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非全息衍射投影

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摘　要：提出了一种无需全息计算和相干照明的衍射投影方法和投影系统，利用非相干的准直 LED 光源和傅里叶变换透镜取代全息迭代计算获得被投影图像的空间频谱，再利用空间频谱在自由空间中的瑞利索墨菲衍射实现了小投射比、无限景深的图像投影.详细推导了投影方法的成像过程，解析了投影系统的强度脉冲响应函数.实验搭建了一套非全息衍射投影系统，对投影过程中产生的像差和亮度不均匀进行矫正，获得了无相干噪音的高品质衍射图像，实现了投射比为 0.87 的无限景深的衍射投影.在相距大于 800 mm 的不同深度平面上同时获得了清晰的投影图像，从而验证了方法的可行性.该投影方法和系统在球幕投影、任意曲面屏幕投影和增强现实投影等领域具有潜在的应用.

关键词：投影系统；傅里叶变换；衍射；成像系统；全息显示；发光二极管
中图分类号：O438.1；TS951.7+6　　**文献标识码**：A　　**doi**：10.3788/gzxb20204901.0111002

Non-holographic Diffractive Projector

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Abstract: A kind of diffractive projection method and projector without holographic computation and coherent illumination was proposed. Instead of holographic iterative calculation, a incoherent collimated light-emitting diode and compact Fourier transform lens were used to generate the frequency spectrum of the projected images in real time. The Rayleigh-Sommerfeld diffraction of the spatial frequency spectrum of the images in free space was used to project the images with short throw ratio and infinite depth of focus. The imaging principles of the projection method were deduced analytically in detail. The intensity impulse response function of the projector was given. A non-holographic diffractive projector was demonstrated experimentally. The aberration and inhomogeneous intensity of the projection images were corrected. High quality diffractive images free from coherent artifact noises are realized. A diffractive projector with 0.87 throw ratio and infinite depth of focus is achieved. The projector can project clear images in different depth planes simultaneously which are separated at a distance more than 800 mm. The projection method and system have potential application in sphere projection, arbitrary surface projeciton, and augmented reality projection.

Key words: Projection systems; Fourier transforms; Diffraction; Imaging systems; Holographic displays; Light emitting diodes
OCIS Codes: 110.0110; 120.2040; 120.4820; 090.2870; 090.0090

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0 Introduction

Digital projectors are widely used in our daily life. Novel projection technologies are emerging to meet the requirements of the handheld and wearable devices. There are mainly three types of digital projection technology. The first is to use projection lenses to relay and magnify the images on the micro Spatial Light Modulator (SLM) to the projection screen based on geometric imaging rules[1]. This type of projector is now commercially available[2-3]. However, complex lens systems including spherical and aspheric lenses are usually required to correct the aberrations, which makes the projectors bulky[4-5]. If the projection lenses are miniaturized, image resolution and light efficiency will be lost inevitably. Because the miniaturized lenses reduce the luminous flux and increase the negative diffraction effect on the lens's aperture[6]. Furthermore, the Depth of Focus (DOF) of this type of projectors is also limited.

The second is to use a scanning laser beam to draw the image on a screen at a very high frequency[7-8]. Since there is no projection lens in the projector, the total volume and cost of the system is reduced. The image distortion of scanning laser projectors is more easily to correct than conventional projectors. The disadvantage of this type of projector is that the image resolution is limited by the divergence angle and diffraction of the laser beam in free space[8].

The third is to use holograms to project an image based on diffractive imaging rules[9-12]. Instead of physical lenses, digital lens phase factors are coded in the holographic projector, which makes the system compact and versatile. The advantages of this type of projectors include lens-less projection, high energy efficiency, wide color gamut and potentials for 3D display. Recently, both the image size and imaging quality of the holographic projector have been improved remarkably[13-14]. Full-HD resolution image is achieved experimentally using a 4k SLM[15]. Miniature holographic projector with cloud computing capabilities is also demonstrated[16]. Although a considerable amount of research has been dedicated to suppress the noise, the speckle noise is still an inherent challenge that deteriorates the image quality[17-21]. Moreover, the throw ratio is still limited by the diffraction angle of the light from the finite size pixels of the SLM. There are two effective methods to get a short throw ratio holographic projector, one is to use zoom lenses, the other is to use a diverging spherical wave illumination system[22-25]. In such projectors, additional lenses are usually required. To avoid using optical lens, photolithography or electron beam lithography is used to make a high resolution hologram to get a short throw ratio projection. However, the projection systems can not achieve dynamic projection[26-27]. In addition, the complicated calculation is still the bottleneck of current holographic projectors. Although the remote computing servers can effectively reduce the size and power consumption of the holographic projector, the total energy consumption of the projection system is still high.

