CURVATURE-APPROXIMATED ESTIMATION OF REAL-TIME AMBIENT OCCLUSION

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Abstract: We present a novel technique for computing ambient occlusion (Akenine-Möller et al., 2008) on real-time graphics hardware. Our method approximates the occlusion for a local illumination model by introducing curvature-dependent function. Using our method, we are able to acquire occlusion at lower computational cost than conventional methods such as SSAO (Bavoil et al., 2008). Our method requires a multi-pass algorithm with the graphics processing unit (GPU). In the first pass curvature is acquired, and in the second pass the occlusion is computed from the curvature. In the calculating occlusion from the curvature, we approximate the geometric shape by a quadric surface function, and then obtain a curvature dependent function which is an approximation of geometric surface. This function depends only on local variables and we are able to calculate the ambient occlusion for the local illumination model. According to our results, both the computational and storage costs are sufficiently low for the technique to be applied to current graphics hardware supported computer games.

1 INTRODUCTION

Currently, a large number of methods such as soft shadows, subsurface scattering, high-dynamic range effects, are being applied in real-time graphics applications.

Ambient occlusion (Akenine-Möller et al., 2008) is one such method which is as a special case of the obscurances technique. This method was first presented by Zhukov et al. and popularized by Landis and Christensen in the movie industry. Ambient occlusion provides a distinctive edge or soft shadow, by taking account of the attenuation of ambient light due to the presence of nearby geometrical features. The method has been used in films as an alternative to large computational global illumination methods, because, it can imitate indirect lighting effects such as global illumination at minimum computational cost.

The ambient occlusion A at a point $\vec{P}$ with surface normal $\vec{n}$ is given by

$$A(\vec{P},\vec{n}) = \frac{1}{\pi}\int_{\Omega_+}(V(\vec{\omega},\vec{P})\lfloor\vec{\omega}\cdot\vec{n}\rfloor)d\omega \qquad (1)$$

Where $\vec{\omega}$ represents random directions from $\vec{P}$ on the surface of the unit hemisphere Ω_+. $V(\vec{\omega},\vec{P})$ is the visibility function which has the value 0 when no geometrical feature is visible in the direction $\vec{\omega}$ from $\vec{P}$, and the value 1 otherwise.

In the past the ambient light was given by a constant value in many cases. Multiplying the general ambient term (Phong, 1975) with (1-$A(\vec{P},\vec{n})$) generates a much better looking result than the constant ambient term only. The ambient occlusion solution bears comparison with the full global illumination solution, because ambient occlusion is able to approximate the ambient term attained by analyzing the global behavior of light.

For this reason, ambient occlusion is also now gaining interest in the game industry. Several approaches have been applied in 3D games, baking ambient occlusion to create texture, ambient occlusion fields (Kontkanen and Laine, 2005), screen space ambient occlusion (Bavoil et al., 2008) and the like.

However, those approaches are based on various direction sampling and the computational cost to implement them on computer video games is high. We are able to reduce the computational cost more than with current ambient occlusion techniques, by introducing an algorithm which computes the occlusion from a curvature dependent function.

The basic idea is as follows. We approximate a geometrical shape at a point $\vec{P}$ by a curvature dependent function $f(\vec{P})$ and we employ the maximum and minimum principal curvatures as this function's vari-

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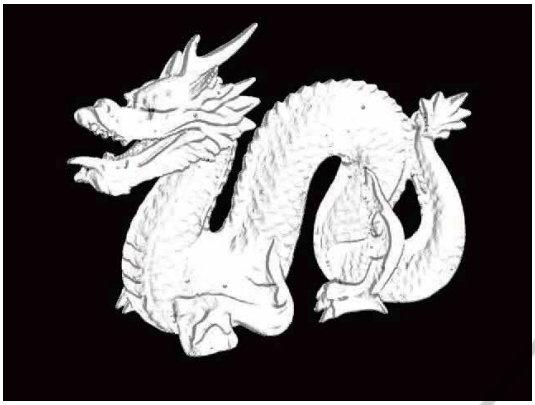


Figure 1: Our ambient occlusion sample applied to the Stanford dragon model.

ables. Then comparing $f(\vec{P})$ with Ω_+, we detect an occluded direction from $f(\vec{P})$ at $\vec{P}$. In the next section we discuss the previous work. The concept of the curvature dependent ambient occlusion is explained in Section 3, the curvature estimation in Section 4 and the implementation in Section 5.

