

Active Aperture Control and Sensor Modulation for Flexible Imaging

Chunyu Gao and Narendra Ahuja
Department of Electrical and Computer Engineering,
University of Illinois at Urbana-Champaign,
Urbana, IL, 61801
Email: cgao@uiuc.edu, ahuja@vision.ai.uiuc.edu,

Hong Hua
College of Optical Science,
University of Arizona,
Tucson, AZ, 85721
hua@optics.arizona.edu

Abstract

In the paper, we describe an optical system which is capable of providing external access to both the sensor and the lens aperture (i.e., projection center) of a conventional camera. The proposed optical system is attached in front of the camera, and is the equivalent of adding externally accessible intermediate image plane and projection center. The system offers controls of the response of each pixel which could be used to realize many added imaging functions, such as high dynamic range imaging, image modulation, and optical computation. The ability to access the optical center could enable a wide variety of applications by simply allowing manipulation of the geometric properties of the optical center. For instance, panoramic imaging can be implemented by rotating a planar mirror about the camera axis; and small base-line stereo can be implemented by shifting the camera center. We have implemented a bench setup to demonstrate some of these functions. The experimental results are included.

1. Introduction

A camera with large field of view (FOV), high dynamic range, high and uniform resolution is highly desirable in many vision applications. A conventional digital camera is, however, limited in almost all these aspects. In the past few decades, many efforts have been made to overcome some of these limitations and improve the performance of a regular camera by using additional means to modify geometric and photometric properties of the camera. Such modifications often involve the manipulation of the lens aperture or the sensor exposure. For example, in [3], a multi-facet beamsplitter is placed inside the lens near the exit pupil to split light into multiple beams which are then directed toward different sensors. By controlling the exposure setting of each sensor, a high dynamic range image can be constructed by fusing the multiple exposure images. In [13], the camera sensor is replaced by a digital

micro-mirror device (DMD), and a relay lens reimages the micro-mirror on the camera sensor. Since the orientation of the micro-mirror is dynamically controllable, the intensity response of the sensor pixels is also controllable. A number of advanced camera functions can be realized by the controlling the placement of the aperture and modulating the sensor response exemplified by the above methods.

Both of the methods reviewed above require reaching into the housing, and therefore a redesign, of the camera. This paper shows that it is possible to modify a given regular camera externally, to gain dynamic access and control of both the lens aperture and sensor without having to manipulate the internal structure of the host camera. We propose a special optical relay system that can be attached in front of the camera lens to achieve the desired dynamic access and control.

The rest of the paper is organized as follows. Section 2 discusses the basic optical design of the proposed relay system. Sections 3 and 4 present examples of imaging functions and applications that are made easier by the proposed system. The experimental results are presented in Section 5.

2. Proposed Relay System

Our goal is to devise an optical system which can (1) reposition the camera center from within to outside of the lens, and (2) provide an intermediate image plane which is optically conjugated to the camera sensor. As indicated by its name, a relay lens is an optical system which can be used to transfer images from one image plane to another, and is often used to extend an optical system or as an interface to couple two different optical systems [16]. Fig. 1 shows a 1:1 relay system from Edmund Optics. The image on the left side of the lens is transferred to the right. However, most of the commercial relay systems are optically optimized for pre-designated conjugate image planes, which can not be applied in front of the camera. Furthermore, these relay systems do not provide a secondary image plane as required by our problem.

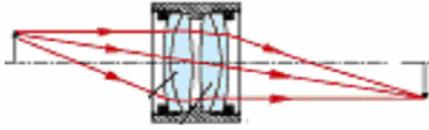


Figure 1: The optical layout of a relay system from Edmund optics. The system is designed and optimized for 1:1 image relay.

Our proposed design uses afocal optics, i.e., its focal points are located at infinity [16]. A pencil of parallel rays passing through an afocal system remains parallel. Telescopes are perhaps one of the most widely used afocal systems. Figs. 2(a) and 2(b) show two typical afocal systems. The first one in Fig. 2(a), known as a Galilean system, combines a positive objective and a negative image lens, in which the back focal point of the positive objective lens coincides with the back focal point of the negative image lens. The second system in Fig. 2(b), known as a Keplerian system, utilizes two positive lenses as the objective and the image lenses, in which the back focal point of the objective lens coincides with the front focal point of the image lens. One of the major differences between these two systems is that the Keplerian system has an intermediate image plane between the two lenses, as needed in our design. As illustrated in Fig. 2(c), an afocal system can also be thought of as a relay system wherein the

object is located at a finite distance. For instance, the front focal plane of the objective lens is conjugate to the back focal plane of the image lens.

