Study of theory for transient imaging of hidden object using single-photon array detector

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Abstract: Traditional imaging limits to the occlusion of the solid medium such as the wall and can not collect the image of the object which is out of sight. Moreover, the speed of light is supposed to be infinite in traditional imaging, so the imaging process is a steady-state light transport and irrelevant to the time of flight of light, which cannot reveal the specific characteristic of object in the light transport. Single-photon imaging is a technology which can detect very weak photon signal and capture the information of distance, intensity and image of objects synchronously. In this paper, a method of transient imaging for hidden object was introduced. In the imaging process, the time of flight of photon was considered as a variable in light transport to realize transient imaging, combining imaging for hidden object with photon counting and using single-photon array detector as a receiver to reconstruct hidden object. Further, this method was demonstrated by simulation. It provides the basic theory and framework for the transient imaging of hidden object using single-photon array detector, which can help to design the imaging system in real world in the future, as well as to achieve a better understanding of the nature of transient imaging for hidden object.

Key words: hidden object;　transient imaging;　single-photon array detector

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基于单光子阵列探测器的隐藏目标瞬时成像理论研究

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摘　要: 传统的成像技术受限于固体介质(例如墙壁)的遮挡,不能对不可见的物体进行成像。而且在传统成像中光速被认为是无限大的,所以传统成像过程是一个固态光传输的过程,与光的飞行时间无关,不能展现光传输中物体的具体特征。单光子成像是一种能够检测到非常微弱的光子信号、并能同步采集物体的距离、强度和图像信息的技术。文中介绍了一种对隐藏目标进行瞬态成像的方法,在成像过程中,将光子飞行时间作为光传输过程中的变量,将遮挡目标成像与光子计数相结合,以单光子阵列探测器作为接收器,重建隐藏物体,并通过仿真来验证了此方法。文中提供了基于单光子阵列探

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测器的隐藏目标瞬态成像的基本理论和框架,可以更好地理解隐藏目标瞬态成像的性质,并有助于未来设计在现实世界中的成像系统。
关键词: 隐藏目标; 瞬时成像; 单光子阵列探测器

0 Introduction

The view of human eyes is limited to the occlusion of the solid medium such as the wall or other obstacles. Similarly, traditional imaging technique and system also have this limitation. Imaging for hidden object is a technology which can "see" a scene out of sight, e.g. around a corner or hidden by some shelter, and realize the reconstruction of objects. This method could not only provide the information for object imaging but also make it possible to observe targets even far away from the targets. Imaging for hidden object has promising applications in many fields, e.g. battlefield surveillance, search, rescue, medical diagnosis and archaeological research.

Currently imaging technique for hidden object has been proved in a number of ways. By studying the characteristics of the reflectance surfaces of different materials and ignoring the possible scattering effects between the reflectance surface and the target, researchers used the laser to illuminate different surfaces such as window glass and building wall to capture the two-dimensional imaging of hidden object[1-3]. Considering the scattering effect of the laser in the imaging process, time of flight of photons, the distance information and intensity information in the multiple scattered light, the hidden target was reconstructed in three-dimensional space [4-6]. This approach was confirmed by femtosecond laser and streak camera[7-8]. Another non-line-of-sight experiment used microchip laser and gated intensified Charge-Coupled Device (iCCD) camera as the emitter and receiver[9-12]. For making the experiment more practical, the compact and inexpensive experimental equipments such as the time modulated source and Photonic Mixer Devices (PMDs) were adopted[13]. In addition to the above methods, a system consists of femtosecond laser, photon counting device and Single-Photon Avalanche Diode (SPAD) detector is designed to complete the three-dimensional reconstruction around a corner [14]. Based on theory of imaging through a small hole, researchers also finished three-dimensional reconstruction of occluded target by a nanosecond laser and a single-photon avalanche photodiode (APD) [15]. Except for imaging, people also work on tracking the hidden moving object in real time with laser and camera[16].

Compared with prior work on global light illumination, transient imaging is a novel imaging approach which can be applied widely in computer vision, computer graphics and scenario understanding[17]. The theory of transient light transport assumes that the speed of light is finite or certain value, which means the light takes different paths during the propagation of light in a scene and different paths take different time to traverse. The time where the photons arrive at places varies with different distances, and the intensity of the light. Fundamentally, except for the amount of irradiance, energy and number of photons, transient light transport also includes the information of time of flight of photons.