2 PREVIOUS WORK

Ambient occlusion was originally regarded as a simplified case of the obscurances illumination model (Zhukov et al., 1998), in which the visibility function contains distance information of the occlusive. In this method, the obscurance W is given as follows.

$$W(\vec{P},\vec{n}) := \frac{1}{\pi}\int_{\Omega_+} \rho(d(\vec{\omega},\vec{P})\lfloor\vec{\omega}\cdot\vec{n}\rfloor)d\omega \qquad (2)$$

where $d(\vec{\omega},\vec{P})$ refers to the distance of the first interception along a ray direction $\vec{\omega}$ from $\vec{P}$. The function ρ ?maps the appropriate distance. Especially in the game industry, there is a great demand for a real-time ambient occlusion computing technique, and there are various attractive methods.

Mendez et al. (Méndez et al., 2003) introduced a real-time computing ambient occlusion method which dynamically updates the obscurance information in the presence of deforming objects. In a moving scene, obscurances are re-sampled only in a selected region of the scene by utilizing temporal coherence. However, the method requires a huge number of patches to give high quality contact shadows.

Ambient occlusion has been popularized in production rendering (Landis, 2002) and has been adopted in the movie, television and game industries. When ambient occlusion is implemented to create content, it is typically computed on the surface of each object in a scene and baked on a texture map to reduce the computational cost in the run-time. However, a huge number of occlusion maps have to be prepared for a movie creation, because one occlusion map of all the objects in each frame is needed. If the computing time per map is long, huge timing complexity arises. Therefore many derivative methods of ambient occlusion have been suggested and developed. In this case, the goal is to evaluate equation(1) on the surface of an object and to implement the ambient occlusion speedily.

Bavoil et al. (Bavoil et al., 2008) introduced screen space ambient occlusion (SSAO) which is a multi-pass rendering technique using a z-buffer. A z-buffer is one of the back-buffers that contains normal vectors and the depth of pixels in the screen space. In SSAO, the occlusion at a point is computed by the GPU from this z-buffer. The basic idea is as follows. The simplified shape of the nearby geometry is detected by the depth and normal vector direction of one (or two) pixels neighboring the depth buffer. The Monte-Carlo collision detection of the ambient occlusion is calculated from this shape information. Thus, Bavoil et al. (Bavoil and Sainz, 2009) introduced a developed version of SSAO for improving the quality of the ambient occlusion effect.

SSAO is employed in the computer game industry more than any other ambient occlusion technique, because it is easy to implement on graphics hardware, and requires no precomputing for rendering. Despite the merits and superiority of SSAO, it has not been adopted for real computer games, because the ray sampling method inevitable with SSAO requires a large computational cost for current graphics processors. Therefore, in the next section, we introduce a novel method for computing high quality ambient occlusion at a lower cost than SSAO.

3 CURVATURE DEPENDED AMBIENT OCCLUSION

Previous real-time ambient occlusion techniques need a great number of functions due to the Monte-Carlo collision detection algorithms. Our goal is to compute ambient occlusion by the GPU in real-time and implement our method at a lower computational cost than previous works.

For this purpose, we approximate the occlusion at a point $\vec{P}$ into a function model which depends on variables given by local features. A technique featuring local variables only is usually called a local illumination model as opposed to a global illumination model. The advantages of the local illumination

Table 1: List of used symbols.