Fig. 3 shows a schematic of the proposed relay system attached in front of a regular camera. The entrance pupil of the camera lens is imaged on plane A outside the camera. Hereafter, we refer to the entrance pupil of the camera lens as the primary aperture, the image of the primary aperture and/or any additional iris (stop) present on plane A as the secondary aperture, and plane A as the secondary aperture plane. If the camera and the attachment are considered as a composite imaging system, the secondary aperture functions as an equivalent of the optical center of the composite system. The proposed system shifts the entrance pupil of the camera lens to a location where it becomes accessible to the user. Consequently the user can control the position, orientation and even transmissivity of the aperture. Many advance imaging functions can be achieved by such manipulations, for example: panoramic imaging by controlling the pupil orientation, and small baseline stereo and super-resolution imaging by changing the aperture position within the secondary aperture plane.

In addition to the aperture, a secondary image plane which is a conjugate to the camera sensor plane (the primary image plane) is formed between the lens pair. The scene is focused on the secondary image plane before being imaged on the sensor. For each pixel on the CCD sensor, there is a corresponding virtual “pixel” in the secondary image plane which captures the light rays from the same scene point as the pixel on the CCD sensor. As a result, it is

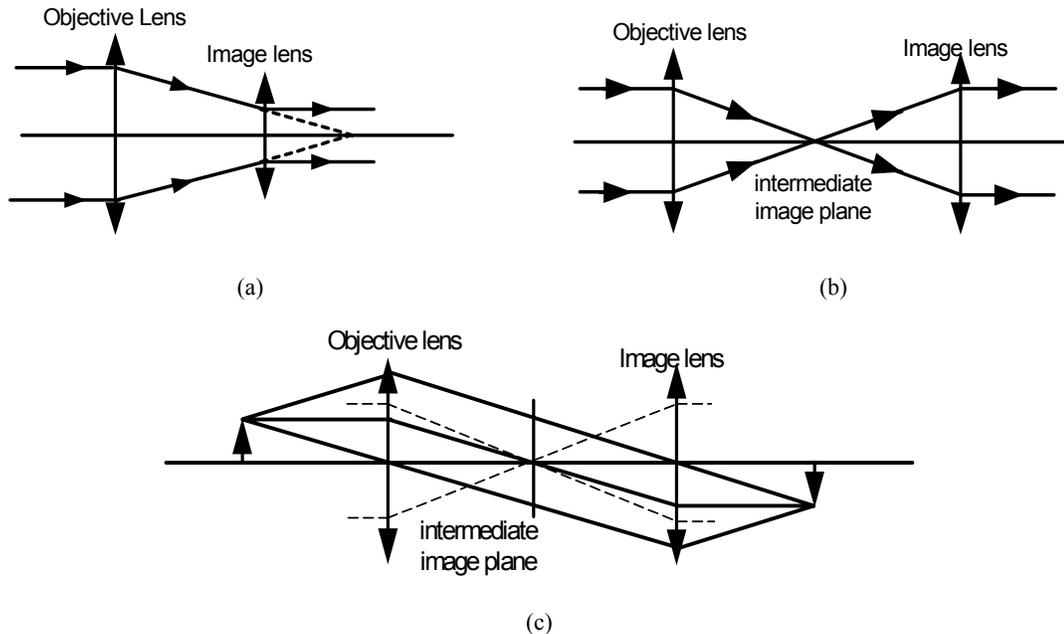


Figure 2: Afocal Systems. (a) Galilean system. (b) Keplerian system. (c) An afocal system is automatically a relay system.

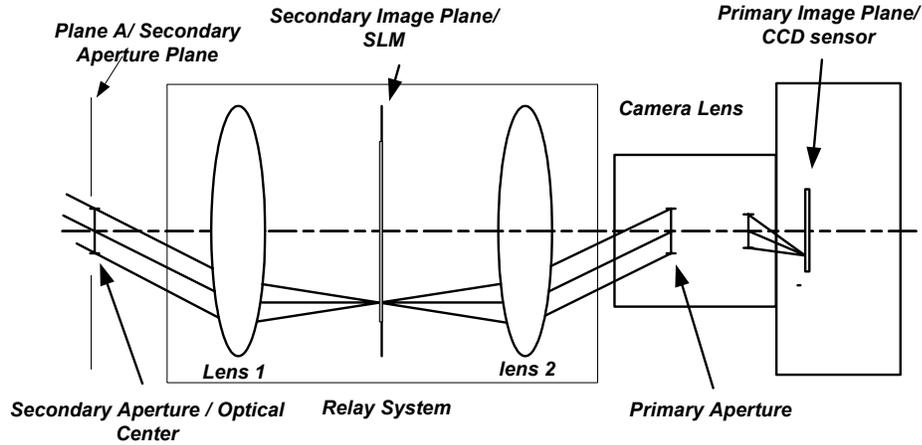


Figure 3: The optical layout of the proposed system. An optical system is mounted in front of the lens of a conventional camera to gain access to the lens center and the image sensor of the camera.

