EpiScope: Optical Separation of Reflected Components by Rotation of Polygonal Mirror

Ryota Maeda
University of Hyogo
Hyogo, Japan
maeda.ryota.elerac@gmail.com

Shinsaku Hiura
University of Hyogo
Hyogo, Japan
hiura@eng.u-hyogo.ac.jp

(a) Setup (b) Usage (c) All (d) Direct (e) Indirect

Figure 1: Overview of EpiScope. (a) Scene and device setup. (b) Observing the scene through device. (c) Both reflection components are observed mixed together. For this scene, EpiScope can select specific reflection component like (d) direct component or (e) indirect component.

ABSTRACT

Separating reflection components is an important task in computer graphics and vision. Episcan3D has been proposed to separate the direct and indirect reflection components in real-time. This method uses a scanning laser projector and a rolling shutter camera, so it requires unmanageably precise geometric alignment and temporal synchronization. In this paper, we propose a novel optical system that achieves the same function without imaging devices. In this method, the ray directions of projection, observation, and presentation are optically and mechanically synchronized by a rotating polygonal mirror. The direct or indirect components can be selected by a mask-based light-field filter. Especially, the selected reflection components can be seen directly by our naked eye, and there are no restrictions on image quality or delays in presentation due to the number of pixels or frame rate of the imaging system.

CCS CONCEPTS

• **Computing methodologies** → **Computational photography**; Mixed / augmented reality; • **Hardware** → *Displays and imagers*; *Scanners*.

KEYWORDS

reflection separation, optical system, Episcan3D

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. Copyrights for components of this work owned by others than ACM must be honored. Abstracting with credit is permitted. To copy otherwise, or republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee. Request permissions from permissions@acm.org.

SA '21 Technical Communications, December 14–17, 2021, Tokyo, Japan

© 2021 Association for Computing Machinery.

ACM ISBN 978-1-4503-9073-6/21/12...$15.00
https://doi.org/10.1145/3478512.3488600

ACM Reference Format:
Ryota Maeda and Shinsaku Hiura. 2021. EpiScope: Optical Separation of Reflected Components by Rotation of Polygonal Mirror. In *SIGGRAPH Asia 2021 Technical Communications (SA '21 Technical Communications), December 14–17, 2021, Tokyo, Japan.* ACM, New York, NY, USA, 4 pages. https://doi.org/10.1145/3478512.3488600

1 INTRODUCTION

The light illuminating a scene is observed after repeating various optical phenomena such as reflection, refraction, and scattering. Therefore the observed light is generally a mixture of direct and indirect components. The direct component is the light reflected only once on the object's surface. The indirect component is the remaining part of the light reflected multiple times due to interreflection and scattering. In computer vision, many scene analysis methods use only specific reflection components. For example, 3D measurements using structured light or Time-of-Flight methods assume only direct components, and indirect components cause error or fault. On the other hand, indirect components can visualize and analyze the internal structure of translucent objects. Therefore, the separation of reflection components is an important issue.

The problems of reflection component separation have been tackled in the context of computer vision and inverse rendering. Nayar *et al.* [2006] separate direct and indirect components with spatially high-frequency illumination patterns. Their method requires multiple fine patterns for projection, and captured images must be computed afterwards. Therefore, their method is inherently weak for dynamic scenes. On the other hand, O'Toole *et al.* [2015] proposed Episcan3D for the selective acquisition of the direct component in real-time, which uses the fact that the direct component satisfies the epipolar constraint while indirect component does not. In this method, the laser projector and the rolling shutter camera should be aligned to match the all pairs of scanning lines on

