Soft bilateral filtering shadows using multiple image-based algorithms

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Abstract This study introduces Soft Bilateral Filtering Shadows method of dynamic scenes, which uses multi-matrices of the light sample points due to lack realism in soft shadows generation in real time. While geometry-based shadow algorithm requires one pass per polygon for rendering shadow that requires time-consuming, the adopted shadow map algo-rithm needs a single rendering pass for each sample point of the light source to generate shadow at low cost. This method renders a complex scenes and accurately eliminating the inherent deficiencies in shadow maps. In order to compute shadow maps, view matrices were used for each sample point of the extended light source. Then penumbra region was used for interpolation based on bilateral filtering to create the soft shadows. They depend on multiple shadow maps which provide antialiasing shadow maps. The method uses fragment shader for rendering multiple shadow maps with penumbra and umbra regions. The main contribution of this article is introducing interpolation bilaterally of image-based shadows. This method makes the most effect of the computation significantly appear at the edges of the penumbra region. Furthermore, the filtering allows to obtain on the soft shadow marvelously at the lowest number possible of the light sample points. The generated soft shadows have good perfor-mance and high quality therefore, they are suitable for interactive applications.

Keyword Soft shadows · Antialiasing shadow maps · Bilateral filtering · Multiple image-based shadows

1 Introduction

Shadow not only is a significant issue in realism, but it also illustrates visual cues of the relationships between the objects in a particular scene Kolivand and Sunar [14]. In order to generate hard shadows, a point light or directional light sources is used. Generally, while soft shadows look realistic and eye-pleasing, hard shadows do not always occur in nature and look artificial. Rendering high equality soft shadows are prohibitively expensive and requires time-consuming computation.

A lot of efforts have been undertaken to solve the problems related to shadows, such as aliasing problem. One could use shadow volumes Crow [7] to avoid aliasing, but this may cause fill-rate problems which develops difficulties in the process of filtering. There are methods [17, 19, 24] for better adaptation of shadow maps and use of the available resolution. These methods speed up the rendering process interactively and could be applied in real time. But the efficiency of many shadow map methods is reduced significantly, when it comes to calculating penumbra. The other shortcoming of these methods is the insignificance of image-based shadows. This may occur when blockers have high depth range.

Both the original shadow map and shadow volume algorithms do shadow computations based on some imaginary point light. In reality, a light source always has some volume Kolivand and Sunar [13]. Therefore, at some points in the image, only a fraction of the light is occluded by a triangle, some points are completely occluded, and some points are not occluded at all. Completely shadowed area is called 'the umbra' Fig. 1a and the partially shadowed area is 'the penumbra'. Figure 1b shows these areas.

This study aims at producing a high quality of the soft shadows by proposing Soft Bilateral Filtering Shadows (SBFS). SBFS consists of two important aspects. Firstly, this method is based on sampling of the points within the light texture to determine multi-matrices of view light. Then, the multiple shadow maps are generated based on the frustum for each point within light source. Secondly, the scene is rendered from the camera in order to interpolate bilaterally of the multiple image-based shadows. The fragment shader is used to render soft shadow of the triangles for each object in scene.

This methods has two main benefits. First, the bilateral filter works on smoothing every part of the image except discontinuous boundaries. This means most effects will be in the

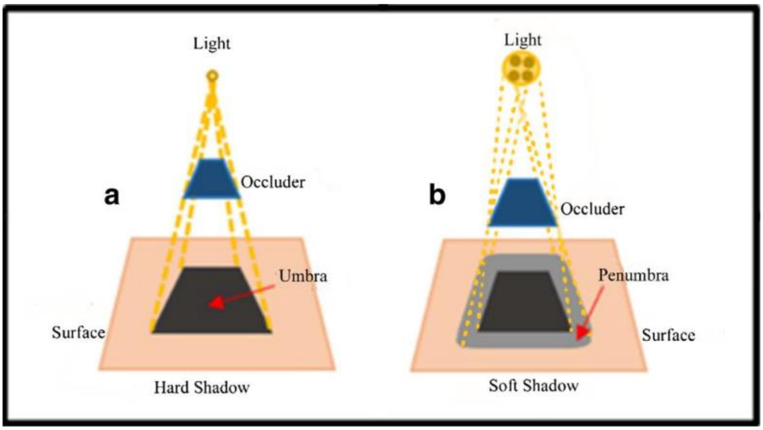


Fig. 1 (a) hard shadow shows the umbra, and (b) soft shadow explains appearance of the penumbra

penumbra region, which creates multi-matrices of the sample points. Secondly, the method significantly reduces the number of sample points of light and makes use of the effective influence of bilateral filtering. This increases the realistic qualities of shadows especially in penumbra region. Through this process, aliasing for shadow map is eliminated and realistic soft shadows are produced. Thus, this method works efficiently and accurately to render soft shadow in real time.

The immediate next section recapitulates related works. Section 3, explores the methodology for rendering the final scene. The results and related discussions are presented in section 4. Section 5 presents the conclusions and puts forward suggestions for future works.

2 Related work

Introduced by Williams [23], shadow maps is a common technique for rendering shadows. Evidence has shown that this method is efficient in being implemented on GPU, but may suffer from aliasing. Eisemann and Décoret [9] proposed visibility swamping on GPU and applications which handles soft shadows interactively. Nevertheless, this is effective only for planar receivers and area light sources. Aila and Laine [1] has proposed several methods for completely inti-alias shadow maps that suggest a software method anti-aliasing shadow maps.