Variable	meaning
$\vec{P}$	3D position
$\vec{\omega}$	direction vector
$\vec{n}$	normal vector on surface
$V(\vec{P},\vec{\omega})$	visibility function
$A(\vec{P},\vec{n})$	ambient occlusion
$A(\kappa_{max},\kappa_{min})$	our ambient occlusion
Ω_+	hemisphere area
r	radius of hemisphere
κ_1,κ_2	curvatures
$\kappa_{max},\kappa_{min}$	maximum, minimum principal curvatures

model are lower computational cost and the ease with which it can be implemented on the GPU. In this section, we introduce our curvature dependent function which computes the occlusion at $\vec{P}$.

The main features described in this section are as follows.

- Approximating the shape of a geometrical surface at point $\vec{P}$ by a function $f(\vec{P})$.
- Obtaining the occlusion at point $\vec{P}$ by comparing $f(\vec{P})$ with the unit hemisphere Ω_+.

3.1 Approximation of Geometry

Current ambient occlusion techniques employ ray tracing algorithms to compute the occlusion at a point $\vec{P}$, because the geometric shape is undetectable by variables at this point. We may regard the geometric surface at $\vec{P}$ as a function $f(\vec{P})$ and we detect the occlusion by analyzing this function over the unit hemisphere Ω_+. However it is difficult to identify $f(\vec{P})$ by the variables at $\vec{P}$, because the geometric shape can, in many cases, be very complex and unpredictable. To analyze this geometrical function easily, we converted the function $f(\vec{P})$ into a Taylor series and considered only the lower terms in the series to simplify it. Furthermore, we put $f(\vec{P})$ in the tangential vector space, by a coordinate transformation. Then the Taylor expansion becomes a Maclaurin series.In the tangential vector space the z axis of the Cartesian coordinates is normal to the surface.

$$\begin{aligned} f(x,y) &= f(0)+f_x(0)x+f_y(0)y \\ &+ \frac{f_{xx}(0)x^2}{2!}+2\frac{f_{xy}(0)xy}{2!}+\frac{f_{yy}(0)y^2}{2!}..(3) \end{aligned}$$

$f_x(x,y)$ is the first order differentiation of $f(x,y)$ with respect to x. The x and y axes are in the tangential and bi-normal vector directions, respectively. The $f(0)$ is equal to 0 because it is the origin of the coordinates. Both $f_x(0)$ and $f_y(0)$ are also equal to 0, because $f(x,y)$ is tangential plane at $(x,y)=(0,0)$. Furthermore $f_{xx}(0)$ and $f_{yy}(0)$ are the curvatures of the lines of intersection between the $x-z$(or $y-z$) plane and $f(x,y)$ at $(x,y)=(0,0)$. We define the direction of each curvature as κ_1 and κ_2. The κ_1 and κ_2 intersect each other. We can transform equation(3) as follows.

$$f(x,y)=\frac{\kappa_1}{2}x^2+2\frac{f_{xy}(0)xy}{2!}+\frac{\kappa_2}{2}y^2... \qquad (4)$$

Then $f_{xy}(0)$ is equal to 0, provided that x and y belong to the axes in which κ_1 and κ_2 are the maximum and minimum principal curvatures(κ_{max}, κ_{min}). Additionally, by removing the higher than second order terms, we obtain the simplified $f(x,y)$ as follows.

$$f(x,y)=\frac{1}{2}(\kappa_{max}x^2+\kappa_{min}y^2) \qquad (5)$$

This function is a quadric surface function and it depends only on the points x and y and the maximum and minimum principal curvatures. Therefore, it is very easy to analyze this function. We regard this simplified $f(x,y)$ as the geometric shape at point $\vec{P}$, and we analyze this function to obtain the occlusion at this point. In the next subsection, we analyze this function on the surface of the unit hemisphere Ω_+ and acquire a curvature dependent occlusion estimation.

