High Dynamic Range Camera using Reflective Liquid Crystal

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Abstract

High Dynamic Range Images (HDRIs) are needed for capturing scenes that include drastic lighting changes. This paper presents a method to improve the dynamic range of a camera by using a reflective liquid crystal. The system consists of a camera and a reflective liquid crystal placed in front of the camera. By controlling the attenuation rate of the liquid crystal, the scene radiance for each pixel is adaptively controlled. After the control, the original scene radiance is derived from the attenuation rate of the liquid crystal and the radiance obtained by the camera. A prototype system has been developed and tested for a scene that includes drastic lighting changes. The radiance of each pixel was independently controlled and the HDRIs were obtained by calculating the original scene radiance from these results.

1. Introduction

The real world has a great variety of scenes regarding brightness, from direct sunlight to deep shadow. When capturing scenes that include drastic lighting changes, the stronger light saturates the receiving elements and the actual light radiance cannot be obtained. For example, the required dynamic range is about 200 dB for capturing direct sunlight. When capturing such a dynamic range with a camera which has a linear response, the camera needs to have a depth of more than 30 bits per pixels. However, typical digital cameras represent brightness information with 8 bits(256 levels).

Even with non-linear imaging techniques like gamma correction, conventional cameras cannot achieve such high dynamic ranges, only achieving 50 – 70 dB of dynamic range. This short range causes a saturation problem, making many computer vision algorithms more difficult. Thus the acquisition of high dynamic range images (HDRIs) has attracted much attention from researchers.

Before presenting our approach, we begin with a brief summary of existing techniques for extending the dynamic range of a camera. Most proposed methods improve the dynamic range by capturing the scene using different exposures. To sequentially capture a scene with changing camera exposure time, a scene is captured by a number of frames and thus camera or scene motion makes the registration of sequential images more difficult [1][4][6][7][8]. Of course these approaches are restricted to scenes without rapid motion. The notion of composing an acceptance surface by receiving elements of different exposures is introduced in [3][5][11][12][13]. In these approaches, a number of receiving elements are considered as one group, and thus spatial resolution is reduced.

Novel approaches to solve these problems have also been proposed in [2][9][10], where the exposure of each pixel is adaptively controlled. These methods use a camera combined with a device that enables the attenuation of the pixels to be independently controlled. The device controls the incident radiance by changing the attenuation based on the intensity of the light, enabling the camera to capture at a proper exposure. These methods do not reduce spatial resolution as they just control the exposure of conventional cameras. While there are limitations in respect to scenes with very rapid motions, they are applicable to a variety of scenes including dynamic scenes.

As a device to control radiance, a transmissive liquid crystal is used in [2][9], and a Digital Micro-mirror Device(DMD) is used in [10]. However, each device has limitations. For transmissive liquid crystal, a drive circuit between liquid crystal elements prevents the focus being on the liquid crystal plane. Hence, pixel-level attenuation cannot be achieved. Since DMD works with time division, precise radiance control is difficult when DMD is combined with a camera that has a fast shutter speed.

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In this paper, we present a high dynamic range camera system that uses a reflective liquid crystal. The system adaptively extends the dynamic range of a camera by controlling the incident radiance.

2. High Dynamic Range Imaging by Radiance Control

In this paper, we introduce a method to extend dynamic range using a reflective liquid crystal. We begin with an introduction of the principle for extending the dynamic range of a camera, and describe devices for this purpose.

2.1. Basic Principle to Extend Dynamic Range

The dynamic range is extended using a system that consists of a camera and an attenuation device. The attenuation device can control its in-out ratio for each pixel independently. The method for extending the dynamic range has two steps.