There are some complete alias-free shadow maps methods. Johnson et al. [12] suggested a hardware modification for rendering alias-free shadow maps, which is still not available. Arvo [2] suggested a GPU-based algorithm in alias-free shadow maps using graphics hardware. This method uses depth peeling, which is rendering the scene once for each depth layer. This method can be very slow for scenes with high depth complexity.

The percentage closer filtering technique was proposed to render the shadow map Reeves [20]. It was able to achieve several such computations in a small mask. This technique could not identify the changes in sample range in shadow maps. This was because the size of filtering mask is constant, which leads to a constant size of penumbra. Fernando [10] presented a technique to enhance the above technique. His technique could calculate the changes in the sample range in shadow mapping through the filtering process. Nonetheless, this method could not produce realistic results. Lili et al. [18] proposed a method for rendering soft shadow. Their method detects the edge shape of frustum that the light launched in 3D space and stretches the edge shape outwards to get penumbra map in various intensities. Then a shadow map and a penumbra map that are rendered by the traditional shadow map are applied for rendering soft shadow Wyman and Hansen [25]. This method only deals with the outer penumbra boundary and the size of umbra remains constant. Hence, it disap-pears, if the umbra drastically shrinks. Chan and Durand [6] presented a technique for rendering soft shadow by applying smoothie edge. It is an extension of penumbra map technique by storing the depth of the occulders, and the depths of frustums and planes. Wang et al.'s [22] work on determining the potential blocking triangles uses bitmask process and rectified shadow map to render soft shadow.

Arvo et al. [3], in his paper, suggested a shadow map flood-fill to approximately render soft shadow. This method extracts the edge pixel of the shadow in image-space. Depending on the size of penumbra region, it executes many passes of penumbra rendering to calculate soft shadows. This algorithm does not always perform well, because of the increase in the number of rendering pass. In addition, this algorithm is time-consuming due to multi-rendering passes based on the size of the part semi-occluded. Cai et al. [5] proposed multi-layered shadow fins to render soft shadow. It constructs the outer and inner semitransparent fins on models to simulate the penumbra region outside and inside hard shadow respectively. This algorithm is not efficient, because of the increased layers of the semitransparent. Willem searched the silhouette of blockers seen from the position of light in image space De Boer [8]. After that, the silhouette is launched into skirts. When the final rendering is running, the semi-occluded parts are determined by applying the depth information of the skirts and random sampling of the shadow mapping. This method runs multiple rendering passes. The number of the passes is based on the size of the part semi-occluded. Thus, when there are big part semi occluded, this method may not be able to provide convenient results.

Atty et al. [4] and Guennebaud et al. [11] were the first who used the term ‘soft shadow mapping’. They partitioned the scene and made each sample as a blocker, and then applied the less complex scene to calculate the radiance. Projection overlap and light leak are the shortcomings of this method. Lawlor [16] presented a technique using linear interpolation between the outer penumbra and inner penumbra without silhouette detection. This technique cannot maintain the shapes of edges; therefore, it does not produce any improvement other than smoothing the shadowing between texels.

The SBFS method is implemented for generating soft shadows based on multiple shadow maps and interpolation using bilateral filter. Since, all light sources affect a scene significantly to appear varying regions in intensity, so this method reflects these effects at more realistic and at lowest cost.

3 Method

SBFS method is inspired from the appearance of the penumbra region at shadows boundaries. In such a case, smooth color gradations are seen between this boundaries with edge-preserving. SBFS uses this quality to simulate soft shadows using some view matrices of light to represent frustums of the sample points of the light. Then, the projection is computed for each frustum to determine the lit and unlit regions onto a surface based on occluder existence in 3D scenes. The unlit region is divided into two parts, the completely occluded (umbra) regions and the partially occluded (penumbra) areas. This study is particularly interested in penumbra. Con-sequently, the penumbra region is processed, using interpolate bilaterally of the pixels along and between edges. This is to provide a penumbra region softly closer to realism.

The SBFS method assumes that a light source is a set of sample points that creates multi matrices view of the light source, which can represent the shadow maps. The advantages of this method is arising an evident soft shadow without developing overlaps between the silhouettes within penumbra region. It also smooth the shadows between edges using bilateral filter. Moreover, this allows any removals from the aliasing at the penumbra region with preserving edges. Since, a penumbra region is a natural phenomenon, so effects can be observed with real soft shadow.

In short, our method depends on determining a sample points within light texture. Thus, the multiple shadow maps are generated based on these points, using camera, at light locations for each sample point. The multiple shadow maps are considered as image-based shadows can be used in filtering operation. The key point in this method is using filtering to make the penumbra region correctly visible. This process is done by interpolated bilaterally to generate better soft shadows. The next sections describe this procedure.

3.1 Compute multiple shadow maps

The scene is rendered from the light source by positioning the camera at the location of the light source. Then, the depth map is rendered based on the light source for each pixel into a shadow map, which represents each depth as distinct color. This is because, when the whole scene is being rendered, each texel in the image-based texture contains the depth of the closest pixel to the light source. Moreover, the scene is rendered from the point of view of the camera by determining the position of the camera in the viewer position. The pixels world coordinates for each pixel are transformed and projected onto the shadow map. Thus, the pixel in the shadow is analyzed to see whether its depth is larger than the one in the map. Figure 2a shows single shadow map of the single point light where the scene is rendered from the light source and also of the camera. Thus, we can notice the appearance of the umbra region which considers hard shadow as it is shown in the red rectangle in Fig. 2a. In contrast, when multiple shadow maps are computed based on the sample points of the light, the scene is rendered from the light source and the camera, which is shown in Fig. 2b. This process is repeated for each sample point to provide the umbra region in addition to the penumbra region. These regions consist of boundaries that are resulted from cut offs at cones for the light sample points. They also have different colors according to the different positions of the sample points within light source. The red rectangle in Fig. 2b shows penumbra region, which focuses attention to computation and the processing procedure in this method.