possible to control the irradiance or brightness of the pixel on the sensor by controlling the transmissivity of the virtual pixel in the secondary image plane. Such control of pixel transmissivity can be realized by placing a spatial light modulator (SLM) in the secondary image plane whose transmissivity can be dynamically set to desired values under program control. This enables many advanced imaging functions such as adaptive dynamic range imaging [12], image augmentation and optical computation [13].

3. Aperture Control

[19] shows that it is possible to achieve a range of imaging capabilities, such as dynamic viewing direction, splitting FOV, and optical computation, using multiple layers of controllable apertures in a pinhole camera. However, images captured through pinhole(s) suffer from low brightness due to the limited light collection ability. If larger size holes are used to increase the amount of light, it adversely affects the quality of focus. Optical lenses, which provide much greater light gathering power, make it possible to use a large aperture while keeping the image in sharp focus. However, the use of optical lenses restricts the control of the geometric and photometric properties of the aperture [19]. The proposed relay system offers the possibility to regain this access and control. The following sections present two examples facilitated by this capability.

Panoramic Imaging: A camera which can capture a large FOV through a single viewpoint is highly desired in many applications. However, with a regular camera lens, it is impossible to place multiple cameras at a single viewpoint due to physical conflict. Many efforts have been made to solve this problem. For example, planar mirrors are used

for virtually co-locating the cameras [5, 10] or curved mirrors are used to increase the camera FOV while preserving a single viewpoint [8, 11, 17]. Using our optical system, multiple cameras can be placed at the repositioned optical center of the camera which is in free space, to form an omni-directional imaging system as illustrated in Fig.

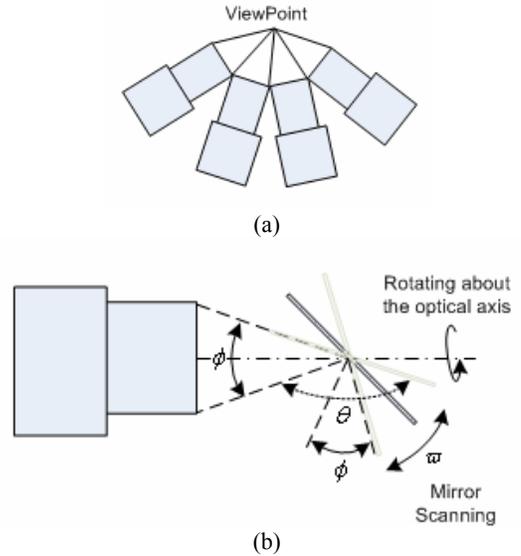


Figure 4: Panoramic imaging systems. (a) The optical centers of the cameras are co-located at the common, single viewpoint. (b) The mirror located at the viewpoint rotates about the optical axis of the camera while panning in the vertical direction to acquire images that are merged to construct a panoramic image. The resulting FOV has cylindrical shape, $\theta \times 360^\circ$, where θ is the vertical extent of the FOV of the still camera and $\theta = 180^\circ - \Phi$, Φ is camera FOV. The maximum mirror scanning angle is ω and $\omega = 90^\circ - \Phi$.

4(a). This system can capture a hemispherical shape FOV from a single viewpoint. The FOV, however, can not be more than 180° since the cameras will then enter into other cameras' FOVs. Furthermore, the front surface of the lens cannot be in round shape since the round shape lens will result in FOV gaps among cameras.

An alternative to the camera cluster solution is to use a mirror to control the orientation of the secondary aperture as shown in Fig. 4(b). 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 about the optical center of the camera; a large FOV can be scanned as a result of the rotation. The resulting FOV has a cylindrical shape, $\theta \times 360^\circ$, where θ is the vertical extent of the FOV of the still camera and $\theta = 180^\circ - \Phi$, Φ is the camera FOV. The maximum mirror scanning angle is ω and $\omega = 90^\circ - \Phi$. Compared with methods that rotate the entire camera [6, 7], a camera based on this rotation scheme offers the advantages of higher scanning speed, due to the considerably low torque required for rotating the light weight mirror, while maintaining the capability of single viewpoint imaging, which the existing rotating mirror system [9] is not capable of.