3.2 Approximation of Occlusion

In the previous subsection, we introduced a curvature dependent function which estimates the geometrical shape at the point $\vec{P}$. We analyze this function along the surface of the unit hemisphere Ω_+ to estimate the occlusion at $\vec{P}$. Before the estimation, we have to transform $f(x,y)$ into polar coordinates, as follows.

$$f(r,\theta,\phi): r\cos\theta=\frac{r^2}{2}\sin^2\theta(\kappa_{max}\cos^2\phi+\kappa_{min}\cos^2\phi) \qquad (6)$$

For the unit hemisphere the radius r is constant, and the range of θ and ϕ are $(-\frac{\pi}{2}\le\theta\le\frac{\pi}{2})$ and $(0\le\phi\le 2\pi)$ respectively.

Previous ambient occlusion techniques require great computational cost because they adopt ray tracing algorithms for collision detection. The Monte-Carlo ray sampling algorithm needs to sample more than 16 rays per pixel, to acquire a practical quality. The reason why ray tracing algorithms are employed is that it is difficult to detect occlusions from the geometry shape surrounding $\vec{P}$. However, now we have the shape of the surrounding geometry and the surface of the hemisphere as functions, we are able to use

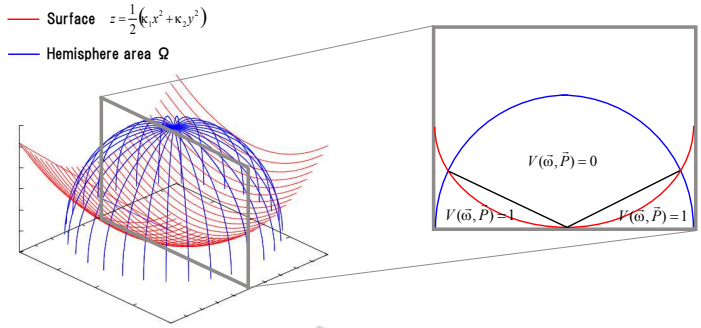


Figure 2: The surface of the hemisphere Ω_+(blue line) and the quadric surface function $f(r,\theta,\phi)$ (red line). In the occluded area, the visibility function $V(\vec{\omega},\vec{P})$ is equal to 0, and is 1 otherwise. We will obtain the occluded area by analyzing this figure estimation.

these analytically to acquire the occlusion. We define the hemisphere Ω_+ to be centered at the origin of the tangential space, and the function $f(x,y)$ to be an occlusive geometry. We estimate the visible parts on Ω_+ from origin as in fig(). Then, we obtain the curvature dependent visibility function $V'(\vec{\omega},\vec{P})$ as follows.

$$V'(\vec{\omega},\vec{P}) = \begin{cases} 1 & (\frac{1}{2}(\kappa_{max}x'^2+\kappa_{min}y'^2) > z') \\ 0 & (\frac{1}{2}(\kappa_{max}x'^2+\kappa_{min}y'^2) \leq z') \end{cases}$$

x',y'andz' refer to the points of intersection between Ω_+ and $f(x,y)=\frac{1}{2}(\kappa_{max}x^2+\kappa_{min}y^2)$. As a result, we obtain the following occlusion estimation function.

$$A(\kappa_{max},\kappa_{min}) = \int_0^{2\pi}\int_0^{\theta} r^2\phi\sin\theta' d\theta' d\phi \qquad (7)$$

$$this\ \theta = \arccos(\frac{-1\pm\sqrt{1+A^2}}{A})$$

$$(A = R(\kappa_{max}\cos^2\phi+\kappa_{min}\sin^2\phi)$$

This function, depending on curvature alone, is a local illumination approximation of occlusion. Adopting this approximation, we can obtain an ambient occlusion effect at low cost, thus the implementation is very easy. When we obtain the occlusion from a static object, we do not need any other process. In this paper, we more simplify equation(8) as follows by using a symmetry between x and y, because it is difficult to implement equation(8) for current computer.

$$A(\kappa_{max},\kappa_{min}) = \frac{2\arccos(\frac{-1\pm\sqrt{1+(\kappa_{max}+\kappa_{min})^2r^2}}{(\kappa_{max}+\kappa_{min})^2})}{\pi} \qquad (8)$$

This is an important update from "Curvature depended local illumination approximation of ambient occlusion" (Hattori et al., 2010). In the paper, we have to adopt some look-up table(LUT) or quite rough approximated function which ignore physical property to implement equation(8). Now, using this equation(8), we are able to implement our ambient occlusion correctly and in real-time. However, our goal is to compute the ambient occlusion for a deformable object, so we introduce a real-time curvature computing technique in the next section.