In real world, shadows mostly arise to have certain rates of softening and smoothing across their edges, so arises are not exactly hard. This method smoothes and softens hard edges of shadows effectively, so that it arises to have smoother edges.

The edges appear within a penumbra region onto a surface in 3D scene, when view-matrices of the light sample points are touching occulder edges. Figure 3 shows multi-matrices of the light sample points (green, red, and blue dots) where their frustums touch the occluder edges to create boundaries of the penumbra region (green, red, and blue arrows). Obviously, the projections position of the frustums on a surface are slightly displaced according to vary positions of light sample points. In addition to abrupt changes in color that may occur within the penumbra region. The key point in this method is choosing the lowest number of the light sample points to create a penumbra region. Although, this process may cause artifact and aliasing problems, bilateral filtering can efficiently solve such problems. This method of problem solving is based on interpolated bilaterally along and between edges.

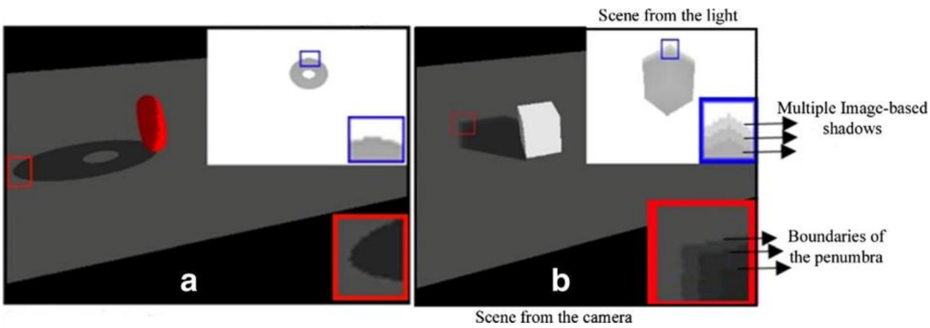
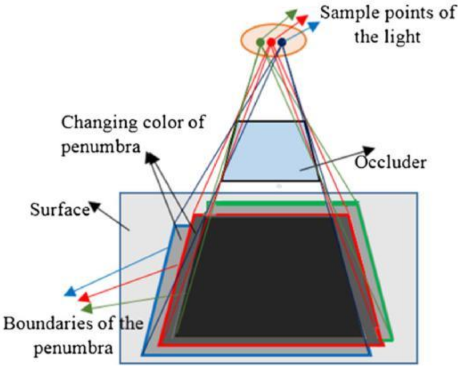


Fig. 2 (a) single shadow map with umbra, (b) the multiple shadow maps using multi-frustum view of light sample points. The scene from the light source and from the camera where the red rectangle indicates boundaries of the penumbra

Fig. 3 Boundaries of the multiple shadow maps using multi-frustum view of sample point of the light in color blue, red, and green



3.2 Bilateral interpolation

This method uses non-linear bilateral filtering, which is replaced the intensity value for each pixel in an image by weighted average of intensity values of neighbor pixels. Moreover, bilateral filtering which has an important characteristic takes the difference of intensities into consideration to preserve edges. Basically, in bilateral filtering two pixels can be close to each other, whether they occupy nearby spatial location or they have nearby values. In order to soften an image Gaussian filter is used, where data processing being in its domain. Gaussian filter is used to do data processing within its range in order to edge-preserving is computed as:

$$g(p) = \frac{1}{W} \sum_{p_i \in M} f(p_i) G_{hr}(|f(p_i) - f(p)|) G_{hd}(|p_i - p|) \quad (1)$$

Where W is a normalization as:

$$W = \sum_{p_i \in M} G_{hr}((|f(p_i) - f(p)|)) G_{hd}(|p_i - p|) \quad (2)$$

Parameters h_r and h_d are measures of the amount of the filtering for image g. G_{hr} is the range kernel for smoothing the differences in intensities (range filtering). This step would reduce the effects of the distant pixels. The domain kernel for smoothing the differences in coordinates is G_{hd} (domain filtering). This step reduces the influence of pixels p with an intensity value, which is different from g(p). In this step, the domain refers to the location of pixels and the range qualifies the amounts that refer to pixel values. The filtered image g(p) deals with the effects of the bilateral filter on the multiple image-based shadow. While f is the original input image to be filtered, p are the coordinates of the current pixel to be filtered, and M is the mask, centered in p. The weight W is assigned using the spatial closeness and the intensity difference Tomasi and Manduchi [21]. In this method the weight is based on Gaussian distribution is computed as:

$$G_h(p) = e^{-hp_2} \quad (3)$$

In order to obtain comparable results, h_d must be adjusted accordingly. Similarly, the differences intensities h_r in the f(p) range is set to achieve the desired amount of the combination of pixel values. That means both h_r and h_d are controlling the bilateral filter. For instance, when h_r increases the bilateral filter, it becomes more similar to Gaussian blur.