Small-baseline Stereo and Super-resolution Imaging: As described in [2], the secondary aperture is the equivalent of the optical center of an imaging system. Shifting the aperture is geometrically equivalent to shifting the camera itself. Thus, images acquired by shifting the aperture can be used to compute depth and simultaneously construct super-resolution images in a way similar to that described in [4]. In Fig. 5, the camera captures the rays of the same object point through two small apertures located in the secondary aperture plane, thus from two different perspectives, with the baseline being the distance between the two aperture centers.

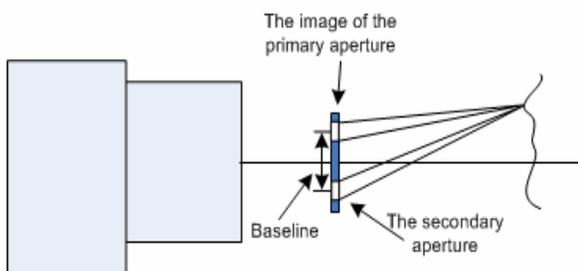


Figure 5: Small baseline stereo system. The host camera captures the scene through two secondary apertures from two different perspectives. The baseline is the distance between the two apertures. Notice that the secondary aperture cannot be outside of the image of the primary aperture.

4. Sensor Modulation

Controlling sensor exposure through filtering has been explored by many researchers [1, 12-15]. For example, [1] and [15] propose the use of a spatially varying neutral density filter in front of the camera to capture high dynamic range image. These two methods must be implemented on a panning camera in order to image every scene point with different exposures. [12] discussed three possible designs to achieve “adaptive” HDR using an SLM, where the SLM is placed adjacent to the camera sensor, in front of the camera lens, or in between the camera lens and sensor with the SLM optically conjugates with the camera sensor. The second design was implemented to validate their idea. However, pixel-level control cannot be achieved when placing the SLM in front of the camera due to the defocus blur caused by the filter mask. Because the blurred masks on the SLM overlap, a special control algorithm is required to find the optimal mask which can detect all the scene points. In contrast, the third design is capable to control the response of individual pixels on the sensor due to the fact that the SLM is a conjugate to the sensor. [13] proposes to control the responses of individual pixels on the sensor by controlling the orientations of the micro-mirrors in a DMD. The DMD system has a similar configuration as the third system in [12], where the DMD is placed in between the lens and sensor and is optically conjugated with the sensor through a relay lens. In our system, the relay lens forms a secondary image plane which is also optically conjugated with the sensor. Therefore, by inserting a programmable SLM in the secondary image plane, we can also control the sensor response at the pixel level. As a result, the imaging functions described in [13], such as high dynamic range imaging, optical computation, etc., can also be performed in our system but with greater ease because of the ready accessibility of the secondary image plane and aperture. In Section 5, we demonstrate implementation of such controls for adaptive, high dynamic range imaging.

As mentioned in the introduction section, the proposed relay system is attached in front of the camera lens which does not require camera structure redesign, while the structure re-design is necessary for the DMD system and the third design in [12] if constructed using off-of-shelf cameras. Furthermore, in the DMD system the sensor plane must be inclined to satisfy the Scheimpflug condition (Fig. 6). As a result, the image of the DMD on the sensor suffers Keystone (perspective) distortion. A square pixel is imaged as a trapezoid shaped pixel. Therefore, the mapping between the DMD and the sensor is not exactly pixel to pixel. The keystone distortion affects the effectiveness of controlling the pixels. In our system, on the contrary, the SLM is parallel with the camera sensor, and hence, the mapping between the SLM and the sensor can be pixel to pixel.

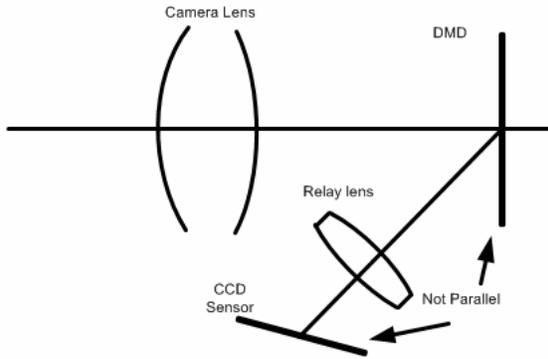


Figure 6: The DMD in the programmable camera proposed in [11] is not parallel to the CCD sensor. As a result, the image of the DMD on the CCD sensor suffers from keystone distortion.