4 IMPLEMENTATION

In the previous section, we obtained the curvature dependent function for estimating an occlusion at $\vec{P}$. By converting this function using the current rendering process, we can acquire an ambient occlusion effect as a local illumination model. However, it is rare for the curvature to be given by current polygon model formats, so we have to calculate the curvature in real-time. In previous works, many real-time estimations of curvature have been suggested and the methods can be simply divided into two categories as follows.

- Estimations in the screen space with no pre-computing.
- Estimations in world space with some pre-computing.

In our method, we employ the screen space algorithm, because the purpose of our work is to obtain an ambient occlusion effect, at lower cost than in previous works and by a method that is easy to implement. It has already been shown that screen space estimation is easy to implement in computer games on current graphics hardware. Wesley et al. (Griffin et al., 2011) introduced real time curvature estimation in the world space. They employed a programmable geometry shader to detect the normal curvature by analyzing the normal and position vectors of neighboring polygons. Yu et al. (Yu et al., 2007) applied their screen space caustics estimation to compute curvature in real time. They used pre-computed shape infor-

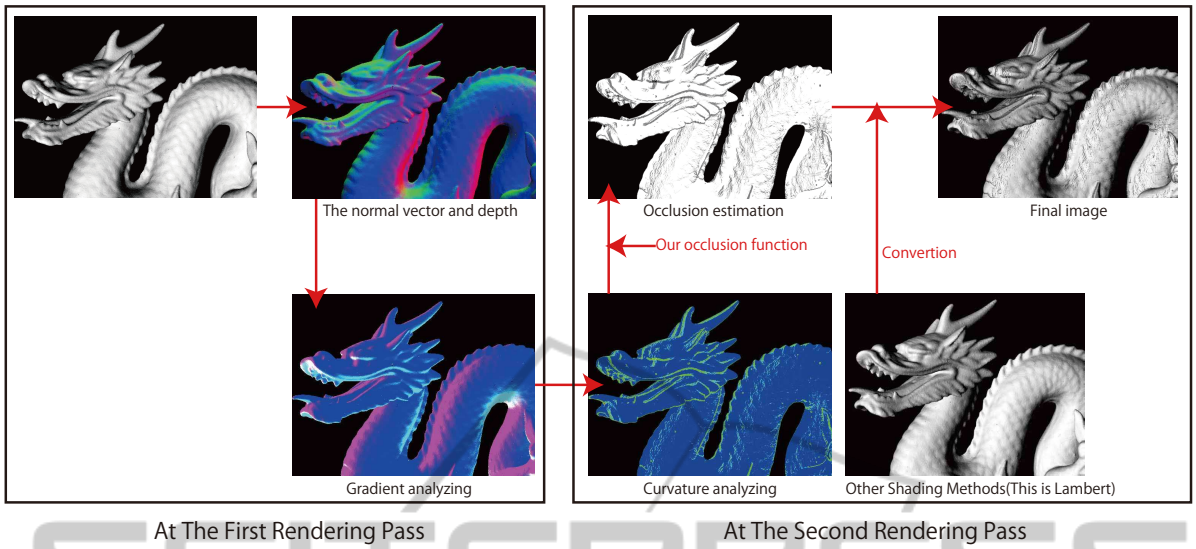
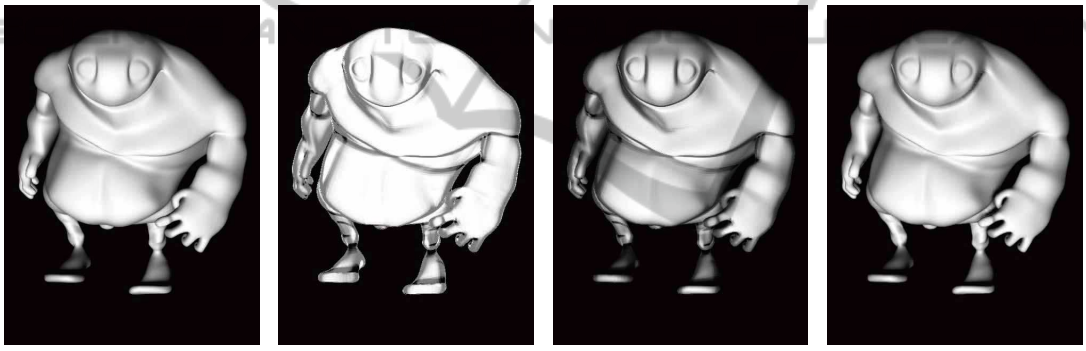