This is because the range Gaussian is flatter. While the domain parameter is increased h_d smooth's larger.

The multiplied weights of the bilateral filtering are important features. This is because when none of the weights is close to zero, no smoothing occurs. In addition, the bilateral filter divides the input image into a large-scale and small-scale component. The large-scale com-ponent is a smoothed the input in which the main edges are preserved. The small-scale component is the residual filter. This component can be interpolated as texture or noise. This method uses the bilateral filter, which efficiently smoothes an image and preserves the edges.

3.3 Penumbra map

As the main step, the SBFS method generates soft shadows on the screen space by using the pixels of the image-based shadows within the penumbra region. Since each pixel in the depth map of the light source is corresponding a pixel in the depth map of the camera, the interpolate bilaterally can be achieved within the image-based shadows. The bilateral filter influences the image, especially along and between the edges of the penumbra region.

Figure 4 illustrates the interpolated bilaterally process. In this figure, the yellow dashed lines denote to measure the domain distances along and between the edges of the penumbra region. The orange dots mark the photometric range of different intensities of the pixel values. The idea is to replace each pixel by a weighted average of pixels that are spatially close to one another. Each spatial region is weighted by a domain component that penalizes the distant pixels and the range component that penalizes with a different intensity. The bilateral filter combines a Gaussian blur with the function of edges that are not blurred. This is to ensure that only the nearby pixels are contributing in the image that is being filtered.

The SBFS method uses Gaussian distribution, where the spatial and intensity functions are multiplied to produce the Gaussian weighting for each output image pixel. Consequently, the bilateral filter is based on the domain of the pixels as well as the range differences such as depth distance and color intensity. Although, this method aims at cutting down noise and smoothing images, the conservative on edges, which is an important feature, develops more realism in the shadows.

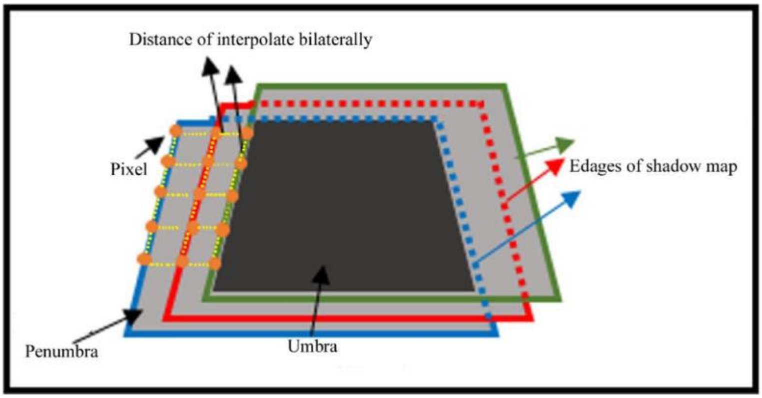


Fig. 4 Interpolate the color for pixels on the screen using a bilateral filter of the edges of penumbra region, yellow dashed lines indicate the distances

The edges from the multiple image-based shadows are nearby and neighbor one another, which allows the bilateral filtering to affect the penumbra region. The pixels along and between the edges of the image-based are dealt with to provide soft shadows. The outmost edge represents the outer boundary of the soft shadow and inmost edge represents the inner boundary of the soft shadow. The region between these boundaries is smoothed with edges-preserving, which increases the realism of the rendered scenes.

Figure 5 illustrates the framework to manipulate the penumbra region by combining the weights in a 3D scene. The red rectangle in Fig. 5a represents the original input image of the multiple image-based shadow. Figure 5b and c represent the domain and range filtering respectively, where domain filtering produce blurred image and range filter produce sharp image. Figure 5d yields multiplication of domain and range weights. Here the regions are smoothed with sharp edges. Since, the normalization term W is close to one, the input image is multiplied by step (d) to obtain the output image of the bilateral filtering shown in Fig. 5e. The output image is better and crispier compared to the input image.

The number and positions of the light sample points lie beyond the appearance of the soft shadow. In other words, increasing the number of the light sample points sparsely improved the appearance of the soft shadows. Nonetheless, this process is prohibitively expensive. In order to solve this problem, interpolated bilaterally is used to gain the best results by determining fewer number of the light sample points regardless of their positions. In this case, the soft shadows are generated simply. The output has high quality and the process performs well based on a simple algorithm, which is introduced in the next section.

3.4 Algorithm

The SBFS method is based on the light sample points to construct view matrices. It computes multiple shadow maps of the light sample points. Multiple image-based shadows are used to create the penumbra regions on the boundaries of the shadows. The bilateral filtering is applied on images-based in order to preserve edges through a smoothing process. The effects of this