2.1.1 Adaptive Attenuation Control in Response to Incident Radiance

First, the system adaptively controls the radiance of incident light. Incident light enters the image detector through the attenuation device. The attenuation ratio of each element is independently controlled based on the measured radiance at the corresponding image pixel. Since incident light passes through the attenuation device before entering the image detector, an increase in the attenuation ratio results in a decrease in the amount of received light. This means that receiving elements can avoid saturation by increasing the attenuation ratio of the corresponding attenuation elements. Thus, the range of acceptable light intensity for the system is adaptively expanded. Note that this function is different from some camera adjustments such as gain control and aperture adjustment. The function does not affect areas which receive relatively small levels of radiance. The measured radiance I_t at time t is written as

$$I_t = L_t \cdot A_t, \tag{1}$$

where L_t is the original radiance of the incident light and A_t is the attenuation ratio of the device. When the device is controlled in real-time, this method is applicable to movies that include dynamic scene changes.

2.1.2 Restoring Original Radiance

After controlling the radiance of incident light, it is possible to calculate the original radiance. The original radiance L_t is derived from the measured radiance and the attenuation ratio by

$$L_t = I_t / A_t. \tag{2}$$

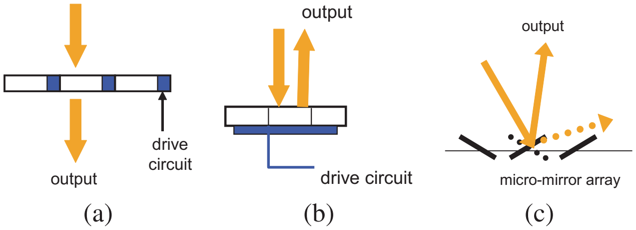

Figure 1. Simple models of light controlling devices: (a) transmissive liquid crystal, (b) reflective liquid crystal and (c) DMD. Properties of each device are compared in Table 1.

Since attenuation control is done on each of the receiving pixels, the original radiance is also restored for each of the receiving pixels according to the above equation. The restored image is the same as the measured image except for the radiance range. The range can be enhanced compared to the dynamic range of the image detector. Considering its radiance value, the restored image is called as a HDRI.

Additionally, the attenuation ratio A_t should be adequately controlled to acquire scene radiance that includes rather small quantization errors. The control algorithm for the attenuation ratio is described in Sec.3.2.

2.2. Devices for Radiance Control

Radiance control of incident light is accomplished using devices that can control the attenuation ratio at a pixel level. A short summary of such devices is as follows,

Transmissive Liquid Crystal Transmissive liquid crystal is a popular device used in LCDs and some other products. A model of the device is shown in Fig.1(a). The device can control the direction of polarization by transmitting the light, and so achieve contrast. Because the device is transmittable for light, drive circuits must exist between the liquid crystal elements. This fact reduces the aperture ratio of the device and so causes some disadvantage with respect to the contrast ratio.

Reflective Liquid Crystal The device has liquid crystal between a semiconductor chip and a glass plate. A major implementation is LCoS(Liquid Crystal on Silicon). A model of the device is shown in Fig.1(b). Contrast is achieved by controlling polarization, but incident light is reflected, not transmitted. Moreover, the device can achieve a rather high contrast ratio because drive circuits can be set on the back.

Digital Micro-mirror Device(DMD) A DMD is a micro-electro-mechanical system that has a tiled micro-mirror array. As shown in Fig.1(c), the device controls the attenuation by controlling the direction of the reflect light. The latest generation of DMDs can

Table 1. Comparison of each device.

	attenuation control at pixel level	combination with high-speed cameras
Transmissive liquid crystal	difficult	works well
Reflective liquid crystal	capable	works well
DMD	capable	not recommended

switch orientations in a few microseconds, thus enabling modulation of incident light with very high precision.

For realizing attenuation control in combination with a camera, the device must satisfy the following specifications:

- capability to control attenuation for each pixel
- compatibility with a high-speed camera

If the focus is on the attenuator, a problem arises in the use of transmissive liquid crystals. Their drive circuit is so large that shadows appear on the captured image when the focus is on the liquid crystal. This problem makes radiance measurement more difficult. While the problem may be solved by special optical devices, such as micro-lens arrays, the solution increases the complexity of the system. Moreover, when light passes through liquid crystal cells, the cells produce a diffraction effect, which causes slight blurring in the captured images[9].