To address the limitations of the projectors mentioned above, a short throw ratio diffractive projection technique with infinite DOF and without holographic computation and coherence illumination is proposed and demonstrated. A compact Light-emitting Diode (LED) is employed to illuminate the projector, which makes the image free of coherent artifact noises. A Fourier Transform Lens (FTL) is used to generate the spatial frequency spectrum of the projected image in real time. The Rayleigh-Sommerfeld diffraction of the frequency spectrum in free space is used to project the image. High quality and short throw ratio diffractive projectors are demonstrated and image with huge DOF is realized.

1 Principle of the non-holographic diffractive projector

Traditional holographic projectors usually use diverging spherical wave illumination to get big images within a short throw distance. As shown in Fig. 1(a), a laser beam is focused by an objective lens to generate a diverging spherical wave. After reflection by the beam splitter, the diverging spherical wave illuminates the hologram on the Liquid Crystal on Silicon (LCOS) device. The hologram then reflects and modulates the spherical wave and generates an image on the projection screen by Fresnel diffraction. The holograms are calculated either in real time or offline. In such a holographic projector, a spherical wave having a large divergence angle can be used to get a short throw ratio, but the image quality is limited by speckle noise, ringing artifacts, zeroth-order and high-order diffracted light. In addition, the complexity of holographic calculations remains unresolved.

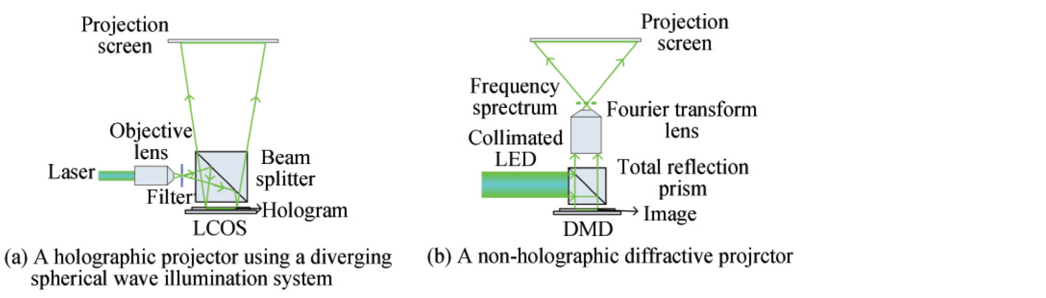


Fig.1 Comparison of the optical setup of holographic and proposed non-holographic diffractive projector.

In comparison, the proposed non-holographic diffractive projector uses a FTL and LED to achieve short throw ratio projection without holographic calculations. As shown in Fig. 1(b), a collimated LED light is used to illuminate the Digital Mirror Device (DMD) with the help of the Total Reflection (TR) prism. The DMD is located in front focal plane of the FTL. The image to be projected is shown on the DMD directly. The light reflecting from the image goes through the FTL and generates a frequency spectrum of the image in back focal plane of the FTL. Then, by the Rayleigh-Sommerfeld diffraction of the image's frequency spectrum, an image will be projected on the screen clearly. Different from the traditional holographic projector, hologram and holographic calculation is no longer needed, which makes the projector simple and efficient. In addition, coherent light source is not necessary, so that the image is free from speckle, ringing artifacts, and other diffraction noises.

To get a short throw ratio diffractive projection, a large diffraction angle is required. Paraxial approximations of the scalar diffraction theory are not applicable to the projector. Rayleigh-Sommerfeld diffraction theory instead of Fresnel or Fraunhofer diffraction should be used in such condition Fig.2 shows the simplified coordinate system of the diffraction projector without counting the reflection. The image to be projected is located in the (x_0, y_0) plane, the frequency spectrum of the image is located in the (x_1, y_1) plane, the projection screen is located in the (x_2, y_2) plane with a distance z from the (x_1, y_1) plane. The front and back focal length of the FTL is F_1 and F_2 respectively. The amplitude and intensity distribution of the image to be projected are $U_0(x_0, y_0)$ and $I_0(x_0, y_0)$ respectively. According to the property of the FTL, the frequency spectrum of the image's amplitude distribution on the (x_1, y_1) plane $U_1(x_1, y_1)$ is given by