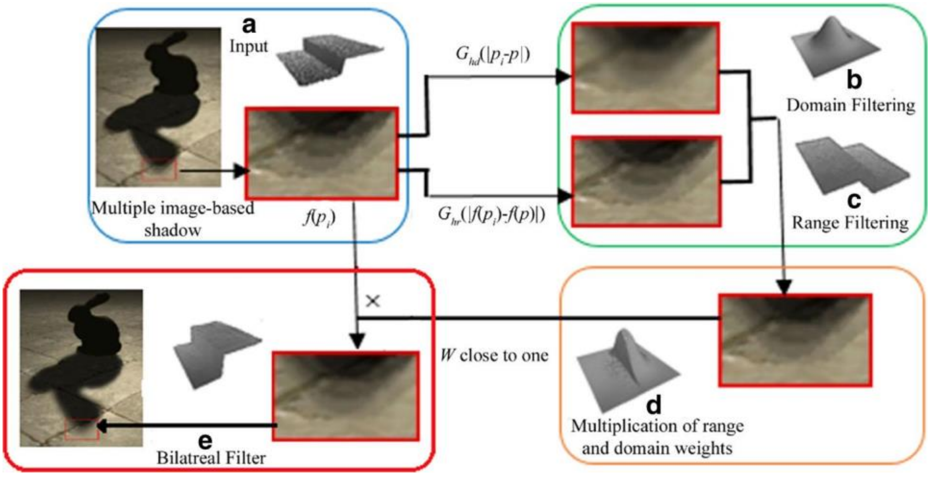


Fig. 5 (a) the input from multiple image-based shadow with artifacts, (b) the domain filtering of the input image and the smoothing effects, (c) the range filtering with sharp boundaries, (d) multiplication of range and domain weights, (e) the bilateral filter effects edge-preserving by smoothing the boundaries of the penumbra region process are obvious in the penumbra region, which also generates soft shadow. Overall, in order to render a 3D scene with triangles, area light source, image screen, and interest view with eye should be taken into consideration. The proposed algorithm renders soft shadow as following:

Step 1. Determining the sample points of the light and construct the cameras with these points
Step 2. Rendering multiple shadow maps for the sample points
Step 3. Applying interpolation between the pixels of the image-based shadows using bilateral filter
Step 4. Rendering the scene with soft shadows

Step 1 is responsible for calculating the light view matrices, which has three stages. First, the initial light view matrix is determined for one sample point by light perspective of the light position, reference, and up. Further, the initial light texture matrix is computed by multiplication of the bias matrix, the light projection matrix, and the initial light view matrix. Second, the projection light is computed based on the light view matrices, normalize, radius, and light position. Third, the above operation is repeated to calculate the light view matrices for other sample points as well as to compute the projection light for each point.

Step 2 the multiple shadow maps are created in light space by rendering the whole scene from each sample point of the light and storing values in the depth map texture using frame buffer object. Then, a whole scene from the camera is rendered to compute depth value in camera space. In fragment shader, the image light space and image camera space are compared. For each fragment, transform and project the fragments world coordinates onto a shadow map. If the fragment is not visible from the light source in the rendering process, it is located in shadow. Otherwise, it is in light. The main aim of this step is to get on image of the multiple shadow maps and use in the next step.

Step 3 the bilateral filter Tomasi and Manduchi [21] is used to manipulate the image from multiple shadow maps in the 3D scene. A combination of the range and domain filtering is needed to compute an average of the nearby and similar pixels values to be replaced with pixel values at p as in Eq. (1). Since a region between the inner and outer boundaries of the penumbra usually has gradient in the intensities, the bilateral filter effects appear significantly in the penumbra region. This would basically work as a domain filter with a sharp boundary and separate the two regions within the penumbra. It also works as a range filter at the regions between and along the edges within the penumbra. When the bilateral filter is placed on a pixel on one side of an edge of the penumbra, it can remove artifacts by smoothing an image with preserving all the crisp edges. Figure 6a illustrates the penumbra from rendering multiple image-based shadow. This figure introduces artifacts and aliasing at the edges of the cube. In Fig. 6a, bilateral filtering is applied to output image which results in the output image shown in Fig. 6b. Obviously in this image, the overall smoothing and the edges of the cube are preserved. The interpolation contributes along each edge yields an interpolated intensities, interpolated bilaterally between two edges, based on weights. Thus, a bilateral filter benefits from the smoothing of the penumbra region to maintain the shapes of the edges which gives a more realistic sense of the soft shadow.

Finally, SBFS method renders the triangles of the objects for whole scene with soft shadow. Texture is an important element in computing a multiple shadow maps in frame buffer object. The fragment shader is used to provide multiple image-based shadows for processing filtering.

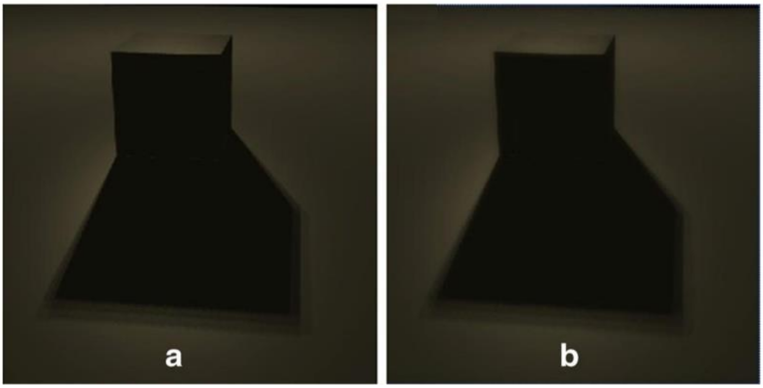


Fig. 6 the soft shadow, (a) the penumbra from rendering multiple image-based shadows with artifacts and aliasing, (b) a smooth penumbra region that maintains the shapes of the edges using bilateral filtering

The generated soft shadows eliminate the inherent shortcomings in the shadow maps to give high realistic and performance in real time.