Raskar et al. presented a basic theoretical framework for analysing light transport[18] On the basis of this framework, Kirmani et al and Velten et al. finished reconstruction of hidden geometry[6,8], Naik et al.investigated the reflectance acquisition[19]. A technique called femto-photography was proposed by Velten et al. [20-21], which could capture and visualize the propagation of light through macroscopic scenes. Heide et al. [22] use the PMDs which are not only cheaper but also sacrifice the temporal resolution and the spatial resolution.

Single photon is not the continuous light and the energy is weak, so detecting this kind of photon signal needs the photodector that has the enough sensitivity to single photon such as SPAD. Using the photon counting technique to sample in temporal and spatial direction could obtain the numbers of scattered photons in different time, which could reconstruct the transient images of target.

Photon counting is a technique that can acquire the information of the number of scattered photons in different time, which corresponding to add the time information in light transport. In our method, we trigger a photon counter after detecting the photons by SPAD array for the transient reconstruction of non-line of sight.

In this paper, we will make a combination of imaging of hidden object and photon counting to achieve the transient reconstruction of occluded objects and propose a method called transient imaging of hidden object using single-photon array detector, we will introduce the theory and framework of this method and demonstrate it by simulation. We also make the discussion about how the parameters of the system effect the non-line-of-sight transient imaging.

1 Principle of transient imaging

In transient imaging, the framework is following.

We suppose that t_0 is the emitting time of the laser in Fig.1, τ is the total time of travelling photons for the light path from the laser to the detector with three reflections, and t is the sum of t_0 and τ. The illumination spot of the laser and detecting spot of the detector on the diffuse wall are S_j and P_k, respectively. $L(S_j,t)$ is the intensity of emitting light, $\rho(\cdot)$ is the diffuse albedo of the patch, w and o represent the patch on the diffuse wall and the object, respectively. And the geometry term $g(x,y)$ can be expressed as

$$g(x,y)=\frac{\cos\angle(y-x,n_x)\cdot\cos\angle(x-y,n_y)}{|y-x|^2} \quad (1)$$

where n_x and n_y are the normal vector of x and y.

Originating from the rendering equation[23], we can infer that the intensity of the light from S_j of the diffuse wall to the o of the hidden object at time t is

$$L(o,t)=L(S_j,t)\rho(w)g(S_j,o) \quad (2)$$

The intensity of the light reflected from o is

$$L(P_k,t)=L(S_j,t)\rho(w)g(S_j,o)\rho(o)g(o,P_k) \quad (3)$$

Making an integral on Eq. (3) to calculate the overall intensity from all the patches of the object,

$$L(\text{overall})=\int_0^t L(P_k,t)\rho(w)\int\delta(t_0+\tau(P_k)-t)\,g(o)v(o)\,\mathrm{d}o\,\mathrm{d}t_0 \quad (4)$$

$$g(o)=\frac{\cos\angle(o-S_j,n_{S_j})\cdot\cos\angle(o-P_k,n_{P_k})}{|o-S_j|^2\cdot|o-P_k|^2} \quad (5)$$

$$v(o)=\rho(o)\cdot\cos\angle(S_j-o,n_o)\cdot\cos\angle(P_k-o,n_o) \quad (6)$$

where $\tau(P_k)$ is the time of the laser$-S_j-o-P_k$ path.

In this paper, we use the idea of transient imaging into another implementation model, the details of the project are described in the following paragraphs.

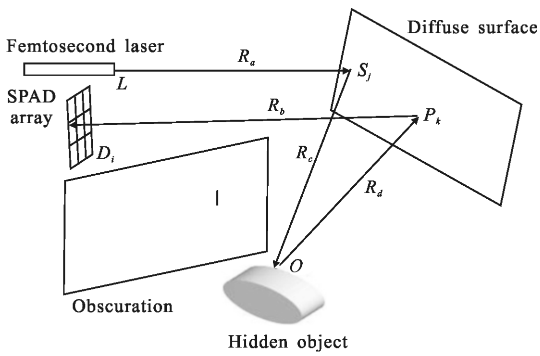

Fig.1 Principle of non-line-of-sight imaging

2 Principle of non-line-of-sight imaging

Figure 1 describes the general principle of non-line-of-sight transient imaging using single-photon array detector.