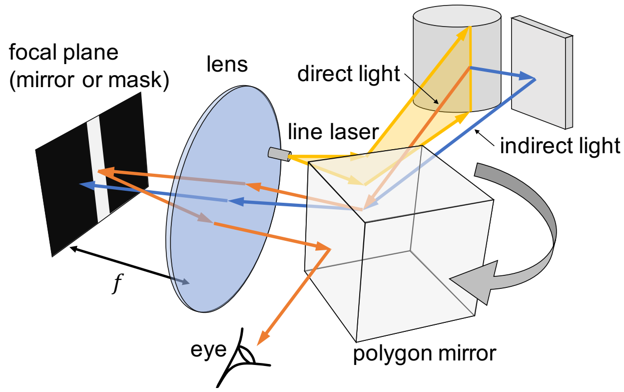


Figure 2: Principle of EpiScope

the corresponding epipolar planes. Moreover, the projector and camera should be synchronized so that the projection line and the imaging line share the same epipolar plane in every moment. Kubo *et al.* [2019] extended this method and showed that indirect light can be selectively acquired by varying two parameters, the delay time of synchronization and the exposure time. However, their methods share the same problem that requires nuisance multi-degree-of-freedom geometric alignment of the projector and camera and high-precision temporal synchronization. Even though their methods do no need image processing, the resultant image should be seen through the camera and display.

In this paper, we introduce *EpiScope*, an purely opto-mechanical system that works in the same way as Episcan3D. As shown in Figure 1, this system can select direct or indirect components by looking through the device and observing directly with the naked eye. As shown in Figure 2, this system consists of only optical elements such as a polygonal mirror and lens. Scanning of the entire scene can be done simply by rotating the polygonal mirror with a motor.

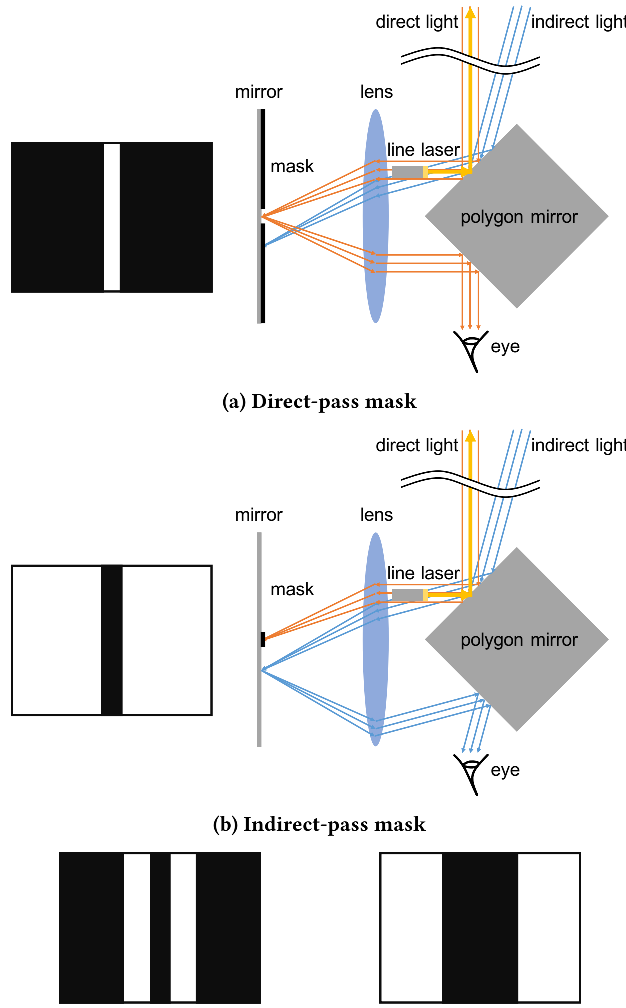
The specific features of EpiScope are:

- The scene can be observed directly without using the camera or display. Therefore, the observed image quality is not limited by the sensor resolution and dynamic range. There is no delay in displaying the image.
- Compared to Episcan3D, the mask design has more flexibility. It can design multiple pass-through regions.
- Since each ray is optically synchronized, there is no synchronization error. The scanning speed can be easily increased by increasing the rotation speed of the polygonal mirror.

2 EPISCOPE

EpiScope is a device that can optically select reflective components by arranging a polygonal mirror, line laser emitter, lens, fixed mirror, and mask as shown in Figure 2.

This optical system illuminates the scene with a line laser and selects the reflected light based on the ray directions. To scan the scene, the polygonal mirror is rotated around the axis. Obviously, there is no synchronization error in principle because both the directions of projected and reflected light are scanned by the same surface of the polygonal mirror.