$$U_1(x_1, y_1) = \mathrm{F}\left\{U_0\left(\frac{x_0}{M}, \frac{y_0}{M}\right)\right\} \tag{1}$$

where $M = F_1/F_2$, F{ } is the Fourier transform operator. The complex amplitude distribution of the light filed on the screen is given by the Rayleigh-Sommerfeld diffraction integral of the image's frequency spectrum, which is as follows.

$$U_2(x_2, y_2) = \iint U_1(x_1, y_1)\frac{z\exp(\mathrm{i}kr)}{2\pi r^3}(1-\mathrm{i}kr)\mathrm{d}x_1\mathrm{d}y_1 \tag{2}$$

where r is the distance between the two corresponding points in the (x_1, y_1) and (x_2, y_2) planes.

$$r = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + z^2} \tag{3}$$

For short throw ratio projection, the spectrum area in (x_1, y_1) plane is much smaller than the projection image in (x_2, y_2) plane and the image distance z meets the conditions $z \gg x_1$, and $z \gg y_1$. So Eq. (3) can be simplified to Eq. (4) as follows.

$$r = \sqrt{x_2^2 + y_2^2 + z^2} \tag{4}$$

Using Eq. (4), the diffraction integral of Eq. (2) can be simplified to Eq. (5) as follows.

$$U_2(x_2, y_2) = \frac{1}{\mathrm{i}\lambda z}\exp(\mathrm{i}kr)\frac{z^2}{r^2}\iint U_1(x_1, y_1)\cdot\exp\left[\frac{-\mathrm{i}2\pi}{\lambda z}\left(x_1\frac{x_2 z}{r} + y_1\frac{y_2 z}{r}\right)\right]\mathrm{d}x_1\mathrm{d}y_1 \tag{5}$$

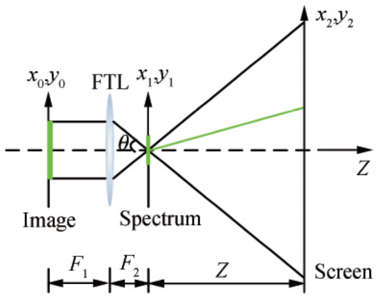


Fig.2 Simplified coordinate system of the diffraction projector without counting the reflection

If the coordinate transformation is defined as follows.

$$X_2=\frac{x_2 z}{r},Y_2=\frac{y_2 z}{r},\xi=\frac{X_2}{\lambda z},\eta=\frac{Y_2}{\lambda z} \tag{6}$$

Eq. (5) can be rewritten as follows.

$$U_2(\xi,\eta)=\frac{1}{\mathrm{i}\lambda z}\exp(\mathrm{i}kr)\frac{z^2}{r^2}\mathrm{F}\{U_1(x_1,y_1)\} \tag{7}$$

According to Eq. (1) and (7), the complex amplitude distribution on the screen can be rewritten as follows.

$$U_2(\xi,\eta)=\mathrm{C}\frac{z^2}{r^2}U_0(-Mx_0,-My_0)=\mathrm{C}\iint U_0(\alpha,\beta)\frac{z^2}{r^2}\delta(\alpha+Mx_0,\beta+My_0)\mathrm{d}\alpha\mathrm{d}\beta \tag{8}$$

where C is a complex constant that can be neglected for the intensity information on the screen, $\delta(x)$ is Dirac function. The amplitude impulse response function of the projector is as follows.

$$h(\xi,\eta)=\frac{z^2}{r^2}\delta(\alpha+Mx_0,\beta+My_0) \tag{9}$$

According to Eq. (9), the intensity impulse response function of the projector is as follows.

$$h_I(\xi,\eta)=|h(\xi,\eta)|^2=\frac{z^4}{r^4}\delta(\alpha+Mx_0,\beta+My_0) \tag{10}$$

According to the properties of linear optical system, the intensity distribution of the image on the screen is as follows.