The whole scene consists of a femtosecond laser, single-photon array detector, a diffuse surface such as a building wall and an object which is hidden from the sight of the imaging system by the obscuration. The laser emits the short laser pulses to the point S_j locates at the diffuse surface, the laser light is scattered to a semispherical space because of the Lambertian character of diffuse surface. Several light are reflected directly to the detector and others illuminate the hidden scene toward the occluded object and go through the second reflection on the object. Then the partial photons of laser light are scattered to the point P_k still locates at the diffuse surface, after the third reflection on P_k, the photons travel back and are captured by the single-photon array detector. Apparently, the photons with three reflections spend more time due to the longer light path, so the time is also equivalent to the distance of light which can be used to locate the object and the numbers of detected photons can be used to reconstruct imaging of object. We use the femtosecond laser to make a scanning illumination and successively change the position of S_j, the laser spot on the diffuse wall.

The photons detected by each SPAD unit correspond to a small field on the diffuse wall.

3 Experimental setup in simulation

In this paper we use a laser as the emitter and an array of SPAD with different size as the detector in the simulation. We simulate that the laser generates 100 fs pulses with a repetition rate of 50 MHz and wavelength of 1 550 nm. We set a time-gated SPAD with 20 μm diameter active area, the area on the diffuse wall which one single SPAD is focusing on is 1 cm^2, and the location of the field of view of detector is fixed during the simulation.

The time-gated character can block the signals from first bounces and other walls so that we can receive the correct signal, in the simulation, we calculate the maximal and the minimal arrival time of correct photons roughly and get rid of the photons which arrive out of this time range to realize the time-gated character. And the ON and OFF transition times of SPAD is 120 ps, the difference of arrival time of detector between head, arms and legs of the mannequin is at least several hundred picoseconds so the SPAD could distinguish the photons from different parts of hidden target.

A Time Correlated Single Photon Counting (TCSPC) is also used to combine the propagation of light with the time of flight of photons for transient imaging of hidden object. The detection efficiency of TCSPC is 70%, the time bin is 1 ps and the time resolution is 25 ps, the max rate frequency is 20 MHz and the dark count rate is smaller than 25 cps. Each detector unit of SPAD array is connected with a TCSPC unit independently. After detecting the photons with SPAD array, the signal would trigger the TCSPC unit to produce a histogram of the photon counts. In an illumination period, the TCSPC could provide several different photon histograms with different time for different SPAD units. The X-axis and Y-axis individually represent the time of photons and the number of photons. Figure 2 shows an example of the histogram of the TCSPC.

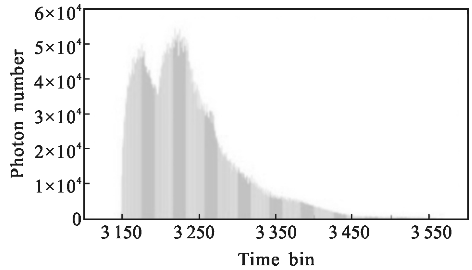

Fig.2 An example of the histogram of the TCSPC

Build the three-dimensional model of the scene and the system using MATLAB, as shown in Fig.3. There is a diffuse wall in the scene. The laser and SPAD are placed toward the diffuse wall. The area where the SPAD array is focus on the diffuse

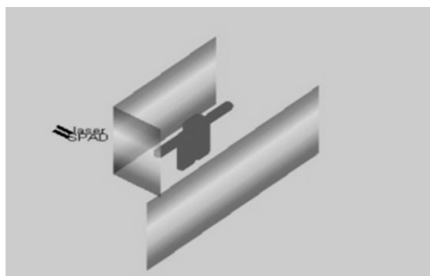

Fig.3 Three-dimensional model of the scene and the system in simulation

wall is approximately 1 m×1 m. The hidden object occluded by the wall is set to a mannequin which is approximately 60 cm×70 cm and is placed about 50 cm from the diffuse wall.

The sizes of the SPAD array detectors we used in simulation are 4×4 pixel, 8×8 pixel, 16×16 pixel, and 32×32 pixel, respectively. Figure 4 shows the time-correlated histograms of single photon produced by the TCSPC connected with different SPAD array.