Since a DMD works with time division, it cannot achieve full contrast if it is combined with a camera which has fast shutter speed. Thus a DMD is not a suitable device to be combined with a camera. Additionally, the mechanism tends to be complex because of the need to synchronize the DMD switching and the camera shutter.

On the other hand, the above problems are all solved using reflective liquid crystal. The drive circuit does not cut off incident light because it is set on the back of the reflective surface. A blurring effect does not occur for incident light reflected at the device. The system also achieves good performance when combined with a camera because the principle to achieve contrast is not time division but polarization.

The above discussion is summarized as Table.1. Comparing each device with respect to the required specifications, reflective liquid crystal is the most appropriate device for our purpose.

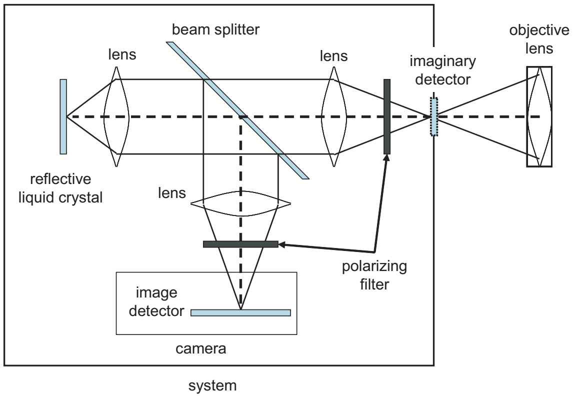

Figure 2. Imaging system using reflective liquid crystal. The incident light is first focused onto the liquid crystal plane. The reflected light is refocused onto the image detector. Relay-lenses advance the versatility of the system.

3. Adaptive Dynamic Range Camera Using Reflective Liquid Crystal

We now present our method to achieve a high dynamic range camera using reflective liquid crystal. The composition of the system and the algorithm to control reflective liquid crystal attenuation for radiance control are described.

3.1. Composition of the System

The optical layout of the system is shown in Fig.2. The incident light is first focused on the liquid crystal plane, and then the reflected light is focused on the image detector. Such focusing enables attenuation at a pixel level. The effect of attenuation is given by Eq. (1).

The versatility of the system is advanced using relay-lens systems. [1] Images focused by the objective lens are relayed to the liquid crystal plane. Without the relay-lens, the objective lens is constrained to have a longer focal length than the beam splitter size. This may limit the choice of some special lenses(e.g. fisheye and tele-photo lenses).

The relay-lens system is composed of two lenses. A pair (left and right in Fig.2) of lenses focuses incident light to the liquid crystal plane, and another pair (left and bottom in Fig.2) focuses the reflected light from the liquid crystal to the image detector. These lenses are placed at either side of the beam splitter so that the system is downsized.

Since the image detector is subjected to attenuated light without blurring, attenuation is achieved at the pixel level. When considering all the components except the objective lens as one group, the concept of an adaptive high dynamic range camera is realized; the focused image using the ob-

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[1] A relay-lens relays images to another point of the optical system with changing the scale. As the relay-lens can relay an image to the liquid crystal, the system can contain another lens attached outside the relay-lens.

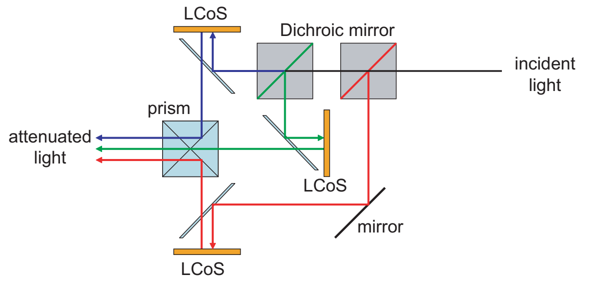


Figure 3. The incident light is separated into RGB colors. Each color is controlled independently. Though many beam splitters are necessary for this composition, the maximum throughput is almost the same as the monochrome control.