5. Experimental Results

5.1 Bench prototype

Typical afocal systems, such as telescope, binoculars, laser beam expander, rifle scopes, have very limited FOV (i.e., only a few degrees) which is too small for many vision applications. In our prototype implementation, a pair of eyepiece lenses, mounted back to back, was used to form an afocal system. The lens pair was designed for Virtual Research V8 HMD (Head Mounted Display) which has a 60-degree FOV (diagonal) for a 1.3" micro-display and an equivalent focal length of 28.6mm. The eye relief is

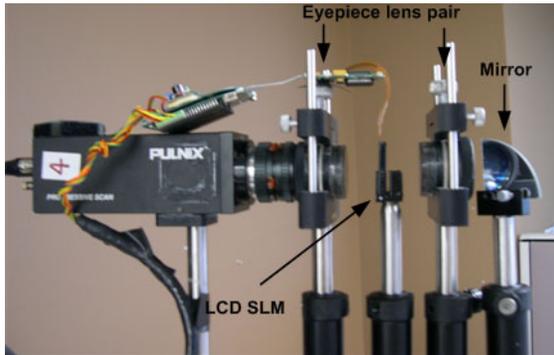


Figure 7: Experimental setup. Two eyepiece lenses are mounted in front of the camera as an afocal system. The LCD SLM is placed between two eyepiece lenses for the sensor modulation experiment. The mirror rotation axis is aligned with respect to the secondary aperture plane for the aperture control experiment. (In this picture, we show both the mirror and the SLM in the setup. In the actual experiments, they are used separately, i.e., using only the mirror for capturing panoramic images and using only SLM for capturing high dynamic range images.)

10-30mm. The reason we choose the eyepiece lens is that unlike the regular camera lens, there is no optical aperture inside the eyepiece lens; the viewer's eye (in our case, the entrance pupil of the camera lens) acts as the optical aperture. Therefore, the aperture matching problem, which is a very important factor to be considered when grouping two optical systems, is automatically solved. Fig. 7 shows the experimental setup. The host camera is a B&W analog camera with 2/3" CCD sensor, equipped with a 16-mm CCTV lens. The resolution of the camera is 640 x 480 pixels. The diagonal FOV of the camera is around 38°. The entrance pupil of the host camera is manually adjustable in the range 0-14 mm. The camera lens is positioned where its entrance pupil is near the back focal point of one of the eyepiece lenses. In most of our experiments, the camera was focused at a finite distance.

Table I shows the intrinsic parameters of the host camera and the composite system including the added relay lens. The parameters are estimated using Camera Calibration Toolbox [18, 20]. The focal lengths of the composite system are slightly different from that of the host camera, which indicates that the magnification ratio of the relay system is very close to 1:1. There are significant differences in the center shifts which are caused by the misalignment of the relay system with the camera lens. The differences can be eliminated by changing the position and orientation of the relay lens if necessary. Also notice that the distortion of the composite system, which is the sum of the distortions of the camera lens and the relay system, is more than double of that seen with only the host camera.

	Focal Length (in pixels)	Center offsets (in pixels)	Distortion (kc)
The host camera	$f_x=1242.62$ $f_y=1236.67$	$cc(1)=329.71$ $cc(2)=247.30$	$kc(1)=-0.2322$ $kc(2)=-0.39147$
With the relay system	$f_x=1277.19$ $f_y=1270.25$	$cc(1)=282.28$ $cc(2)=217.76$	$kc(1)=-0.6198$ $kc(2)=1.3513$

Table I: The intrinsic parameters with or without the relay system

Two experiments were designed to verify that the lens aperture is indeed imaged out and the new aperture (the secondary aperture) is indeed the optical center of the composite system after adding the relay system. In the first experiment, we replaced 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 the lens pupil should be expected on the secondary aperture plane. Fig. 8 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 the lens pupil (the secondary aperture) is formed (Fig. 8(c)). To verify that the optical center of the composite system is indeed the secondary aperture, we placed a

checker board in front of the camera and estimated the distance from the board to the camera using 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 entrance pupil of the camera is around 440 mm. This shows that the optical center of the composite system is the secondary aperture, not the original camera lens center.

