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The Smallest projection optics for the Vertical shaped Ultra short throw Projector

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Abstract
We have developed a smallest optics for a Vertical shaped Ultra short throw Projector which can project a Full HD (1920 × 1080 pixels) image. In order to realize the smallest optics, we have designed three specific optical parts. First, we have designed a negative distortion lens to minimize each optical parts. Second, we have put a flat mirror to bend optical paths. Finally, we have designed a freeform mirror to correct the distortion of a projected image. By using these parts, we have realized the smallest optics and excellent image quality for the Vertical shaped Ultra short throw Projector.

Introduction
In recent years, front projectors have been commonly used in schools, business meetings and home theaters to produce large-sized images on screens. Conventional projectors require long projection distances to display large-scale images, as shown in Figure 1. Therefore, when we use a conventional projector in a classroom, a meeting room or a living room, we cannot place objects between the projector and the screen because they block the light; this restricts the overall layout of the room. Additionally, when giving a presentation with a conventional projector, the presenter is aware of the glare of the projection beam, and their shadow is likely to fall on the screen.

The ultra-short throw projector, which can project large-sized images from a very short distance, was therefore developed [1-5]. This type of projector allows us to ignore shading problems and room layout restrictions. Furthermore, during a presentation, the presenter will not experience the two problems that were described above. However, conventional ultra-short throw projectors are so large that they cannot be moved freely. Therefore it is difficult, for example, for the presenter to change the projector arrangement and to carry the projector from one classroom to another.

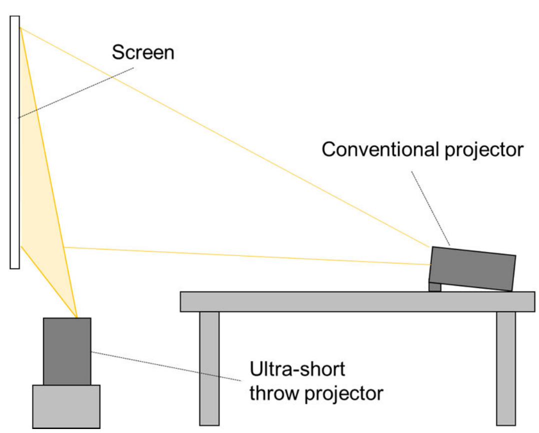


Figure 1 *Schematic diagram of the projector arrangements*

We therefore developed the smaller vertical-shaped ultra-short throw projector in 2011 [6,7]. This vertical-shaped ultra-short throw projector was small in size (257×144×221 mm) and lightweight (3.0 kg). Consequently, the portability of the vertical-shaped ultra-short throw projector was greatly improved when compared with conventional ultra-short throw projectors, and we opened up a new market for mobile and ultra-short throw projectors through this innovation.

In recent years in the display market, support of increasingly high resolution displays, such as full high-definition (HD) (1920×1080 pixels) and 4K (3840×2160 pixels) displays continues to progress. The same is true of the ultra-short throw projector. Home theater projectors in particular require full HD and increased resolution. However, the vertical-shaped ultra-short throw projector that we developed in 2011 did not support full HD resolution, so it was necessary to develop a new vertical-shaped ultra-short throw projector that did support full HD as quickly as possible.

In this report, we will describe the smallest-scale optics that we developed for the vertical-shaped ultra-short throw projector, discuss the issues encountered in supporting full HD using the optics, and the optical technology used to resolve these issues.

Ultra-Short Throw Projector
As part of the development of the projection optical system, we have shortened the projection distance, as described above. In this report, we separate the projectors into the following four categories from the viewpoints of projection distance and the optical system used.

1. Conventional projector with lens system;
2. Short throw projector with lens system;
3. Horizontal ultra-short throw projector with concave mirror and lens system;
4. Vertical ultra-short throw projector with freeform mirror, flat mirror and lens system.