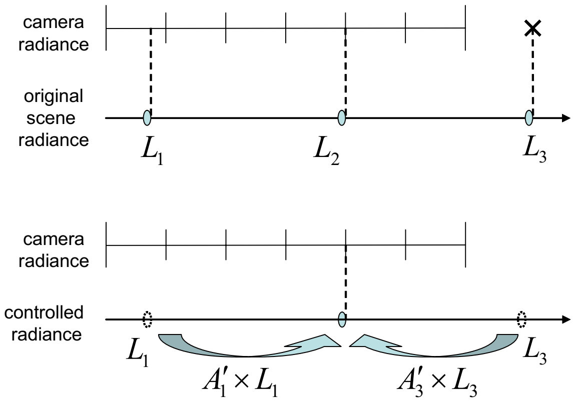


Figure 4. Attenuation control enables the image detector to accept various ranges of radiance with the least quantization errors.

jective lens is refocused on the image detector with radiance control.

In our system, polarizing filters are used to achieve the contrast of the liquid crystal so that incident light is attenuated regardless of the wavelength.

If one wants to control each color independently, the system requires more liquid crystal planes and beam splitters (e.g. Fig.3 for RGB). Incident light is separated into certain colors by dichroic mirrors, and each color is controlled independently, as for monochrome control. The maximum throughput is almost the same as for monochrome control though many beam splitters are necessary. As shown in fig.3, color control requires more space than monochrome control. Here, monochrome control was chosen for the reason of size of the system.

3.2. Control Algorithm for Reflective Liquid Crystal

The concept of adaptive attenuation control is represented in Fig.4. Let us assume that the attenuation of three pixels are equal (i.e. $A_1 = A_2 = A_3$), and that these pixels are subjected to radiance L_1, L_2 and L_3, respectively. The bright light L_3 causes saturation. The weak light L_1 is measured with massive quantization errors, however the measured radiance is below the saturation level. Thus the quality is reduced by these errors. The solution to acquire a more precise HDRI is to properly control the attenuation; saturation is suppressed by the increase in attenuation from A_3 to A_3', and the quantization error is reduced by the decrease in attenuation to A_1'.

Attenuation is calculated based on the measured radiance I_t according to the above description. Let the subscript t correspond to the time that the radiance is measured. When attenuation is properly controlled, the measured radiance at the next frame $t+1$ will be the optimal radiance I_{opt}. Here, the optimal radiance I_{opt} is defined in order to rather precisely reconstruct the scene radiance. When the measured radiance is known, the optimal attenuation is clearly found from Eq. (1).

$$A_{t+1} = \min(\frac{I_{opt}}{I_t + \varepsilon} A_t, 1) \tag{3}$$

where ε is a small number that is used only to preventing A_{t+1} from being unstable.

Note that the time of controlled attenuation becomes $t+1$, since measured radiance is needed for the calculations. After attenuation control, the following equation is formed unless the scene changes. From Eq. (1),

$$I_{opt} = L_{t+1} \cdot A_{t+1}. \tag{4}$$

The next problem is to determine the desired radiance. The most precise HDRI requires controlled radiance just under the saturation level. However, this method of radiance control is a trade-off with a potentially unsuitable measurement due to a radiance increase. That is, a small increase may cause saturation and hence the actual radiance would not be obtained. The radiance increases between adjacent frames are empirically assumed to be at most twofold, thus, I_{opt} is defined as the median of the camera radiance in consideration of the above trade off. That is,

$$I_{opt} = \frac{I_{max} + I_{min}}{2} \tag{5}$$

where I_{max} and I_{min} are the maximum and minimum radiance values of a camera's dynamic range, respectively.