5.2 Sensor modulation for high dynamic range imaging

A color LCD spatial light modulator (SLM) is placed at a position between eyepiece lenses, at the shared focal point 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 [12-14]. 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 on the image detector, and the HDR image is constructed by selecting the “right” response from among the neighbors, thus 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 with two static scenes: foam head scene and window scene. The experimental results are shown in Fig. 9. 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.

5.3 Aperture control for panoramic imaging

To demonstrate geometric control of the aperture, we placed a planar mirror on a rotation stage with its rotation axis aligned with the vertical axis of the camera as discussed in Section 3. Since the rotation axis passes through the optical center, the images captured must be from a single viewpoint. Therefore, image mosaic becomes very simple: the images can be simply overlaid to form a panoramic image and no geometric warping is necessary. Fig. 10(a) shows a set of input images; 10(b) shows the corresponding panoramic image.

6. Conclusions and Future Work

We have shown that by adding the relay system in front of the camera lens, we gain easy access and control of both the camera optical center and the sensor which allows easy flexible imaging, e.g., by controlling the pixel exposure and manipulating the geometric properties of the aperture. We have demonstrated the resulting performance improvement in two applications using a simple experimental setup. We plan to explore additional applications using our current system. We also plan to conduct a quantitative analysis on the performance of the system after appending the relay system in front of the camera.

Acknowledgments

The support of the National Science Foundation under grant NSF IBN 04-22073 is gratefully acknowledged.

References

- [1] M. Aggarwal and N. Ahuja, “High dynamic range panoramic imaging,” in *Proc. of International Conference on Computer Vision*, Vancouver, Canada, July 2001, pp. 2-9.
- [2] M. Aggarwal and N. Ahuja, “A pupil-centric model of image formation,” *International Journal of Computer Vision*, 48(3), 2002, pp. 195-214
- [3] M. Aggarwal and N. Ahuja, “Split aperture imaging for high dynamic range,” *International Journal on Computer Vision*, Vol. 58, No. 1, June 2004, pp. 7-17.
- [4] C. Gao and N. Ahuja, “A refractive camera for acquiring stereo and super-resolution images,” in *Proc. of IEEE Conference on Computer Vision and Pattern Recognition*, Volume 2, June 2006 pp. 2316 - 2323, New York.
- [5] H. Hua and N. Ahuja, “A high-resolution panoramic camera,” in *Proc. of IEEE Conference on Computer Vision and Pattern Recognition*, 2001, pp. 960-967.
- [6] A. Krishnan and N. Ahuja, “Panoramic image acquisition”, in *Proc. of IEEE Conference on Computer Vision and Pattern Recognition*, 1996, pp. 379-384.
- [7] A. Krishnan and N. Ahuja, “Range estimation from focus using a nonfrontal imaging camera,” *Int. Journal of Computer Vision*, Vol. 20, No. 3, 1996, pp. 169-185.
- [8] S. S. Lin and R. Bajcsy, “True single view point cone mirror omni-directional catadioptric system,” in *Proc. of IEEE International Conference on Computer Vision*, Vol. II, July 2001, pp.102-107.
- [9] T. Nakao and A. Kashitani, “Panoramic camera using a mirror rotation mechanism and a fast image mosaicing,” *ICIP01*, Vol.2, pp. 1045-1048.

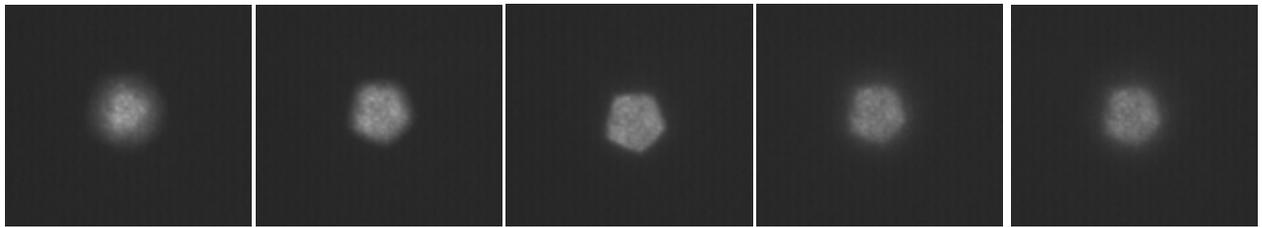
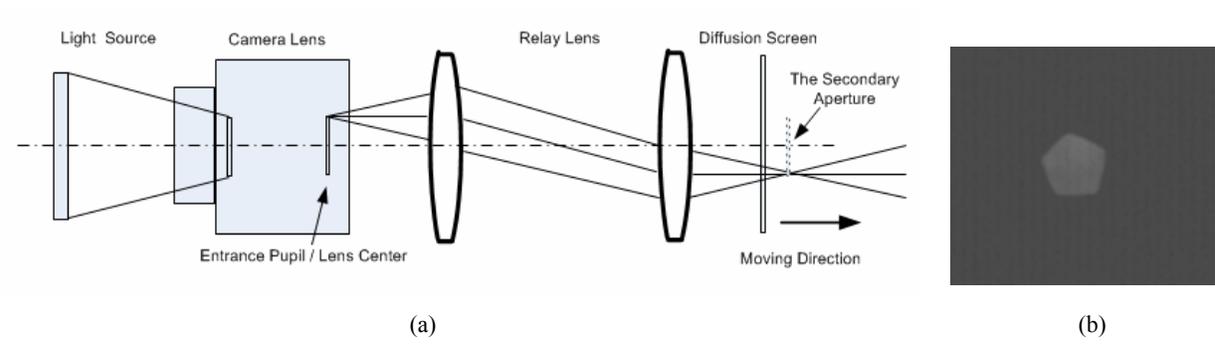