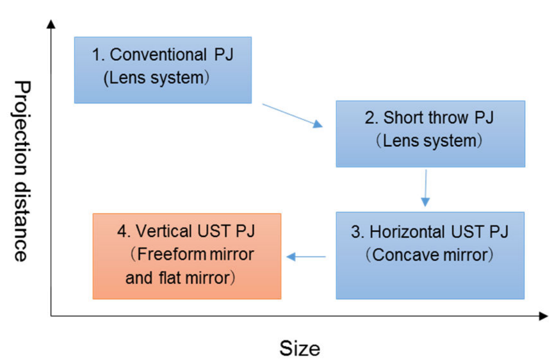


Figure 2 *Relationship between projection distance and size for the four projector systems (PJ: projector)*

(In general, these systems are ranked in order of projection distance as 1 > 2 > 3 = 4, as will be detailed later.)

In Figure 2, the vertical axis represents the projection distance and the horizontal axis indicates the size of the projector. The areas of the categories given above are shown in Figure 2.

As indicated by Figure 2, when we design the lens system to have a shorter projection distance, we must therefore design a projection lens that is capable of achieving wide angle projection, and thus the front lens must increase in size. As a result, the overall size of the projection system also increases. Therefore, there must also be a projection distance limit for the short throw projector. The projection distance limit for an 80 in image is approximately 0.8 m [8,9]

To break through this projection distance barrier, the horizontal ultra-short throw projector with concave mirror and lens system was developed [1]. The projection system can project an 80 in image on a screen from less than 0.6 m away. Figure 3a shows a schematic diagram of the optical system of this projector.

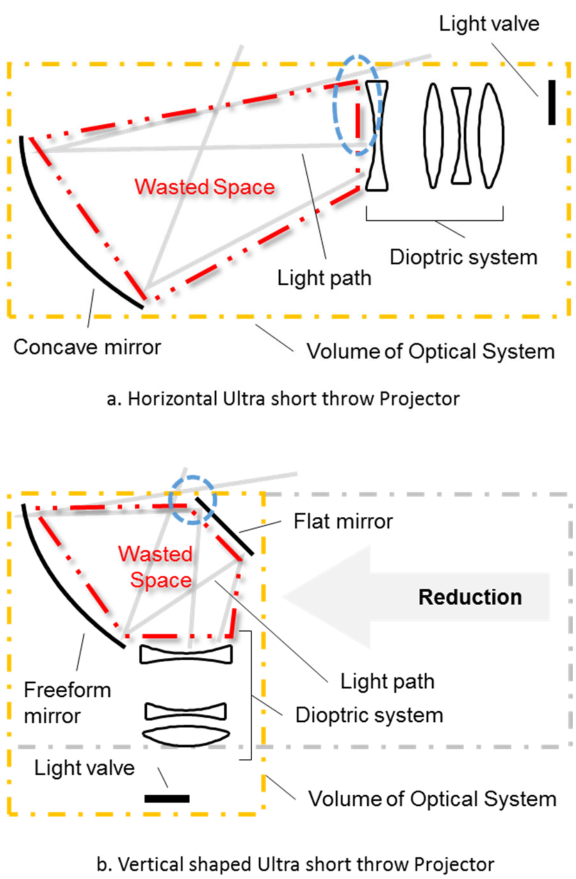


Figure 3 *Schematic diagrams of optics of (a) horizontal UST projector and (b) vertical-shaped UST projector (UST: ultra-short throw).*

The lens system consists of, in order from the light valve side to the screen side, a refractive optical system with multiple lenses and a concave mirror (the light valve is an image display element such as a digital micro mirror device or a liquid crystal panel). As indicated by the red two-dot-chain line shown in Figure 3a, the system requires a large space to be provided between the front lens of the lens system and the concave mirror for the design of the concave mirror and lens system. The optical system needs, in principle, an intermediate image between the concave mirror and the lens system, and also needs to increase the distance between the concave mirror and the dioptric system to avoid interference between the light that is reflected from the mirror and the lens system and is indicated by the blue dashed line in Figure 3a. Therefore, the horizontal ultra-short throw projector is large in size. To enable reduction of the optical system size for the ultra-short throw projector when using a concave mirror, it is important to reduce the space between the dioptric system and the concave mirror.