4. Experimental Results

In this section, a developed adaptive dynamic range camera is described and experimental results are presented.

4.1. Prototype System

The developed system is shown in Fig.5. Its optical layout is presented in Fig.2. The LCoS used as the reflective

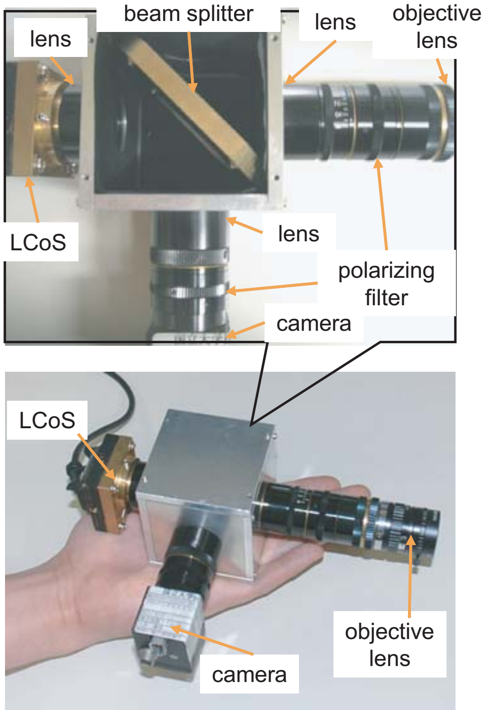


Figure 5. An overview of the prototype. The system consists of a monochrome camera, reflective liquid crystal, objective lens, and relay-system as presented in Fig.2.

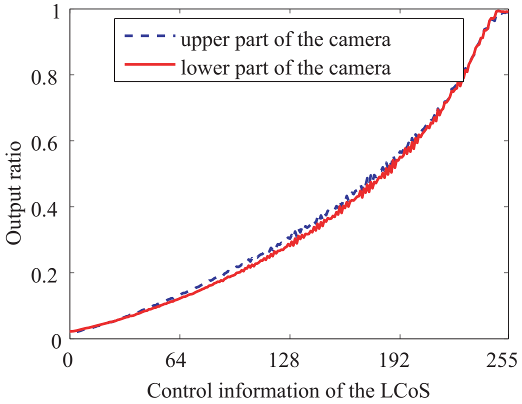


Figure 6. LCoS output response for 8 bit control. The response is measured at the upper and lower parts on the camera coordinate. The vertical axis represents the output ratio of the LCoS. The horizontal axis represents the depth of attenuation control. A depth of 255 refers to the highest attenuation, similar to the color representation used in many image formats. The output ratio is normalized with the maximum value, thus the ratio value which corresponds to the control information of 255 is 1.0. The minimum output ratio is not 0 as the darkest output of projectors and monitors is brighter than real darkness.

liquid crystal is a Brillian Z86D-3 model with 800×600 elements. A PointGreyResearch Flea 8bit monochrome camera with 1024×768 pixels is used. The camera captures about 500×400 pixels of the LCoS. Though the system requires accurate alignment, the current prototype alignment is not perfect. A non-polarizing beam splitter is used with polarization filters to achieve the LCoS contrast. The transmittance of the beam splitter is about 30% (1 passing), and the transmittance of the polarizers is about 15% (parallel setting). The incident light passes through the beam splitter twice and polarizers once, thus the maximum transmittance of incident light is about $15\% \times 30\% \times 30\% = 1.3\%$. Though the combination of beam splitter and polarizers is used in this system, polarizing beam splitter is generally used. In that case, the transmittance will be improved to about $50\% \times 50\% = 25\%$.