(a) Direct-pass mask

(b) Indirect-pass mask

(c) Short-indirect mask

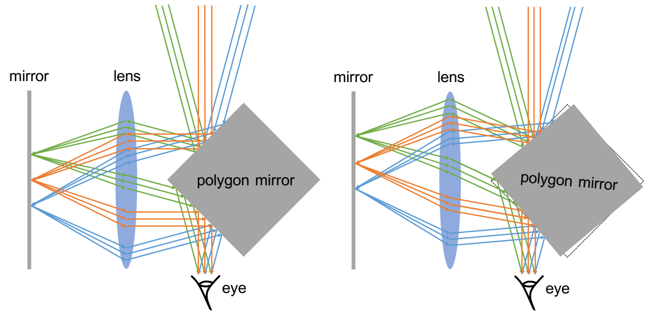
(d) Long-indirect mask

Figure 3: Relationship between mask design and light rays. (a) By covering the mirror to the edge, only direct light is selected. (b) By covering only the center of the mirror, only indirect light is selected. By covering the mirror with multiple openings, as in (c) and (d), short- and long-range indirect light can be selected.

The lens, and the fixed mirror attached with a mask, are used to select the light in specific ray directions. The mask is placed on the fixed mirror at a distance f (focal length of the lens) from the lens. In this case, the lens acts as an optical device that transforms the direction of incoming rays to the position on the mask. The direction of the light ray can be selected according to the design of the mask. The lens and the polygonal mirror are also responsible for presenting the image on the mask to the naked eye.

2.1 Design of the Mask

The reflection components that pass through EpiScope are determined by the design of the mask. This mask design exploits the fact



(a) (b)

Figure 4: Even if the polygonal mirror rotates, the orientation of the incident light from the scene and the light presented to the naked eye do not change. In contrast to (a), (b) has a 5° rotation.

that the direct light always reaches the center of the focal plane regardless of the rotation of the polygonal mirror. Figure 3 shows the relationship between the mask design and each ray. Figure 3(a) shows an example of selecting only direct light. By covering the mirror to the edge of the focal plane, indirect light is removed and only direct light is selected. On the other hand, Figure 3(b) is an example of indirect light selection. By covering the center of the mirror, only indirect light is selected.

Compared to Episcan3D, our method has high degrees of freedom for selecting reflective components. Episcan3D has two degrees of freedom, exposure time and synchronization delay [Kubo et al. 2019]. In contrast, our method has multi-degrees of freedom (more than two) that can create multiple pass-through areas. For example, Figure 3(c) and Figure 3(d) have multiple pass-through areas, which can obtain short- or long-range indirect components.

2.2 Stable Image Regardless of the Rotation of the Polygonal Mirror

As shown in Figure 4, the direction of the incident light from the scene and the outgoing light to the observer are always the same, regardless of the angle of the polygonal mirror. Therefore, our eye can observe the stable image even if the polygonal mirror is rotated. In addition, the observed image is the same size as it is when we look at the scene directly without EpiScope, since the magnification of this optical system is one (*i.e.* life size).

2.3 Application for Computer Vision

EpiScope can be applied to various types of image sensors and/or light sources. For example, Time-of-Flight (ToF) imaging, which uses a ToF image sensor and a modulated light source, can be robust to ambient light and indirect light, like EpiToF [Achar et al. 2017].

In this paper, we discussed the case of a simple line laser source and a fixed mask, but it can be extended further. For example, we can use a variable 2D pattern by a projector instead of a simple line laser and a spatial modulation device such as LCoS (Liquid Crystal on Silicon) instead of a fixed mask. By extending it in this way, we can analyze light transport [Kubo et al. 2019] and estimate the deep structure of translucent objects [Liu et al. 2020].