For this reason, we developed the vertical-shaped ultra-short throw projector with freeform mirror, flat mirror and lens system. A schematic diagram of the optical system for this projector is shown in Figure 3b. We inserted a flat mirror into the wasted space between the dioptric system and the concave mirror in the horizontal ultra-short throw projector. The flat mirror can bend the light paths, thus allowing us to reduce the wasted space. By bending the light paths, the interference conditions described above were relaxed as shown by the blue dashed line in Figure 3b, and we could thus further miniaturize the ultra-short throw projector. This system can also reduce the space required through use of the freeform mirror, which has a great deal of design flexibility [10-13] and can increase the system's capability to correct distortion. We were thus able to reduce the volume of the optical system, as indicated by yellow dot-chain line in Figure 3b.

Method for Support of Full HD

In addition, we newly developed the optical system to realize both miniaturization and high resolution (full HD support), thus improving on the previous vertical-shaped ultra-short projector described above. In general, when designing a lens system, a higher lens system resolution requires a larger lens system size. The same is true for the vertical-shaped ultra-short throw projector. In Figure 4, the vertical axis denotes the resolution of the optics, while the horizontal axis denotes the projector size. The areas of the various vertical ultra-short throw projector types are shown in Figure 4. If we designed the above optics to support full HD resolution, the optical system size would become very large as indicated by the black dotted arrow in Figure 4.

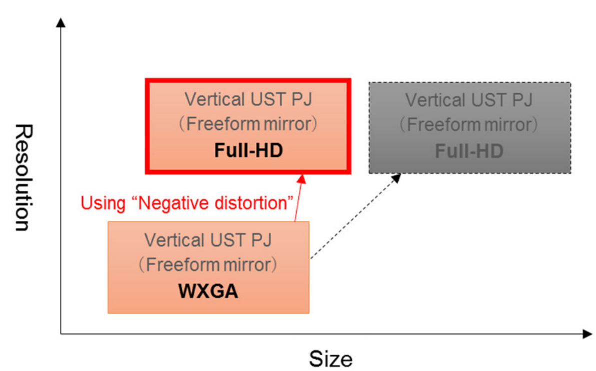


Figure 4 *Relationship between image resolution and system size.*

To reduce the space between the dioptric system and the freeform and flat mirrors, we attempted to add negative distortion to the dioptric system. This allowed us to greatly reduce the space in question, as indicated by the red arrow in Figure 4. This also allowed us to restrict the size of the projection optics required for high resolution to a minimum.

In general, positive distortion is generated by achieving a wide angle [14, 15]. It is difficult to achieve both negative distortion and a good image simultaneously. To generate the required negative distortion, we must correct the lens system distortion excessively, but such excessive correction generates image curvature. We therefore tried to design an optical system that separated the rays at the magnification side of the dioptric system, and optimized the focusing method (floating focus) and the shape of an aspherical lens that was positioned on the magnification side to control each of the rays. We were thus able to balance the image curvature with the negative distortion. Additionally, we corrected the distortion using the freeform mirror. We were thus able to achieve both negative distortion and good image quality simultaneously for the first time.

Schematic diagrams of a) a general lens design with positive distortion characteristics and b) the new lens design with negative distortion characteristics are shown in Figure 5. In the figure, blue lines indicate the light paths and red dotted lines indicate the space between the mirrors and the lens systems. The general shapes of the distortion for both systems were indicated by the diagrams on the left side of each optical system schematic in Figure 5.

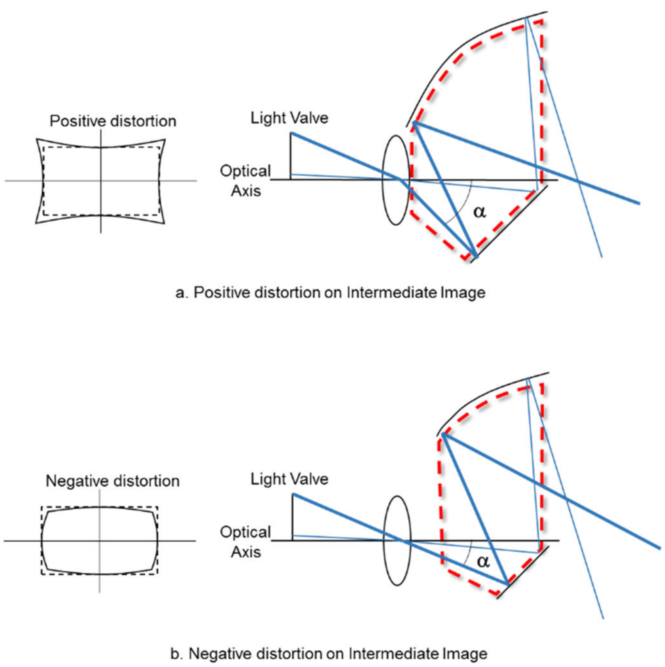


Figure 5 *Schematic diagrams of lens designs with (a) positive distortion and (b) negative distortion.*