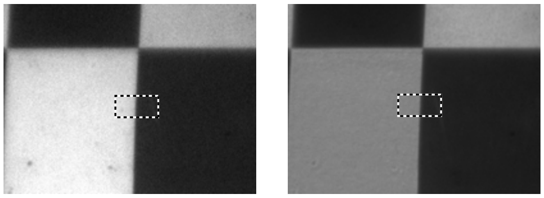
The resolution of each device does not have a one-to-one correspondence, and radiance control cannot be strictly achieved for each pixel. This problem is due to the lower resolution of the LCoS compared to the camera and imperfect alignment. The problem will be solved by an increase in the LCoS resolution so that it is more than the camera resolution and more accurate alignment.

Off-line calibrations were conducted for both the geometric and radiometric properties of the system. For the geometric calibration, mapping between the LCoS and CCD pixels was obtained using homography. Radiometric calibration involves the relationship between LCoS control and its attenuation ratio. This relationship is important for proper radiance control. The radiometric calibration was done by measuring the actual radiance changes that occur in response to LCoS control. Figure 6 shows the result of the radiometric calibration. In the figure, these changes of attenuation are almost the same regardless of the location.

As described above, the resolution of the LCoS is less than that of camera. Thus independent radiance control at each pixel is difficult. As an example, the radiance of a checkerboard-like scene is controlled. The captured images before and after radiance control are shown in Fig.7. The radiance value of each image is partly (around the marked region) plotted along the x-axis, as shown in Fig.8. The radiance was over controlled at some points, while the original radiance was under I_{opt}(=128 in this system). In this manner, the effect of resolution difference appears mainly at the edges.

4.2. Dynamic Range of the Prototype System

The dynamic range of the prototype system was evaluated by measuring the camera outputs for incident radiance. The incident radiance was precisely varied by changing the shutter speed of the camera. The system adjusts the attenuation of the LCoS to avoid saturation with maximum effort. To compare with a conventional camera, the same measure-



(a) (b)

Figure 7. An experimental result of radiance control: (a) before control, (b) after control. The radiance value of the white area is larger than I_{opt}, thus radiance was controlled as (b).

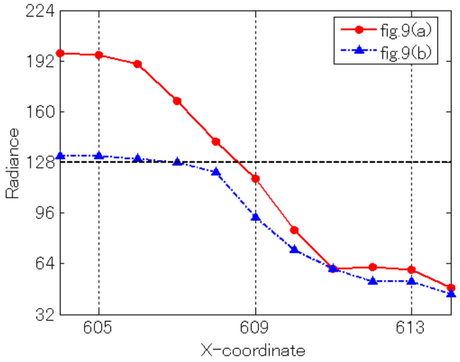


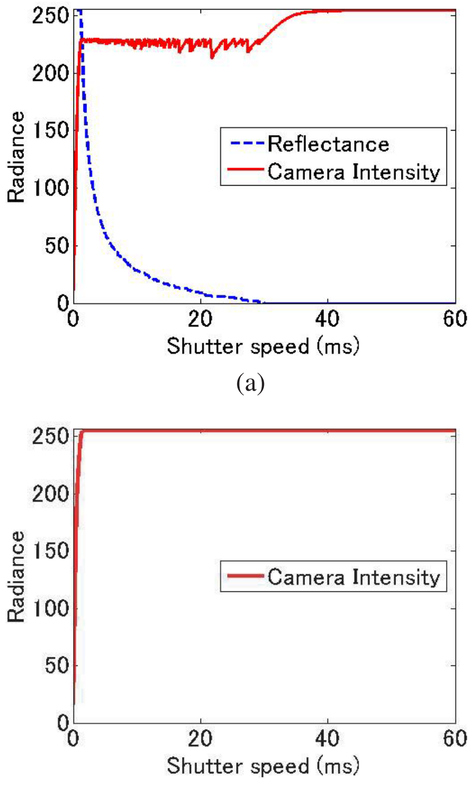
Figure 8. Radiance value at edges of Figs.7(a) and (b). While Eq.(3) shows that the attenuation ratio does not decrease for pixels where the radiance is less than I_{opt}, the radiance at $x = 609$ decreased after radiance control. This is because of the resolution difference between the LCoS and the camera.

ment was conducted with the attenuation control turned off. The results of the measurements are shown in Fig.9. The outputs are compared in Fig.10.