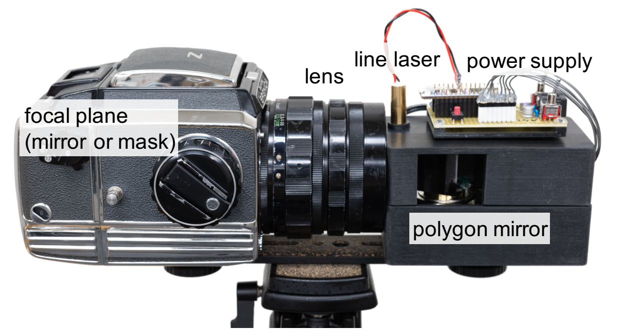


Figure 5: Prototype of EpiScope

3 EXPERIMENTAL RESULTS

Figure 5 shows the prototype of EpiScope. We use a Nidec Copal Electronics PD30LA as a polygonal mirror, which is a cube of 25 mm, with maximum rotation speed of 4000 rpm (since there are four mirrors, it can scan 267 times per second). To hold the lens, fixed mirror and mask, we use a Zenza Bronica S2, a medium-size format film camera. The fixed mirror and mask (Figure 6) are installed on the film plane. The lens is a Sankyo Kohki Komura 135mm f/2.3. The line laser is a Quarton VLM-520-28 LPT (green color, the maximum output power is 1 mW). Since the distance to the scene is finite, we place a close-up lens (convex lens with focal length 1400 mm) between the polygonal mirror and the scene.

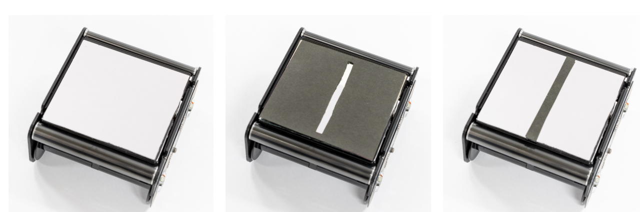
This device can observe the scene with the naked eye, but in this paper, we capture the image with a SONY α7SIII and FE 50mm F1.8.

3.1 Selection of Reflectance Components by Changing Mask Design

We captured several images through EpiScope with different mask designs as shown in Figure 7. The target scene consisted of a disco ball on a wax pedestal, surrounded by a V-shape wall. By changing the mask, EpiScope can select not only direct or indirect components but also short- or long-range indirect components. We can confirm that the indirect components of inter-reflection from the disco ball and subsurface scattering in the wax can be separated.

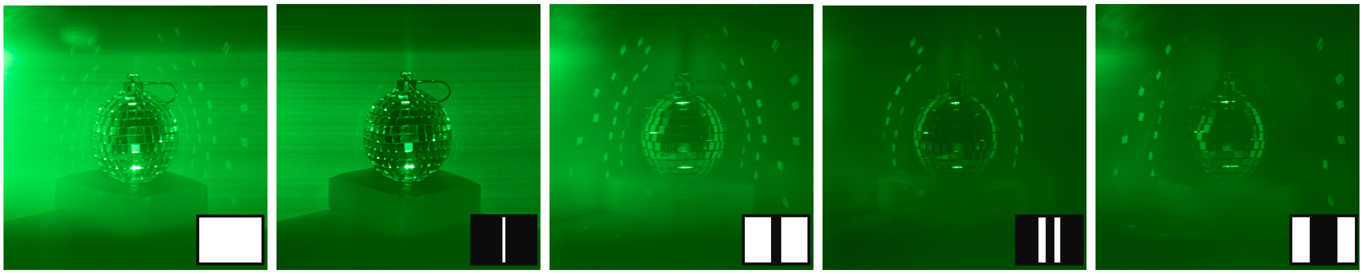
3.2 High-Speed Imaging for Dynamic Scene

The scanning speed of the EpiScope is determined by the speed of the motor. Since it is relatively easy to increase the speed of the motor, the EpiScope can perform high-speed scanning.



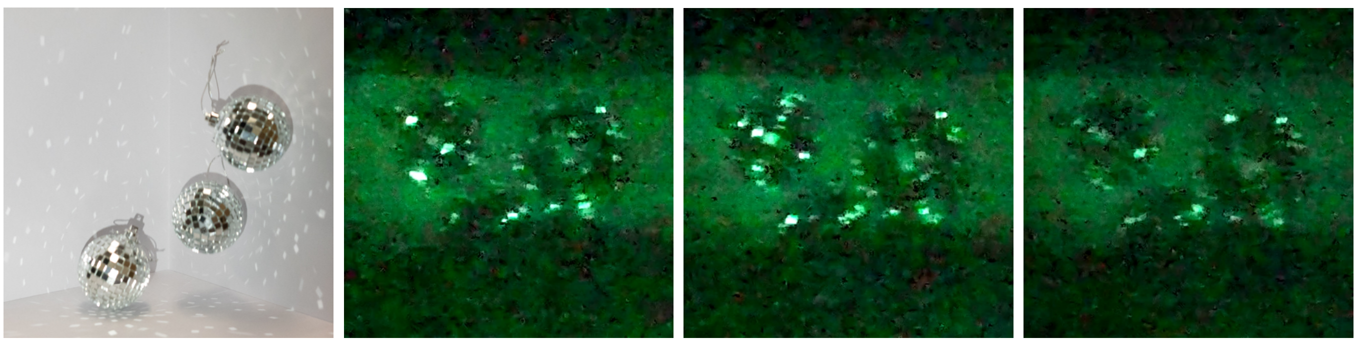
(a) Mirror only **(b) Direct-pass mask** **(c) Indirect-pass mask**

