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Research on Multi LOD Rendering Method of Ocean Wave

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Abstract: Ocean waves are an important part of natural scenes. It is hard to simulate ocean waves due to its wide space and random movement. And it is difficult to use a common method to represent the ocean waves' characteristic of dynamic, optics and space-time as a whole. Therefore, a multi LOD method to render ocean waves in real-time is proposed in this article, the method has hierarchy details. First, the contour of waves is constructed based on Gerstner method, the parameters of ocean waves are based on ocean wave spectrum. Then the bump mapping is used to simulate the details of ocean waves' meso-structure. To simulate the optics details of ocean surface, the Bidirectional Reflectance Distribution Function is used based on GPU. The simulated results can acquire a good performance in geometry and optics effects and can achieve high efficiency rendering.

Key words: Ocean wave, multi LOD, wave spectrum, real-time rendering

INTRODUCTION

Ocean Wave is a very complex natural phenomenon, is irregular regardless of time or space. Ocean wave modeling is to use mathematical model to describe the inherent law of the sea surface, truly describing its complex characteristics (Li *et al*., 2008). At present, the main methods of modeling ocean waves can be summarized as four categories as follow: Geometric modeling method, physical modeling method, spectral analysis method and modeling based on wave motion (Iglesias, 2004).

Geometric modeling is based on constructing functions or graphic texture modeling, which is in pursuit of visual effects similar to physical phenomenon and is not necessarily associated with the ocean in physical factors. The waves modeled based on physical modeling method can get a shape very close to the real physical phenomena, but the method cannot meet the real-time requirements.

Modeling method based on wave motion includes particle system model and cellular automata model etc. (Wcislo *et al*., 1998).

Spectral analysis method break down the fundamental sea surface into sine waves based on statistical ocean wave spectrum and wave spectrum obtained empirically. Then the inverse fast Fourier transform algorithm is used to create highly-field model. This method can take into account both the randomness of the waves and certain physical characteristics, which can get a better visual realism, but the details of the performance is still lacking.

In this study, inspired from models of multiple levels of detail, a multi-level detail of the waves drawing methods is introduced. The study is organized as follows: In Section 2, modeling method of ocean waves' basic outline based on Gerstner method is introduced at first, the parameters is acquired through the wave spectrum; In section 3, to add microscopic details of surface waves to simulation results, method based on normal bump mapping is used; In section 4, an Bidirectional Reflectance Distribution Function method is used to realize the optical detail rendering. The results show that the method can reproduce the optical properties of the ocean surface and geometric details of the structure and can achieve efficient real-time rendering. Finally, a summary of the full text and future research aspects is proposed.

OCEAN WAVE SHAPE MODELING

Trochoidal wave theory is based on the Gerstner wave functions derived from a totally different angle wave expression. It belongs to the non-linear, with spin wave theory. For a water point at an arbitrary coordinate (x_0, z_0), the trajectory equation (Hou *et al*., 2009; 2010) is as follow:

$$\begin{cases} x = x_0 - ae^{kz_0}\sin(kx_0 - \omega t) \\ z = z_0 + ae^{kz_0}\cos(kx_0 - \omega t) \end{cases} \tag{1}$$

where, x axis to the right, z axis to up, (x_0, z_0) is a fixed point of the vertical plane, k is the wave number, ω is the angular frequency, a is the controlled equivalents.

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Consider a single point motion in time t, set the amplitude of the wave, the wave number, angular frequencies to A, k, w. As linear wave theory, the waves are composed of different waves with different amplitude and angular frequency. Therefore, can easily extend the Eq. 1 to the following three-dimensional discrete form:

$$\begin{cases} x = x_0 + \sum_{i=1}^{n} A_i \sin(k_i x_0 - \omega_i t + \phi_i) \\ y = y_0 + \sum_{i=1}^{n} A_i \sin(k_i y_0 - \omega_i t + \phi_i) \\ z = z_0 + \sum_{i=1}^{n} A_i \cos[k_i (x_0 + y_0) - \omega_i t + \phi_i] \end{cases} \quad (2)$$

where, the xy plane defines as the plane of the water surface at rest, x-axis toward the right, y-axis outward, z-axis is vertical, forward facing, each point (x, y, z) on the sea all act in a circular motion around its resting position (x_0, y_0, z_0). In general, $z_0 = 0$. A_i is the amplitude of wave element, k_i is the wave number of unit; w_i is the angular frequency of the wave element, the wave is spread in the xy-plane along the horizontal direction of the x-axis in angular ϕ_i; n is the cell number of waves.

In this study, the amplitude, angular frequency and wave direction of each unit wave is acquired by wave spectrum approach. The common wave spectrums are Laumann spectrum, Pierson-Moscowitz (PM) spectrum, JONSWAP spectrum and standardized spectrum etc. In this study, to obtain the elements of the waves, the PM spectrum according to the method in literature (Yang and Sun, 2002) is used as the energy spectrum. The result formulas of Stereo Wave Observation Project are used as the direction functions of waves. The calculation method of Energy spectrum and orientation function is not going to elaborate.