As shown in Figure 5b, the maximum exit angle α of the rays from the lens system with negative distortion is smaller than that for the lens system with positive distortion. Therefore, the distance between the rays that were reflected from the flat mirror and the dioptric system is greater for the lens system with negative distortion than that for the lens system with positive distortion. Consequently, we were able to greatly reduce the space between the freeform mirror and the dioptric system.

Results

We have developed new projection system optics with improved performance when compared with the previous optics (for the vertical-shaped ultra-short throw projector developed in 2011). The specifications of the optics are listed in Table 1. In this report, we define the distance between the edge of the freeform mirror and the screen as the throw distance.

Similar to the previous optics, the new optics can project large-sized images over very short distances when compared with the performance of conventional horizontal ultra-short throw projectors. The new optics can project an 80 in image onto a screen from only 0.45 m away.

Table 1: Specifications of previous optics and new optics

	Previous optics	New optics (this report)
Resolution	WXGA	Full HD
Lens Distortion	Positive	Negative
Light Valve size	0.65 in	0.65 in
Pixel pitch	10.8 μm	7.56 μm
Throw distance(80 in)	0.38 m	0.45 m

Diagrams of the optical systems of both the previous optics and the new optics are shown in Figure 6. In both systems, the rays from the lens system are bent by the flat mirror and the freeform mirror. Because of this layout, the previous optics and the new optics require a very small space for implementation.

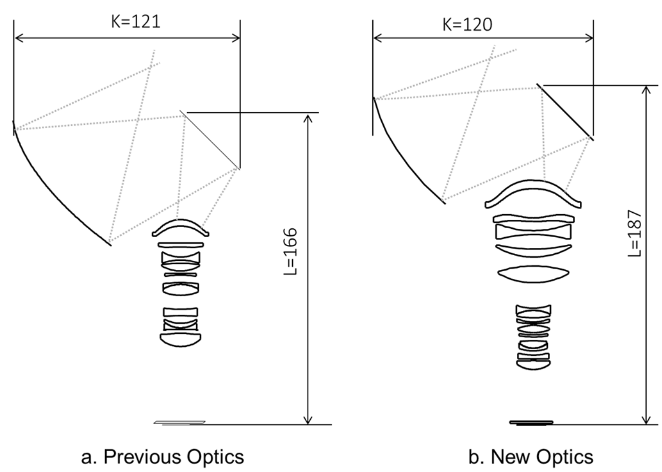
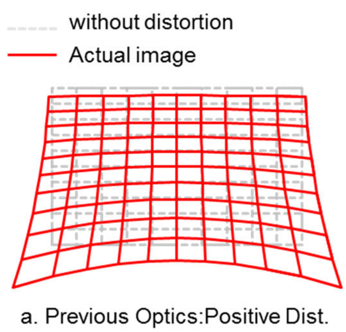


Figure 6 *Diagram of (a) the previous optics and (b) the new optics*

The new optics for full HD support were developed by improving the previous optics. As shown in Table 1, the sizes of the light valves of the previous optics and the new optics are identical, but the light valve resolution in the new system becomes full HD (1920×1080 pixels) rather than Wide Extended Graphics Array (WXGA, 1280 × 800 pixels) resolution. The pixel size required for the light valve for the new optics is thus 0.7 times that of the previous optics, so we had to greatly increase the optical system resolution. In general, when designing a lens system, a higher lens system resolution leads to larger lens system size, as mentioned above. We found that we can minimize the size of the vertical shaped ultra-short throw optics by applying a negative distortion lens. We show the distortion grids of the dioptric systems both of the previous optics and the new optics in Figure 7. The gray dotted line indicates the rectangular grid without distortion, while the red solid line indicates the distortion grid of the intermediate image of the dioptric system.