Figure 6: Mirror and mask



(a) Regular (no mask) (b) Direct (c) Indirect (d) Short-indirect (e) Long-indirect

Figure 7: The results using various designs of the mask (bottom right). In the target scene, the disco ball is placed on the wax pedestal and surrounded by a V-shape wall. (a) Inter-reflection from the disco ball and subsurface scattering in the wax are observed in the regular image without the mask. (b) With a direct-pass mask, the inter-reflection and subsurface scattering are removed, and only the direct component is observed. (c) With an indirect-pass mask, direct reflections are removed and only indirect components such as inter-reflections and subsurface scattering are observed. By changing the design of the mask, we can observe (d) short-range indirect components and (e) long-range indirect components.



(a) Scene (b) Sequential frames of video with only direct components

Figure 8: The direct component was captured in a high-speed video of 240 fps. (a) Multiple disco balls are dropped in the target scene. (b) The video records the process of falling disco balls, and the inter-reflection from the disco balls is removed. The video is unclear because the scene is dark and the exposure time is short, which causes a lot of noise in the camera.

The polygonal mirror used in the prototype can scan a maximum of 267 times per second. Therefore, we set the frame rate of the camera to 240 fps and the number of scans per second was matched to 240 by controlling the motor speed. The result is shown in Figure 8 where we used a direct component mask (Figure 3(a)). In the video, the falling process of the disco ball is recorded, and the inter-reflection from the disco ball is removed. Note that the noise in the video is caused by the insufficient intensity of the laser beam and the short exposure time of the camera.

The rotation speed of the polygonal mirror can be easily increased up to 5×10^4 rpm. If we do not need direct observation by the naked eye, the mirror can be made smaller, or the number of faces can be increased, so higher speeds are possible.

4 CONCLUSION

In this study, we proposed EpiScope, which can selectively acquire direct and indirect components by rotating a polygonal mirror with a motor and directly observing them with the naked eye. By changing the design of the mask, we have shown that the EpiScope can selectively acquire the direct and indirect components, as well as the indirect components at short and long distances. We also showed that the selected reflection components could be captured in a high-speed video of 240 fps by increasing the motor speed.

REFERENCES

Supreeth Achar, Joseph R Bartels, William L'Red' Whittaker, Kiriakos N Kutulakos, and Srinivasa G Narasimhan. 2017. Epipolar time-of-flight imaging. *ACM Transactions on Graphics (ToG)* 36, 4 (2017), 1–8.

Hiroyuki Kubo, Suren Jayasuriya, Takafumi Iwaguchi, Takuya Funatomi, Yasuhiro Mukaigawa, and Srinivasa G Narasimhan. 2019. Programmable non-epipolar indirect light transport: Capture and analysis. *IEEE Transactions on Visualization and Computer Graphics* (2019).

Chao Liu, Akash K Maity, Artur W Dubrawski, Ashutosh Sabharwal, and Srinivasa G Narasimhan. 2020. High resolution diffuse optical tomography using short range indirect subsurface imaging. In *2020 IEEE International Conference on Computational Photography (ICCP)*. IEEE, 1–12.

Shree K Nayar, Gurunandan Krishnan, Michael D Grossberg, and Ramesh Raskar. 2006. Fast separation of direct and global components of a scene using high frequency illumination. In *ACM SIGGRAPH 2006 Papers*. 935–944.

Matthew O'Toole, Supreeth Achar, Srinivasa G Narasimhan, and Kiriakos N Kutulakos. 2015. Homogeneous codes for energy-efficient illumination and imaging. *ACM Transactions on Graphics (ToG)* 34, 4 (2015), 1–13.