These results clearly show that our system is able to capture scenes that require a rather high dynamic range. Our system achieves 45.2 times extended range of output compared with a conventional system.

4.3. Adaptive Radiance Control

The function for attenuation control was tested by capturing a scene which includes drastic lighting changes. The result is shown in Fig.11. Our method requires two iteration steps for radiance control (the first is the capturing image, and the second is the controlling of the attenuation of the LCoS based on the captured image). The results are obtained sequentially; starting from (a), and reaching (c) through (b). In the scene, five iterations are needed for convergence. Figures 11(b) shows the result of radiance control after two iterations. In Fig.11(a), the mask image has no scene information because the radiance is not controlled, so the bright region in the captured image(window region) is saturated. In Fig.11(c), the scene radiance is controlled adaptively except for regions subjected to especially strong light (fluorescent lights and the strong reflection from outdoor).



(a)

(b)

Figure 9. Captured radiance and attenuation are measured for each incident radiance: (a) with attenuation control, (b) without attenuation control. The incident radiance is precisely controlled by the programmed shutter speed control; that is, in tens of microsecond steps(about 140 points between 0 – 2 ms). The vertical axis represents the depth of the camera radiance and attenuation. The highest depth of 255 corresponds to the highest value as described in Fig.6. To compare with a conventional camera, the measurement was done without the attenuation function. Thus, the attenuation is not recorded in (b).

As described in Sec.3.2, the goal of attenuation control is to measure the incident radiance at a optimal value I_{opt}. However, attenuation control was not our final goal. The outdoor view is not clear in the image after attenuation control. However, it is possible to view the outdoor scene in images obtained with radiance control.

4.4. Result of High Dynamic Range Imaging

HDRI is obtained by calculating the original radiance. The original radiance is derived using the measured radiance and the corresponding attenuation (Fig.11(c)), according to Eq.(2). The results of restoring HDRI are shown in

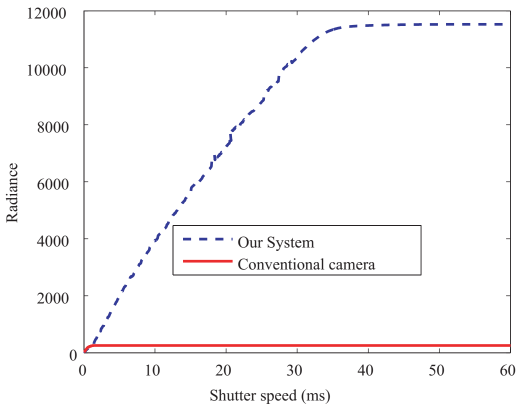


Figure 10. Comparison of system outputs obtained from Fig.9. These outputs are calculated from Eq.(2).

Fig.12. The restored scene is the same as that shown in the previous section. HDRIs have to be compressed somehow to be displayed on a usual 8-bit monitor. Here, the HDRI has been represented with simple image processing; the range of interest is changed in Figs.12(a) and (b), and the HDRI is converted to a log-scale in Fig.12(c). Figures12(a) and (b) show information approximately equivalent to the images captured with changing the camera exposure. In Fig.12(c), both bright and dark regions are seen at the same time. These results indicate that our system has the ability to represent a large amount of information.

5. Conclusion

In this paper, a high dynamic range camera has been presented that uses a reflective liquid crystal as a device to control incident radiance. The camera system controls the incident radiance for each pixel by controlling attenuation of the liquid crystal. A prototype system was constructed and its applicability was verified through experiments. As the system is composed of conventional devices, it will be possible to collaborate with other HDR imaging techniques reviewed in Sec.1 and realize further high dynamic ranges.