4 Results and discussion

We implemented and measured the SBFS method on a 2.5 GHz Intel(R)HD Core(TM) i5-3210CPU using an ATI Radeon HD 7670 M Graphics 4000. SBFS was written in OpenGL 3.3 and the shader was compiled with Shader Model (3.0). All scenes were tested at 1024 × 1024 resolution for rendering models. Realistic soft shadows were directly proportional to the number of sample points of light, but was expensive. In other words, the greater number of sample points of light make the appearance of soft shadows more realistic. Nevertheless this would decrease the efficient of the performance. Conversely, the lower number of light sample points would increase the efficiency of rendering soft shadow, but at the expense of realism. In order to resolve these issues, the lower number of the sample points of the light was determined using bilateral filtering. Figure 7 shows two different situations for Elephant model using three sample light points which only needed three passes to render shadow maps, in addition to geometric spread $h_d = 3$ and photometric spread $h_r = 0.5$. Although the outcome shadow is eye-pleasing, overall the two images are slightly blur. This effect is significantly visible at the boundaries of the shadow onto the floor as shown in the Fig. 7 in the red rectangles. These are the effects of filtering process that was done using the bilateral filter. Through this process, the regions between edges got smoother using domain filtering. At the same time, the crisp edges were preserved using range filtering. On the other hand, the filtering process and the minimum number of sample points of light were combined to decrease the costs of rendering soft shadows.

The values of parameters geometric and photometric are controlled to maintain the effects of the filter on the resulting image. The experiment of testing the balance process and the effects of range filtering and domain filtering led to pleasing and attractive results.

In Fig. 8, five light sample points, which led to five passes for rendering shadow maps. Also, the geometric spread $h_d = 5$ and photometric spread $h_r = 0.5$, the complex scene was used

Fig. 7 The two different scenes of Elephant, the results of SBFS method using three light sample points and $h_d = 3$ and $h_r = 0.5$, the blur regions are increased between the boundaries of the shadow with edges-preserving

for Dragon and Buddha models that had folds and creases. In this case, the appearance of the two images are blurred more than the images in Fig. 7. This was due to the increase in geometric spread h_d, which also had a small computational cost due to the increased number of the light sample points; nonetheless, the edges remained crisp. The red rectangles in Fig. 8 mark the effects of the interpolated bilaterally within penumbra region in which soft shadows are more realistic and eye-pleasing.

Figure 9 illustrates the rendering result of Dragon and Buddha models using SBFS method and Bidirectional Penumbra Map Lili, W. et al.'s work [18]. In real life, extended light source would appear at penumbra regions. Figure 9 (left) represents result of Bidirectional Penumbra Map to generate soft shadows. Figure 9 (middle) represents result of our method to generate

Fig. 8 The two different scenes of Dragon and Buddha models, the results of SBFS method using five light sample points and $h_d = 5$ and $h_r = 0.5$, the blur regions are increased between the boundaries of the shadow and the edges were preserved

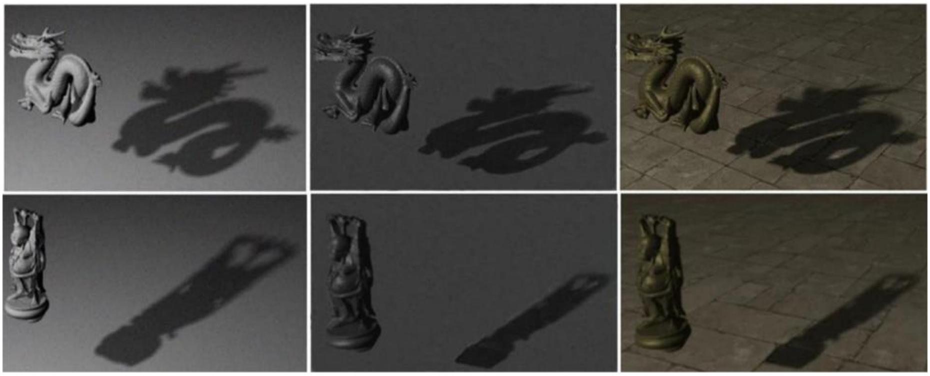


Fig. 9 Rendering the Dragon and Buddha models: Left is the results of Bidirectional Penumbra Map [18], Middle: our method with background similar to in (left). Right: our method texture background

soft shadows with background similar to Fig. 9 (left). Figure 9 (right) results of our method with background. Figure 9 (middle) (right) gives more natural plausible due to a penumbra region is smoother and crisper under the sample points of the light source from the Bidirectional Penumbra Map method. The reason behind these qualities is that the Bidirectional Penumbra Map method does not consider the appearance of the soft shadows; therefore, the intensity of the color is changing gradually from the inner to outer penumbra region, which results in overlapping and distort. This is while the SBFS method smoothly changes the color gradient of the soft shadows and perseveres edges from inner to outer penumbra region.

Figure 10 illustrates a side-by-side comparison of the Bunny and Elephant models. The left column shows the results of Bidirectional Penumbra Map. The middle column presents the results of the SBFS with background similar in left column to generate soft shadows. The right column is our method with texture background. Figure 10 shows effective our method in generating soft shadows.

Fig. 10 Rendering soft shadows of the Bunny and Elephant models: left: the result of the Bidirectional Penumbra Map [18], Middle: result of the SBFS with gray scale background, Right: result of the SBFS method in texture background

The SBFS method presents the proper appearance of soft shadows, where the penumbra spreads smoothly from inner to outer regions emerging by the sample points of light. The actual appearance of the soft shadows based-on subtle effects happen at the boundaries and the edge of the shadow.