$$I_2(\xi,\eta)=I_0(\xi,\eta)\star h_I(\xi,\eta)=\frac{z^4}{r^4}I_0(\alpha,\beta)\star\delta(\alpha+Mx_0,\beta+My_0)=\frac{z^4}{r^4}I_0(-Mx_0,-My_0) \tag{11}$$

where $I_0(\xi,\eta)$ is the ideal intensity distribution of the image to be projected on the screen, the operator $\star$ denotes the convolution. According to Eq. (6) and Eq. (11), the intensity distribution on the screen can be rewritten as follows.

$$I_2(X_2,Y_2)=\frac{z^4}{r^4}I(-M\lambda zx_0,-M\lambda zy_0) \tag{12}$$

For paraxial approximation, the parameter z meets the condition $z\approx r$, Eq. (9) can be simplified as follows.

$$I_2(x_2,y_2)=I(-M\lambda zx_0,-M\lambda zy_0) \tag{13}$$

Eq. (12) means that in the non-paraxial approximation region, with some coordinate transformation and intensity variation, the light field's intensity distribution on the screen is a magnified version of the image's intensity distribution to be projected. Eq. (13) means that in paraxial approximation region, without any transformation, the light field's intensity distribution on the screen is a magnified version of the image's intensity distribution exactly. We can use Eq. (12) and Eq. (13) to design the diffractive projector. The magnification of the projector is $M\lambda z$. The projection image will always keep in focus in any projection distance if the approximate condition in Eq. (4) is valid.

From the perspective of geometric optics, this method extends the DOF of the projection system by essentially reducing the aperture diameter of the imaging system. As shown in Fig. 2, there will be a focal spot on the back focal plane of the FTL when the reflected light from the DMD is focused by the FTL. For short throw ratio projector, the focal spot is small enough to be considered as a point source. This system can be considered as a pinhole projector. Similar to pinhole camera, the DOF of the imaging system is infinite.

2 Experiments

It has been proven that the proposed projector is experimentally feasible. Figure 3 is the experimental apparatus of the non-holographic diffractive projector. A blue collimated LED is used to illuminate the DMD through a TR prism. A pair of relay lens is used to relay the image on the DMD to the front focal plane of the FTL. A custom-designed FTL is used to generate the frequency spectrum of the image. A mirror is used to reflect the frequency spectrum to the screen. Through the Rayleigh-Sommerfeld diffraction of the frequency spectrum, images are projected on the screen clearly. The collimated LED light (Thorlabs SOLIS-445C) has a wavelength of 445 nm and a clear aperture of 48 mm, respectively. The resolution of the DMD is 1024×768, and the pixel pitch is 13.68 μm (TI DLP7000). The magnification of the relay lens is 0.5 (Edmund Optics). The parameter M and numerical aperture ($N.A.$) of the FTL are 10 and 0.5 respectively.

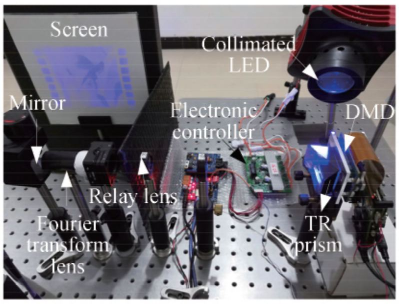


Fig.3 Experimental apparatus of the diffractive projector

Fig.4 shows the imaging results of the diffractive projector. Fig.4(a) is the target grid image to be projected. Fig.4(c) is the projection result with pincushion distortion and intensity variation when Fig.4 (a) is showed on the DMD. The imaging results are coincided with the calculation of Eq. (6) and Eq. (12). To correct the distortion and the variation, inverse transformations are digitally done to the grid image according to Eq. (6) and Eq. (12), as shown in Fig.4(b). Fig.4(d) is the projection result when Fig.4 (b) is shown on the DMD. As shown in Fig.4(d), the curves due to the distortion of the large-angle diffraction return to a straight line. The intensity variation of the projection image which is similar to the vignetting effects of the lens but due to the big angle diffraction again is compensated digitally. These results show that the pincushion distortion and intensity variation are well corrected.