Figure 3: The flow of our implementation.



(a) Lambert. (b) Our method. (c) Our method + Lambert. (d) Lambert + SSAO.

Figure 4: Curvature dependent ambient occlusion images(b)(c) and SSAO(d).

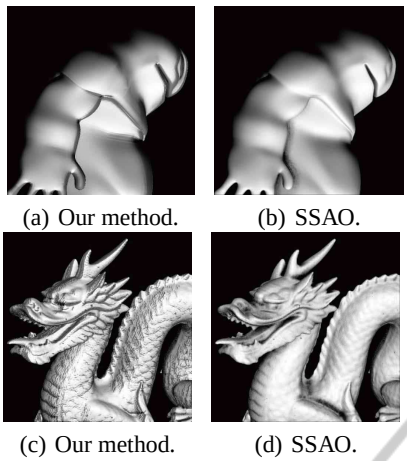
mation to compute curvature with low computational running cost. Employing these methods we can acquire a greater variety of ambient occlusion effects. When we adopt Wesleyfs technique, we can obtain the characteristics of a three-dimensional geometric shape. In some cases, this is a great advantage, so we shall be implementing this method in our future work.

5 RESULT AND DISCUSSION

We show a result obtained by employing our method in Figure(4). (a) shows a Lambert-rendered image, (b) shows our method, and (c) shows an image composed of (a) and (b). (d) shows the image rendered by SSAO. The speed of rendering a 1280×960 pixel image by applying our method is 60fps and applying SSAO(16 rays sampling with no blur) is 26fps using an Intel 1.6GHz dual core cpu and a nVIDIA GeForce 320M machine. The result shows our method runs 130 percent faster than SSAO. Furthermore, Our method is a local illumination method to realize a fast run time and easy implementation. It is extremely easy to implement, and, in addition, by adopting the curvature dependent method, we can obtain a more detailed occlusion estimate than with the conventional method using collision detection. The following figure, Figure (5) shows close up images, in which we can see the effect of having more detailed occlusion information.

We can see that even for a fairly small shape changes in geometry are detected. From these results, we find that our method is effective for determining small changes in geometry.

Thus, by adjusting the scale of the curvature, creators are able to change the strength of the ambient



(a) Our method. (b) SSAO.

(c) Our method. (d) SSAO.

Figure 5: More closed consideration between our method and SSAO.

occlusion. The results demonstrate that our method is easy to implement and runs fast on current graphics hard ware, thus making it effective for rendering small changes in geometry and adjusting the ambient occlusion intensity.

6 CONCLUSIONS

In this paper, we introduced a curvature dependent ambient occlusion estimation algorithm. Our method approximates the ambient occlusion in a local illumination model by introducing a curvature-dependent occlusion estimation function. Since the function is a local illumination model, we are able to render ambient occlusion in real-time, and the proposed method can be easily implemented. Furthermore, the rendering speed is twice as fast as SSAO. Using this method, smoother, more detailed and equal or better quality occlusion can be achieved than by using the conventional method (Figure 5), because the curvature is continuous on the surface. These results demonstrate that our method is effective for implementing in computer games. Adopting our method, we can reduce the personnel and computational cost, which would be beneficial for the game industry.

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