Steps of ocean wave shape modeling based on Gerstner are as follows:

- **Initial setup:** Set the wave parameters of each component waves, including angular frequency, significant wave height, wave direction and other parameters. And calculate the wave number through the corresponding angular frequency and depth of the sampling points
- According to the Gerstner wave equation given by Eq. 2, put the above wave parameters into the equation, calculates the wave height of the computational grid nodes and get sea surface height field
- Rendering the ocean surface height field with triangle mesh

MESO-STRUCTURE MODELING BASED ON BUMP MAPPING

Bump mapping is an expression of fine relief structure surface method proposed by Blinn. The method is simple and easy to implement and has been widely used.

Typically the concavo-convex structure of the surface needs to be expressed by the corresponding lighting effects, Blinn simulate the partial illumination effects on vertices by modifying the normal of vertices on the surface. With this method, the structure of the surface irregularities of the object can be simulated.

Take the time t as a continuous time variable, H (x, y, t) represent the wave height field at time t. to generate the vertex displacement of vertices, add the coordinates of mesh vertices with the function and can achieve dynamic effects of the wave. Although through Gerstner wave superposition method can be relatively satisfied with the waveform, but it can only simulate the approximate outline of actual ocean surface. In order to improve the authenticity of the details, in this study, the structure of the surface simulation is achieved by adding disturbance to each pixel of the sea surface using bump mapping.

According to Eq. 2, we can obtain the coordinate of a certain vertex at a certain position and certain time. To achieve each pixel vector perturbation, the normal vector of each pixel is calculated at first. The method is described as follow.

Construct a coordinate system at each vertex, in this coordinate system, the vertex normal vector always points to the positive z-axis. In addition, each vertex has two tangent vectors tangential to the surface and these two vectors formed orthogonal basis vectors. Thus formed coordinate system is called tangent space. In specific calculations, the light should transformed into this tangent space. Then use the 3 × 3 transformation matrix to transform the corresponding bump mapping vector from the local tangent space into world coordinates.

For a certain point P (x, y), the tangent vector is calculated as follows:

$$\vec{B} = \frac{\partial(x, y, H(x, y, t))}{\partial x} \quad (3)$$

$$\vec{T} = \frac{\partial(x, y, H(x, y, t))}{\partial y} \quad (4)$$

$$\vec{N} = \vec{B} \times \vec{T} \quad (5)$$

where, $\vec{B}$, $\vec{T}$, respectively present the tangent vectors at the vertex, $\vec{N}$ is the vertex of the normal vector.

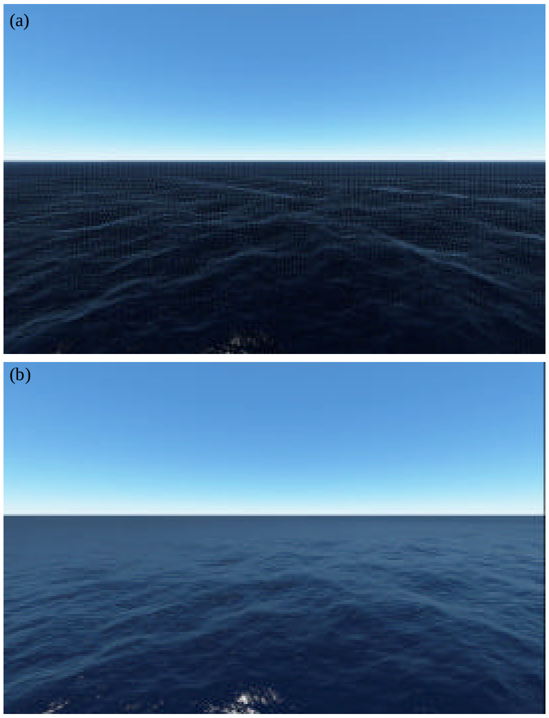

Fig. 2(a-b): Ocean effects based on Gerstner wave and bump mapping

The disturbance of the normal direction is achieved by the random function, the random function is calculated in the CPU and then stored in the texture. In the GPU processing, a random number is obtained by looking in the textures and then according to wave height, the random number multiplied with a related adjustment factor, to get a realistic disturbance result to add to the normal of vertices.

The results of Bump mapping effects are shown as Fig. 1 where, the (a) is the grid map of ocean wave based on Gerstner with bump mapping effects, the (b) is the rendering effects of Gerstner wave combined with bump mapping.