Comparing the models in Figs. 9 and 10, the number of the triangles have a small effect on the rendering frame-rate of SBFS method. Specifically, the number of triangles is imperceptible in the outcomes. Nevertheless, the SBFS method is time consuming and compromises the quality. One of these problems is the values for geometric spread h_d and photometric spread h_r

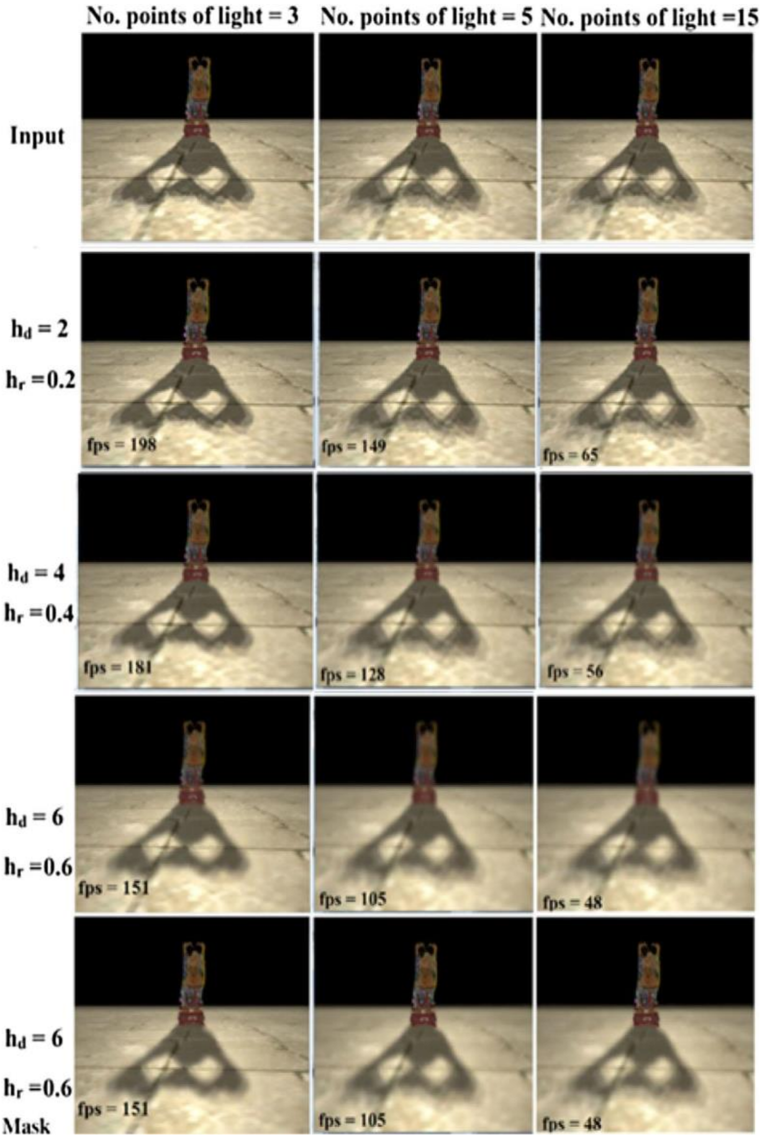


Fig. 11 Generating soft shadows using SBFS. Employing parameters h_d and h_r to control on effective and efficient of the soft shadows according to sample points of light source

of the bilateral filtering, and the other is for the number of the light sample points to determine a penumbra regions. Using large values for h_d and h_r result in improved soft shadow within the penumbra region, but at the same time the entire image gets blurred. Increasing the number of the light sample points develop more realistic soft shadow, through a time-consuming computation process. This is because of the increasing number passes for rendering shadow maps. In order to achieve the balance between quality and performance proper values for h_d and h_r with minimum number of the light sample points for interpolated bilaterally should be chosen.

Figure 11 shows SBFS results on various values of sample points of light source, with domain parameter h_d, range parameter h_r, and average frame rate. In general, in most of the cases, the fps is remarkable compare to previous works like [18, 22]. In the first case, when the number of sample points of light is 3, the results are good in the case of quality, while gives some blur when increasing h_d and h_r. The scenes with 5 sample points of light source gives also better quality, but appears blur and decrease frame rate. Further more the method is tested with 15 sample points of light source loosing considerable amount of frames per second and makes a scene more blur with increasing h_d and h_r but the shadows look completely soft. To overcome this issue, creating a simple mask is employed to avoid applying the filtering on the occluders. Thus, not only the results look acceptable but also the fps is remained.

The effectiveness of SBFS on rendering more complex scenes that containing overlapping shadows of multiple objects can be seen in Fig. 12. Note that the SBFS method correctly tackles the boundaries sharp of shadows as well as overlapping of multiple occluders.

In Fig. 12 (left) occluder 1, occluder 2, and the shadow receiver are located in different depths from light source to show what the result is in overlapping. There is no bleeding of light when SFBS is applied (Fig. 12 (right)), while light bleeding of LVSM method [15] is obvious in Fig. 12 (middle). This makes our method suitable to be used in complex scenes.

Figure 13 is plotted as a compares the performance of SBFS method and Bidirectional Penumbra Map method for rendering the above models of 1024 × 1024 resolution. While SBFS renders Elephant (39290 69451 tri.), Bunny (69451 tri.), Dragon (871414 tri.) and Buddha (10877716 tri.) models in 95 fps, 94 fps, 87 fps, and 84 fps respectively, the Bidirectional Penumbra Map method renders Elephant (39290 69451 tri.), Bunny (69451 tri.), Dragon (871414 tri.) and Buddha (10877716 tri.) models in 36 fps, 36 fps, 30 fps, and 28 fps respectively. SBFS shows the highly interactive rates, which are roughly about three times faster than Bidirectional Penumbra Map. This indicates that our method can render the complex scenes in real-time effectively.