Figure 8: The experiment on the formation of the secondary aperture. (a) Experimental setup. (b) The image of the entrance pupil of the camera lens, (c) The images of the secondary aperture on the diffusion screen, as the screen moves away from the relay lens along the optical axis. The third image is the one in focus which implies that the secondary aperture is formed at this position.

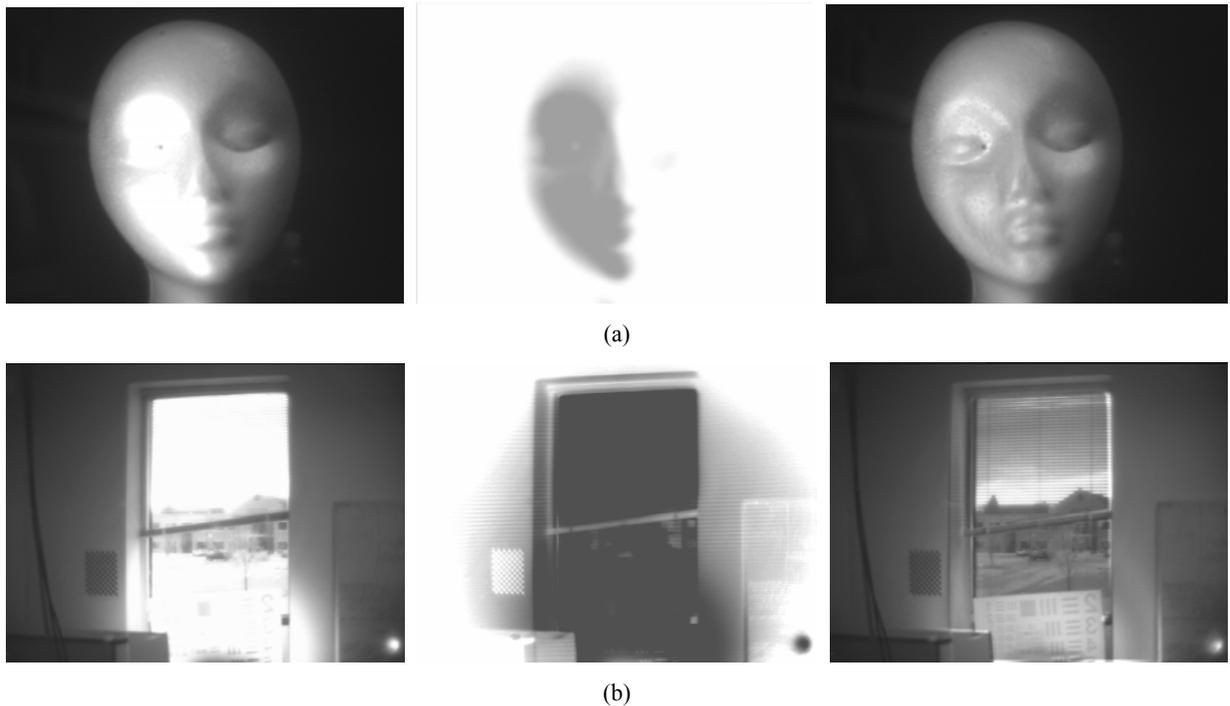
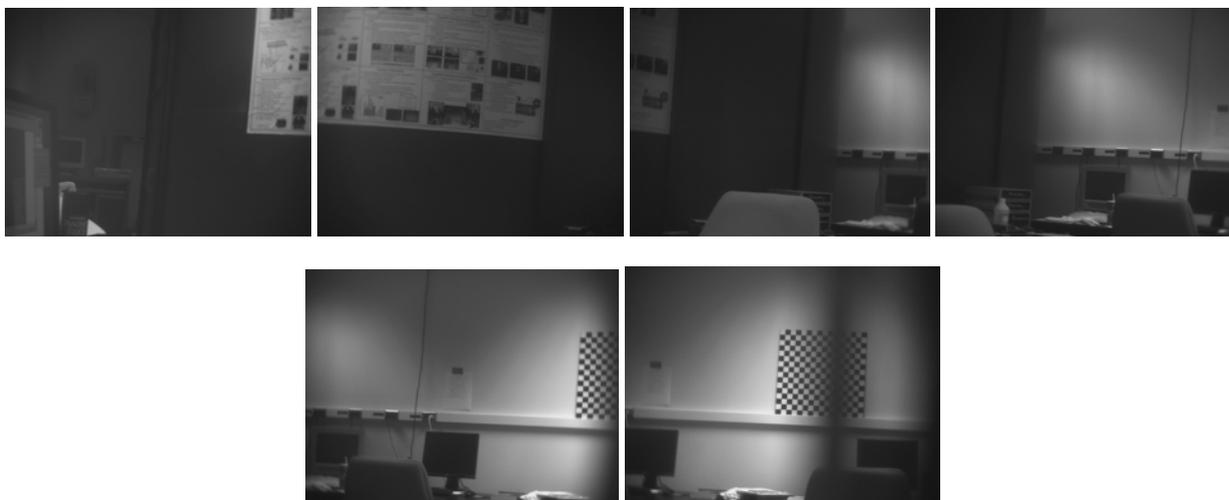