However, our current system is larger than we would wish as it requires complex optics, as shown in Fig.2. In future work, hopefully with some ingenuity, the system will be reduced in size (e.g. using Fiber Optic Plate(FOP)).

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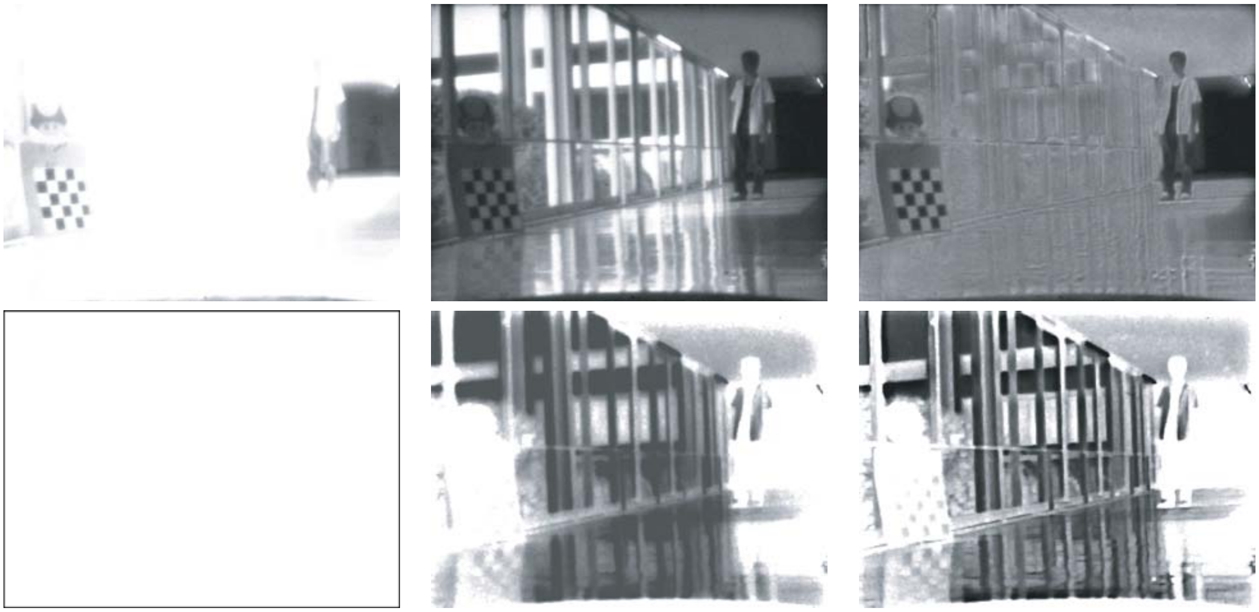

(a) (b) (c)

Figure 11. Experimental results of radiance control using the proposed system: (a) before radiance control, (b) intermediate step, (c) after radiance control. Upper row shows captured images and lower row shows mask images. At initial step (a), the mask image has no information because the radiance is not controlled. Thus, the bright region in the captured image is saturated. To converge the radiance control of the scene, five iterations of capturing and the LCoS control are needed. (b) represents the intermediate step(after two iterations). According to our method, the radiance of the captured image is controlled so that the controlled radiance(c) does not saturate except for the area subjected to especially strong light (fluorescent lights and strong reflection from outdoor). The mask image used for radiance control represents additional information for bright regions.

(a) (b) (c)

Figure 12. The HDRI obtained by the proposed system. The HDRI is represented by simple image processing for display on an 8-bit monitor: the range of interest is changed to be (a) a dark region and (b) a bright region, and for (c) the brightness value is converted to a log value. Images (a) and (b) are approximately equivalent to the images captured with the changed camera exposures. Information for both bright and dark regions is clearly visible in these images; the checkerboard and stuffed toy represent information of a dark region, and the outdoor view represents information of a bright region.