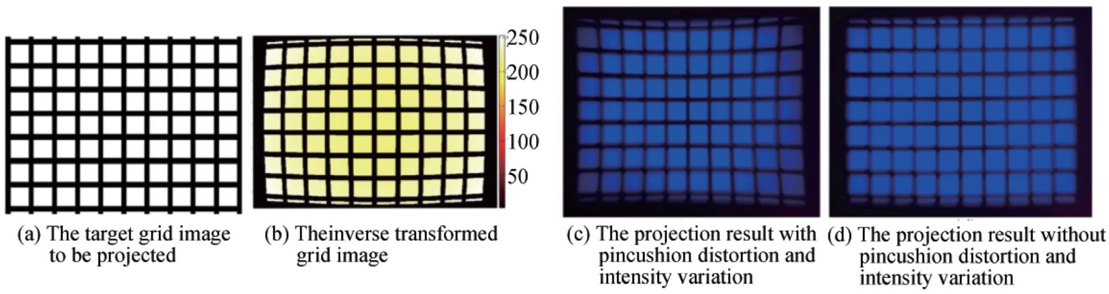
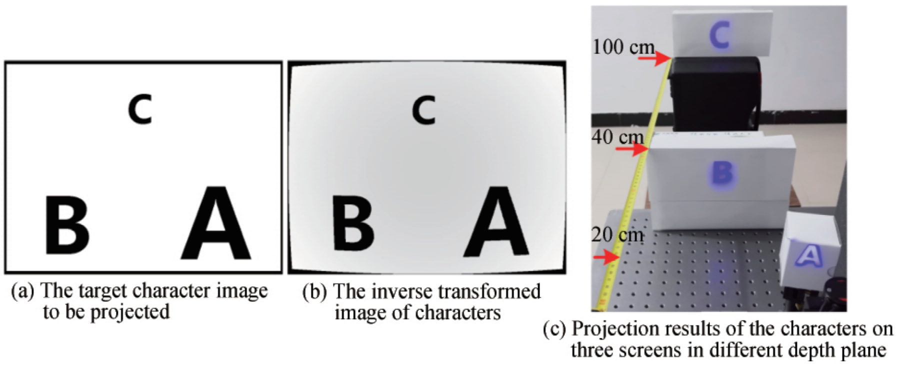


Fig.4 Imaging results of the diffractive projector

Fig.5 gives the projection result of the grayscale image. Comparing with the holographic projection, no obvious speckle and other diffraction noises are observed. The contrast and the grayscale representation of the image are fine. Thanks to the characteristics of far-field diffraction, the proposed diffraction projector has near-infinite DOF. Fig.6 shows the imaging result of the ultra large DOF projector. It projects images on three different depth screens clearly and synchronously. Fig.6(a) is the target character image to be projected, the character A, B, and C are located in different area of the image frame. Fig.6(b) is inverse transformed image of character A, B, and C. The projection result is shown in Fig.6(c). The screens to capture the images are located in the plane at $z=20$ cm, 40 cm, and 100 cm apart from the projector, respectively. The projected character A, B, and C are all in focus and clear. If we move the screen further away, the projection image will always keep in focus, although the intensity of the image will decrease as the image leaving away from the projector. If the screen is moved close to the projector, the projection image will always keep in focus until the projection distance z is so small that Eq.(3) can't be simplified to Eq.(4). In experiments, images are blurred when the projection distance z is smaller than 3 cm. So the DOF range of the projector is $z \in [3, \infty]$. The infinite DOF projector can be widely used in 3D projection display and augmented reality.

(a) The target grayscale image to be projected (b) The inverse transformed grayscale image (c) Projection result of the image

Fig.5 Projection result of the grayscale image



(a) The target character image to be projected (b) The inverse transformed image of characters (c) Projection results of the characters on three screens in different depth plane

Fig.6 The imaging property of the ultra large DOF projector

All the analysis above did not consider the lens aberration which will actually deteriorate the image quality. So a high quality FTL is requried in the proposed projector. The additional optical lenses in the projector will challenge the limited space of the compact projector. Like holographic projection systems, these limitations can be addressed by using high resolution SLM or compact optical lenses.

3 Conclusion

To summarize, the concept of non-holographic diffractive projection technique using incoherent light was demonstrated. A collimated LED light combined with a FTL is used to generate the frequency spectrum of the projected image in real time. Rayleigh-Sommerfeld diffraction of the frequency spectrum is used to generate the clear image. The advantages of the projectors include: 1) No coherent light and holographic computation are required. 2) Images are free of coherent artifact noises. 3) Big image in a short throw distance. 4) Infinite DOF. The main drawback of the presented technique is that additional optical lenses are required in the projector. Optimal design of the optics and mechanical structures are required in future work.

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