Figure 9: Sensor modulation for high dynamic range imaging. (a) Foam head scene. (b) Window scene. The first column shows the images captured with a white (full transmittance) pattern displayed on the SLM. The second column shows the feedback masks displayed on the SLM to attenuate the bright pixels present in the captured images. The third column shows the resulting images.



(a)



(b)

Figure 10: Aperture control for panoramic imaging. (a) Six input images captured as the mirror rotates; (b) Mosaiced panoramic image. In (b), 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 the single viewpoint property of our system through the geometric alignment between images, the intensity difference between the input images was not compensated.

- [10] V. Nalwa, "A true omnidirectional viewer," Technical report, Bell Laboratories, 1996.
- [11] S. K. Nayar, "Catadioptric omnidirectional camera," in *Proc. of IEEE Conference on Computer Vision and Pattern Recognition*, 1997, pp. 482-488.
- [12] S. K. Nayar and V. Branzoi, "Adaptive dynamic range imaging: optical control of pixel exposures over space and time," in *Proc. of International Conference on Computer Vision*, pp. 1168-1175, 2003.
- [13] S. K. Nayar, V. Branzoi, and T. Boult, "Programmable imaging using a digital micromirror array," in *Proc. of IEEE Conference on Computer Vision and Pattern Recognition*, pp. 436-443, 2004.
- [14] S. K. Nayar and T. Mitsunaga, "High dynamic range imaging: spatially varying pixel exposures," in *Proc. of IEEE Conference on Computer Vision and Pattern Recognition*, pp. 472-479, 2000.
- [15] Y. Y. Schechner and S. K. Nayar, "Generalized mosaicing," in *Proc. of IEEE International Conference on Computer Vision*, Vol.1, pp.17-24, Jul, 2001.
- [16] Warren J. Smith. "Modern optical engineering," McGraw-Hill, 3rd edition, NY, 2000.
- [17] K. Yamazawa, Y. Yagi, and M. Yachida, "Omnidirectional imaging with hyperboloidal projection," in *Proc. of International Conference on Intelligent Robots and Systems*, 1993, pp. 1029-1034.
- [18] Z. Zhang, "A flexible new technique for camera calibration," *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 22, no. 11, pp. 1330-1334, 2000.
- [19] A. Zomet and S. K. Nayar, "Lensless imaging with a controllable aperture," in *Proc. of IEEE Conference on Computer Vision and Pattern Recognition*, pp. 339-346, June 2006.
- [20] "Camera calibration toolbox for matlab," 2002, http://www.vision.caltech.edu/bouguetj/calib_doc/