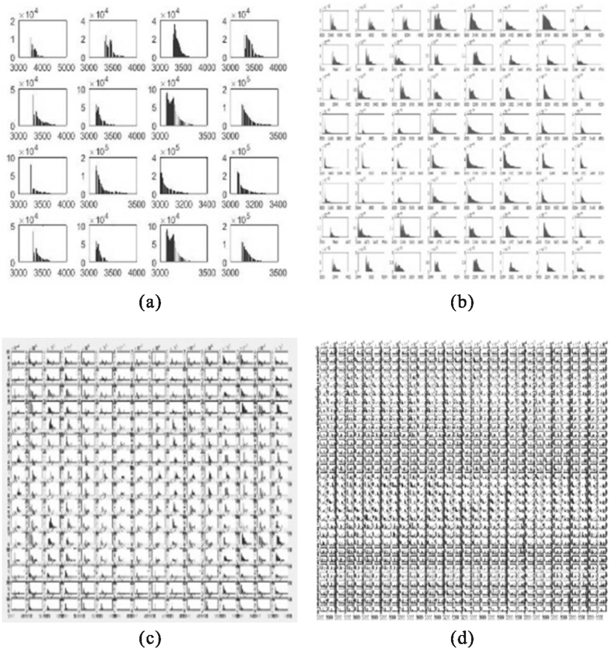

Fig.4 Histograms produced by the TCSPC connected with SPAD array in 4×4, 8×8, 16×16 and 32×32 pixel

4 Reconstruction method

With the variable histograms received by the experimental devices, we use the inverse algorithm for transient imaging of hidden object. In Fig.1, the laser is L, every detector unit of SPAD array is $D_i(i\geqslant 0)$. On the diffuse wall, the spots of laser scanning are S_j and the spots corresponding to every detector unit of SPAD array are P_k. Setting the appropriate coordinate system and locating the coordinate of points above in space so that we can make the following calculation. Using the coordinates of L and S_j to calculate the distance R_a between L and S_j, similarly, we can obtain the the distance R_b between D_i and P_k. Using R_c and R_d to indicate the distance between S_j, P_k and hidden object separately.

S_j and P_k constitute the point pair $<S_j,P_k>$. Different point pairs would trigger every detector unit of SPAD array in every scanning of laser and produce the corresponding histogram of the photon counts with TCSPC in an illumination period.

According to the time information in the histogram, we can interpret the overall round trip path of light R_{all}:

$$R_{all}=c\times t=R_a+R_b+R_c+R_d \tag{7}$$

where c is the speed of light and t is the time of flight of photons. R_a and R_b are pre-measured so R_c+R_d can be calculated. Therefore, an ellipsoid is defined by foci S_j and P_k with the focal length of R_c+R_d. Different moments can form different ellipsoids which is assigned to the value of corresponding numbers of photons. All ellipsoids overlap in three-dimensional space and accumulate at the intersections to produce a confidence map $C(x,y,z)$ that includes the probability of the light being reflected by the object in the occluded space.

For more precise reconstruction, we compute the confidence map $C(x,y,z)$ with the Gaussian filtering for smoothing and then compute the Gaussian result $G_\sigma(x,y,z)*C(x,y,z)$ with the Laplacian filtering for sharpening and the Laplacian result can be indicated as $C_f(x,y,z)=\nabla^2[G_\sigma(x,y,z)*C(x,y,z)]$.

The confidence values of the final map $C_f(x,y,z)$ represent the possibility of the points mapping to the hidden object, we use a threshold to remove the points with less possibility and obtain the final images of object.

5 Simulation and results

In Fig.5, the imaging results of the mannequin are depicted. Figure 5 (a)-(d) are the original imaging produced respectively by 4×4, 8×8, 16×16 and 32×32-pixel SPAD array and Fig.5 (e)-(h) are the corresponding filtered images. With the change of the size of SPAD array, the quality of image of hidden object is variational linearly. The larger the size of SPAD array is, the better the quality of corresponding reconstruction is. However, the larger size always accompanies with more data, which will lead to the longer processing time of image. Compared with previous results, this simulation uses multiple SPADs as detectors so that we could get more pairs of laser and camera which is mentioned in Part 4, during the reconstruction, more pairs could provide more information of hidden target which could improve the imaging quality and resolution.