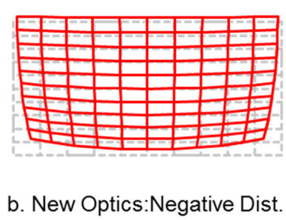


Figure 7 *Intermediate images of (a) the previous optics and (b) the new optics.*

In Figure 7, the previous optics have positive distortion, but the new optics have negative distortion. Consequently, we are able to reduce the space between the freeform mirror and the dioptric system when using the new optics. We were also able to reduce the sizes of the freeform mirror and the flat mirror using negative distortion.

Finally, we compare the cross-sectional areas of the previous optics and the new optics, as shown in Figure 6. While the resolution of the new optics is 1.5 times higher than that of the previous optics, the area of the new optics is only 1.1 times greater than that of the previous optics; this is the effect of the negative distortion.

Conclusions

We newly developed a vertical-shaped ultra-short throw projector that supports full HD resolution, thus improving upon the previous optics that were developed in 2011. We were also able to keep the size of the new optics to a minimum by adding negative distortion to the dioptric system.

In future work, we intend further development of the vertical-shaped ultra-short projector with the freeform mirror and the flat mirror as our unique technology.

References

[1] S. Shikama, H. Suzuki, K. Teramoto, "Optical System of Ultra-Thin Rear Projector Equipped with Refractive-Reflective Projection Optics," SID 02 DIGEST, pp. 1250-1253, 2002

[2] K. Agata, J. Ogawa, K. Furuichi, H. Fukunaga, T. Takeuchi, "An Ultra Short-Focus Front Projector Using Reflective Projection Optics," Nec Technical Journal, vol. 1, No.3, pp. 89-93, 2006

[3] S. Matsumoto, R. Amano, M. Okuda, T. Adachi, S. Okuno, "Ultra-short Throw Distance Front Projector wth Mirror-Lens Hybrid Projection Optical System," 2008 Digest of Technical papers ICCE, pp. 445-448, 2008

[4] M. Yatsu, K. Hirata, "Super-Wide Angle Projection lens with free Shaped Mirror For Projector", in 36th Optical Symposium, Tokyo, 2011

[5] T. Takahashi, I. Abe, K. Fujita, "A Development of Optical System for Ultra-Close-Range Projection, " Ricoh Technical Report, no.38, pp. 15-21, 2012

[6] I. Abe, K. Fujita, T. Tatsuya, H. Tatsuno, "Development of Optical System for Ultra-Close-Range Projection with Free-Form Concave Mirror," in 38th Optical Symposium, Tokyo, 2013

[7] J. Ogawa, A. Osaka, "The trend of UST Projector," Latest Technologies in the Projection Display II, pp. 191-202, Tokyo :CMC books, 2010

[8] T. Kubota, "Development of Wide-angle lens for Projector – Topics of High-zoom-ratio lens," Optics Design, No.53, pp. 12-20, 2013

[9] K. Araki, "Extension of Non-Co-Axial Optics into the Imaging Systems," Kogaku, vol. 37, No. 6, pp. 334-339, 2008

[10] K. Hayashi "Jiyukyokumen to Hitaisyokougakukei," in ODG & JOEM Toutrial, No.1, Tokyo, 2007

[11] A. Yabe, "Desensitization of axially asymmetric optical system", Advanced Optical Technologies, vol. 2, No. 1, pp 63-73, 2013

[12] C. Menke, G. W. Forbes, "Optical design with orthogonal representations of rotationally symmetric and freeform aspheres," Advanced Optical Technologies, vol. 2, No. 1, pp 97-109, 2013

[13] G. W. Forbes, "High-precision freeform optics … the shape of some important things to come," in ODF'12, St. Petersburg, 2012

[14] J. Nakagawa, Lens sekkei kogaku, Tokyo :Tokai Daigaku Shuppan-kai,1986

[15] E. Takano, Lens Design guide, Tokyo :Shashin Kogyo Shuppan-sha, 1993

Author Biography

Yohei Takano received his MS in Materials Science and Engineering from Tokyo Institute of Technology (2005). Since that time, he has worked for Ricoh in Kanagawa. His work has focused on the development and design of camera and projection lenses.