Table 1 shows a comparison of performance between state-of-the-rate of shadows maps (Bidirectional Penumbra method [18] and GEARS method [22]) and SBFS when using a 1D filter in x direction followed by using another 1D filter in y direction. The filter 3 × 3 with 3, 5

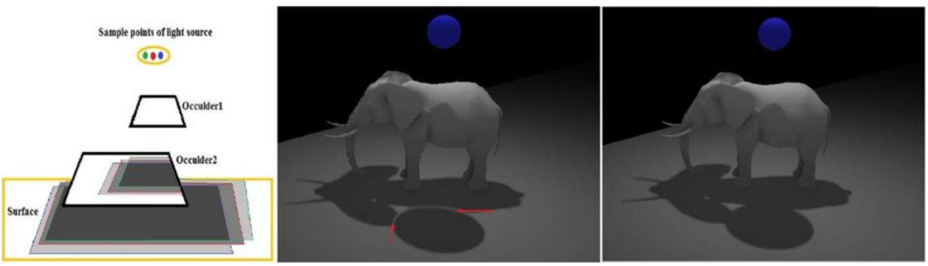


Fig. 12 Overlapping shadows of multiple objects, (left) The theory of our method, while middel of is the result of LVSM [15] with light bleeding, (right) the result of our method

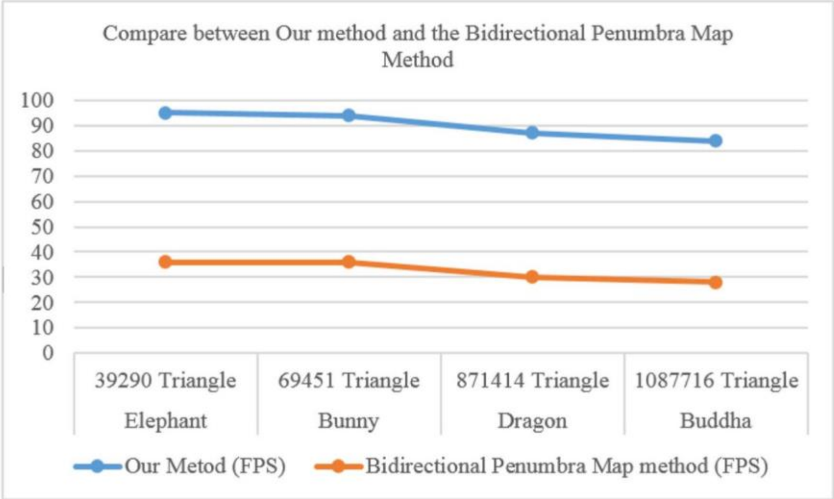


Fig. 13 Frame rate of SBFS method compare with the Bidirectional Penumbra Map Method [18]

and 15 sample points of light source on a shadow map of 256 × 256, 512 × 512, and 1024 × 1024 resolution are employed. The soft bilateral filtering shadows show a better performance compare to bidirectional penumbra method [18], GEARS method [22] and

Table 1 Performance comparison between SBFS, Bidirectional Penumbra Map [18], GEARS [22], and HSM (Hybrid Shadow Maps) [14] with two different models

Model	No. Tri	Resolution	Bidirectional Penumbra [18] (fps)	HSM [14] with 7 layers	GEARS [22] (fps)	SBFS	
						Sample points of light	(fps)
Bunny	69451	256^2	205	165	148	3	316
						5	223
						15	108
		512^2	122	112	72	3	237
						5	181
						15	72
		1024^2	36	87	34	3	126
						5	94
						15	57
Dragon	871414	256^2	112	102	87	3	281
						5	184
						15	96
		512^2	71	68	43	3	205
						5	144
						15	64
		1024^2	30	25	19	3	143
						5	89
						15	46

HSM (Hybrid Shadow Maps) [14]. Note that even the number of sample points of the light source is increased to 15 points, our method still maintain on high rate frame. According to the number of fps for both cases of 3 and 5 sample points of light, SBFS looks more effectiveness. Although the fps with 15 sample points of light is almost low, the high quality of soft shadows is remarkable.

5 Conclusions and the future work

We proposed a Soft Bilateral Filtering Shadows method based on the multi- matrices of the light sample points. The method adapts the shadow map technique, hence it ensures speed rendering of the whole scenes. As a result, it increases the frame-rate rendering even when scenes are complex. The contribution of SBFS method is rendering soft shadows using multiple shadow maps with interpolated bilaterally for scenes with huge number of triangles in real time. Multi-matrices of the view light avoids the aliasing in some environments when the size of the area of light source changes and causes wide umbra region. SBFS improves the visual cues of soft shadows for scenes by edge-preserving noise-reducing smoothing for images. The findings of this developed method are promising. Although this method reduces the rendering process, it still can be a feasible method. In order to improve the visual quality of shadows, the multiple image-based shadows method for the penumbra area can be used. We have proposed an accurate solution to the general soft shadow sampling problem. The our future work of SBFS method we will apply soft shadow to improve volumetric shadows by generating soft volumetric shadows while maintaining the edges in space to render more realistic images in real time.

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