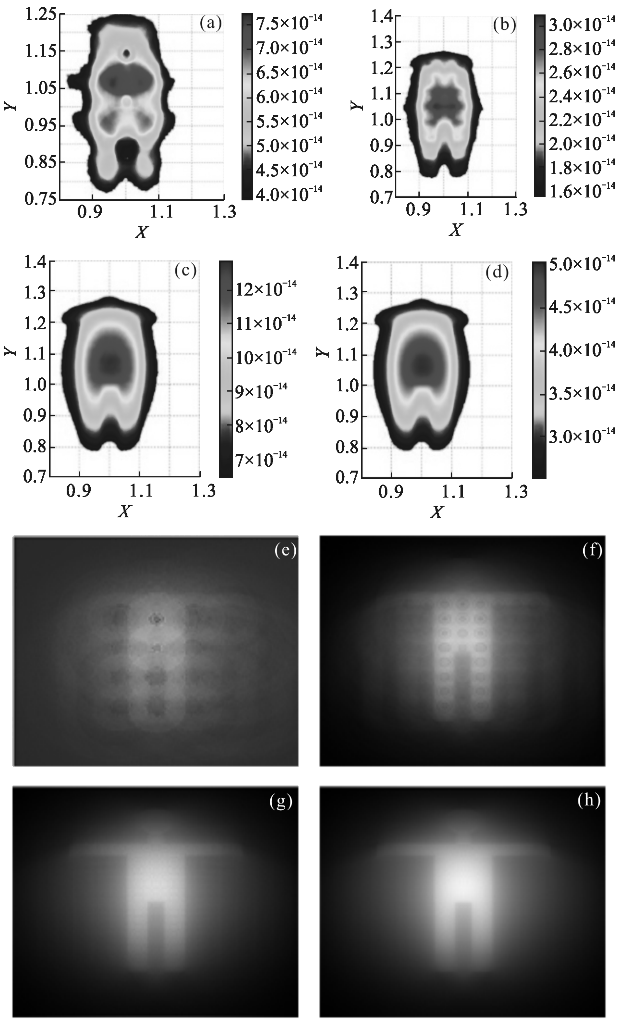

Fig.5 Imaging results of the mannequin (a)-(d) are the original images which are produced respectively and (e)-(h) are the filtered images

6 Discussion and conclusion

This paper introduces a method of transient imaging of hidden object and uses the MATLAB for the simulation of this method, which demonstrates that it is possible to make an application with the laser, the SPAD array and the TCSPC for transient imaging of occluded target. In the simulation, we use the different sizes of the SPAD array to detect the echo photons from the occluded mannequin, then we use the histograms with variable numbers and back-projection algorithm to reconstruct the images of mannequin. The simulation results show that using multiple SPADs can improve the imaging quality and the SPAD array with larger size can provide the higher resolution of images of objects, certainly accompanied by the more data and longer processing time for imaging. As discussed, this method is still needed to be improved in many aspects. For instance, this method only provides a two-dimensional image. A three-dimension reconstruction is needed in the future. And the object in this paper is 60 cm×70 cm which is small, researchers should make the improvements on this method using a bigger object. Furthermore, the algorithm also needs to be developed for the faster imaging, higher resolution and real-time display in non-line-of sight imaging.

This paper explains the theory and the details about how to use the SPAD array to realize the non-line-of-sight transient imaging, which make several bases for the application of this approach in practical and real life. There are huge challenges in this way but also provides significant opportunities for interesting fields.

References:

[1] Ove Steinvall, Magnus Elmqvist, Håkan Larsson. See around the corner using active imaging [C]//SPIE, 2011, 8186(1): 523-532.

[2] Xu Kaida, Jin Weiqi, Zhao Shenyou, et al. Image contrast model of non-line-of-sight imaging based on laser range-gated imaging [J]. ***Opt Eng***, 2014, 53(6): 061610.

[3] Xu Kaida, Jin Weiqi, Liu Jufu, et al. Analysis of non-line-of-sight imaging characteristics based on laser range-gated imaging [J]. ***Acta Armamentarii***, 2014, 35(12): 2006-2009.

