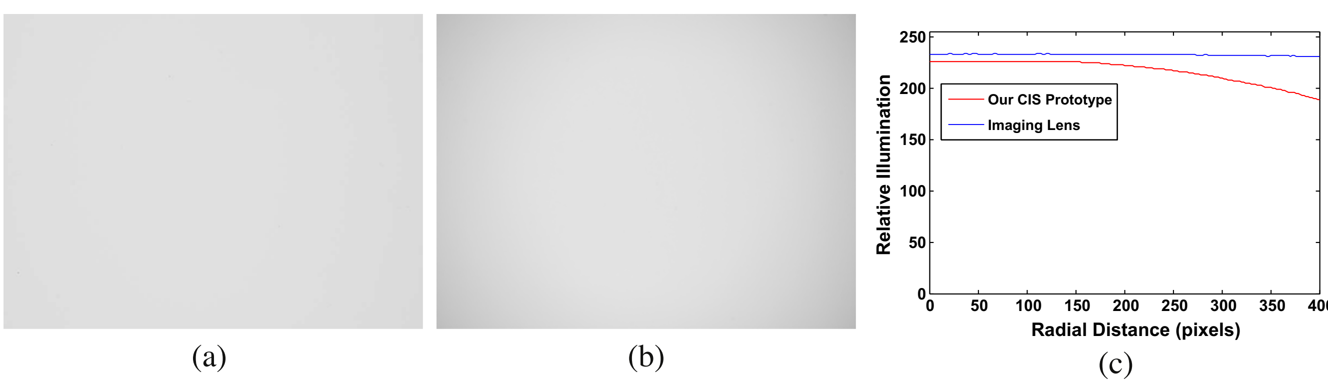

Fig. 22. Vignetting calibration at the imaging lens $f/\# = 5.6$. Images captured from (a) COSMICAR imaging lens and (b) CIS2 prototype. (c) Illumination chart (from center to corner).

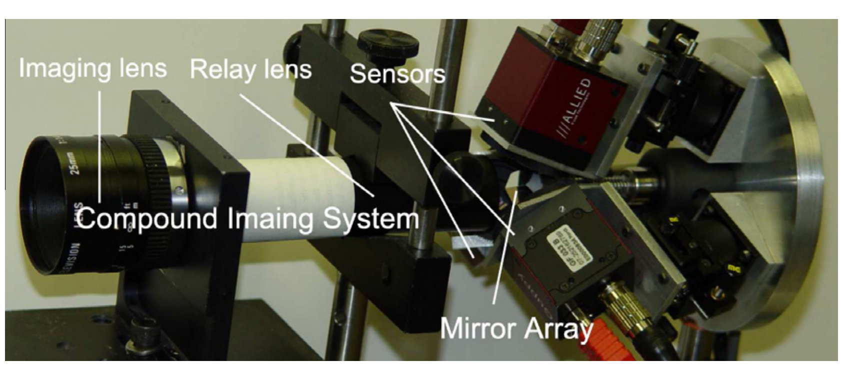

Fig. 23. Prototype of a high dynamic imaging system constituted by CIS2.

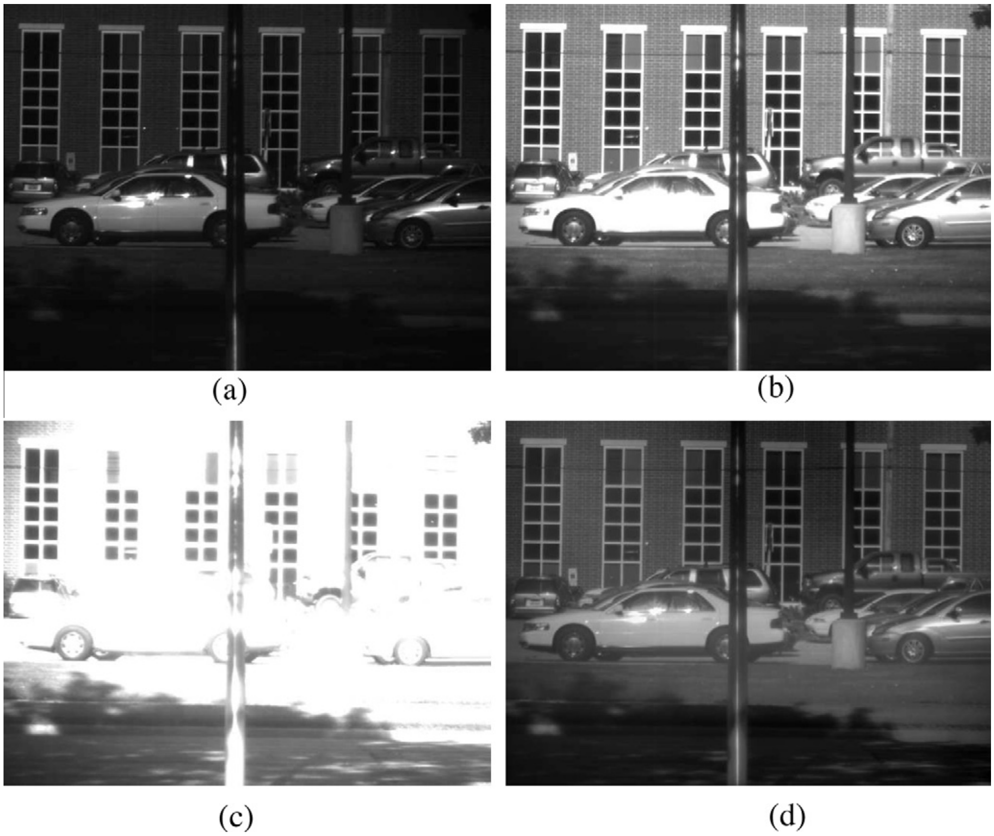

Fig. 24. (a) Under-exposed image, (b) normally-exposed image, (c) over-exposed image, and (d) fused HDR image.

7. Conclusions and discussion

In this paper, we propose two practical solutions to accessing and manipulating aperture—compound imaging systems CIS1 and CIS2. Compared to previous methods, CIS1 and CIS2 can provide externally (front or rear) accessible apertures and image planes simply by attaching an off-the-shelf relay lens, without modifying the structure of the imaging lens. In addition, these compound imaging systems can maintain the high imaging quality of the imaging lens by allowing aperture manipulation and relay lens optimization to be done independently. By repositioning the equivalent apertures at external (front or rear) locations, CIS1 and CIS2 can be used for different aperture manipulation applications. For example, CIS1 provides an externally accessible aperture of the imaging lens, which enables superimposition of multiple apertures at a common optical center for panoramic imaging. CIS2 provides a rear-accessible aperture of the imaging lens, providing a flexible platform for aperture manipulations such as aperture coding or aperture splitting. The experimental results (panoramic imaging on the CIS1 prototypes and HDR imaging on the CIS2 prototype) demonstrate that our CIS systems are indeed practical solutions to aperture access and manipulation.

The major negative point with our design is the limited availability of high-quality, large relative aperture relay lenses. To solve this problem, we might need to design a high-quality relay lenses with the specific focal length and relative aperture, which is much easier than designing a high quality imaging lens with external aperture. Once the high-quality relay lens that meets the requirements in the Section 4.2 is available, the procedure for building CIS1 and CIS2 is quite easy—just mounting the relay lens at some designed distance in front of or behind the imaging lens. In the future, we will design several universal relay lenses with high imaging quality and larger relative aperture, so that our CIS systems can be used for a wider range of aperture manipulation applications.

Acknowledgements

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