(in Chinese)

[4] Kirmani Ahmed, Hutchison Tyler, Davis James, et al. Looking around the corner using transient imaging [C]// International Conference on Computer Vision, 2013: 159-166.

[5] Kirmani Ahmed. Femtosecond transient imaging [D]. Cambridge: Massachusetts Institute of Technology, 2010.

[6] Kirmani Ahmed, Hutchison Tyler, Davis James, et al. Looking around the corner using ultrafast transient imaging [J]. ***International Journal of Computer Vision***, 2011, 95(1): 13-28.

[7] Gupta Otkrist, Willwacher Thomas, Velten Andreas, et al. Reconstruction of hidden 3D shapes using diffuse reflections [J]. ***Optics Express***, 2012, 20(17): 19096-19108.

[8] Gupta Otkrist, Willwacher Thomas, Velten Andreas, et al. Recovering three-dimensional shape around a corner using ultrafast time-of-flight imaging [J]. ***Nature Communications***, 2012, 3: 745.

[9] Laurenzis Martin, Velten Andreas. Non-line-of-sight laser gated viewing of scattered photons [J]. ***Optical Engineering***, 2014, 53(2): 023102.

[10] Laurenzis Martin, Christnacher Frank, Klein Jonathan, et al. Study of single photon counting for non-line-of-sight vision [C]//Advanced Photon Counting Techniques IX. International Society for Optics and Photonics. 2015, 9492: 94920K.

[11] Laurenzis Martin, Velten Andreas. Feature selection and back-projection algorithms for nonline-of-sight laser-gated viewing [J]. ***Journal of Electronic Imaging***, 2014. 23(6): 063003.

[12] Laurenzis Martin, Velten Andreas. Investigation of frame-to-frame back projection and feature selection algorithms for non-line-of-sight laser gated viewing [C]//Proceedings of SPIE, 2014, 9250: 92500J.

[13] Heide Felix, Xiao Lei, Heidrich Wolfgang, et al. Diffuse mirrors: 3D reconstruction from diffuse indirect illumination using inexpensive time-of-flight sensors [C]//Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition, 2014: 3222-3229.

[14] Buttafava Mauro, Zeman Jessica, Tosi Alberto, et al. Non-line-of-sight imaging using a time-gated single photon avalanche diode [J]. ***Optics Express***, 2015, 23(16): 20997-21011.

[15] Jin Chenfei, Song Zitong, Zhang Siqi, et al. Recovering three-dimensional shape through a small hole using three laser scatterings [J]. ***Optics Letters***. 2015, 40(1): 52-55.

[16] Genevieve Gariepy, Francesco Tonolint, Robert Henderson, et al. Detection and tracking of moving objects hidden from view[J]. ***Nature Photonics***, 2016, 10(1): 23-26.

[17] Jarabo Adrian, Masia Belen, Marco Julio. Recent advances in transient imaging: A computer graphics and vision perspective [J]. ***Visual Computer***, 2017, 1(1): 65-79.

[18] Raskar, R. & Davis, J. 5d time-light transport matrix: What can we reason about scen e properties [R]. MIT Technical Report, 2008. URL: http://hdl.handle.net/1721.1/67888.

[19] Naik Nikhil, Zhao Shuang, Velten Andreas, et al. Single view reflectance capture using multiplexed scattering and time-of-flight imaging [J]. ***ACM Transactions on Graphics***, 2011, 30(6): 171.

[20] Velten Andreas, Wu Di, Jarabo Adrian, et al. Relativistic ultrafast rendering using time-of-flight imaging [C]//ACM SIGGRAPH 2012 Talks, 2012: 41.

[21] Velten Andreas, Wu Di, Jarabo Adrian, et al. Femto-photography: capturing and visualizing the propagation of light [J]. ***ACM Transactions on Graphics***, 2013, 32(4): 44.

[22] Heide Felix, Hullin Matthias B, Gregson James, et al. Low-budget transient imaging using photonic mixer devices [J]. ***ACM Transactions on Graphics***, 2013, 32(4): 45.

[23] Kajiya James T. The rendering equation [C]//ACM Siggraph Computer Graphics. ACM, 1986, 20(4): 143-150.