OPTICAL DETAILS RENDERING BASED ON BRDF

Bidirectional reflectance distribution function (BRDF for short) describes the reflection regular of surface of opaque material which is infinitely small or material uniformly. BRDF is defined as the reflected light in the direction of the incident direction of the light intensity ratio of illumination. Take the light reflectivity of the surface as the function of the incident light direction, the sight line direction and the wavelength of the light. The basic description is shown as the following equation:

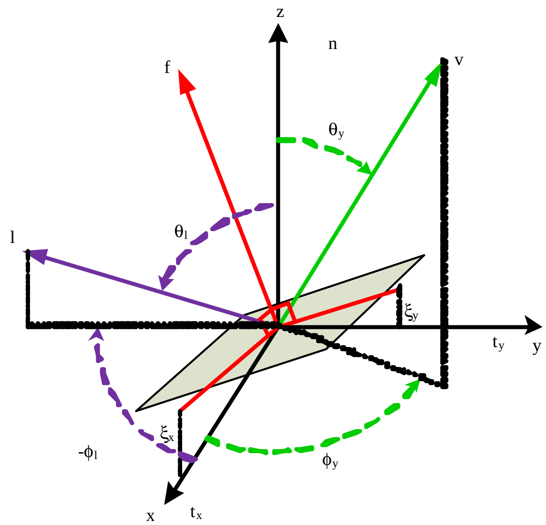

Fig. 3: Schematic of BRDF model

$$f(\theta_i,\phi_i,\theta_o,\phi_o)=\frac{L_r(\theta_o,\phi_o)}{L_i(\theta_i,\phi_i)} \quad (6)$$

where, $L_r(\theta_o,\phi_o)$ is the reflected light intensity $L_i(\theta_i,\phi_i)$ is the incident light intensity, θ and ϕ, respectively represent the spherical coordinates of incident light and reflected light. As shown in Fig. 3, v and l is the reflected light and incident light, f is the normal of micro-surface element, which the slope in x and y directions is ζ_x and ζ_y, respectively.

In ocean optics simulating, Ross and Dion (2007) established a very precise BRDF model based on the assumption that the slope and height of the sea surface satisfy the Gaussian distribution. The method get the BRDF model of ocean surface by calculating the visibility of a micro-surface element slope of which is ζ as shown in Fig. 3, the micro-surface element of slope ζ can be visible in the direction of sight and the reflected light, f is the normal of the element, p is the Gaussian distribution of ocean surface slope.

Ross et al used the hatched parameters of literature (Smith, 1967) and established a uniform distribution expression of normalized visibility. Bruneton *et al.* (2010), through the analysis of Gerstner waveform, find out that the height and slope of the ocean surface established based on Gerstner can be satisfied with the Gaussian distribution. And then, they used the BRDF model proposed by Ross and achieved the realistic simulation of optical effect of the ocean surface. In this study, the sea surface microstructure is simulated with the method proposed by Eric Bruneton *et al*, the optical properties of ocean surface modeling is based on Ross model.

Cook and Torrance (1982) proposed a one statistical model to represent the ocean scattering at first, expanded the density function of the ocean surface slope based on Gram-Charlier. To simplify the model, retain only the first order term of Gaussian distribution:

$$p_0(\zeta|U) = \frac{1}{2\pi\sigma_x\sigma_y}\exp\left\{-\frac{1}{2}\left(\frac{\zeta_x^2}{\sigma_x^2}+\frac{\zeta_y^2}{\sigma_y^2}\right)\right\} \quad (7)$$

Add correction to the kurtosis and skewness:

$$p = p_0\left\{1-\frac{1}{2}c_{21}(Y^2-1)X-\frac{1}{6}c_{03}(X^3-3X)+\frac{1}{24}c_{40}(Y^4-6Y^2+3)+\frac{1}{4}c_{22}(Y^2-1)(X^2-1)+\frac{1}{24}c_{04}(X^4-6X^2+3)\right\} \quad (8)$$

where, $X = \zeta_x / \sigma_x$, $Y = \zeta_y / \sigma_x$

In the above Eq. 7 and 8, U is the wind speed of the ocean surface at 12.5 meters high, σ_x^2 and σ_y^2 are upwind and cross-wind direction variance. The parameters in Eq. 8 are related to wind speed. Through the observation and analysis of the sea photos under solar radiation, Cox *et al* proposed an approximate formula for calculating the variance of sea as follows:

$$\sigma_x^2 = 0.00316U \quad \pm 0.004 \quad (9)$$

$$\sigma_y^2 = 0.003 + 0.00192U \quad \pm 0.004 \quad (10)$$

At the same time, the simplified formula of coefficients in the kurtosis and skewness correction term is given as follows:

$$c_{21} = 0.01 - 0.0086U \;\; c_{03} = 0.04 - 0.033U \quad (11)$$

$$c_{40} = 0.40, c_{22} = 0.12, c_{04} = 0.23 \quad (12)$$

Ross *et al.* (2005) got the ocean surface BRDF model by analyzing and calculating the visibility of a micro-surface element of which slope is ζ. And got a normalized visibility distribution q_{vn} through the analyzing results

$$q_{vn}(\boldsymbol{\zeta}, \mathbf{v}, \mathbf{l}) = \frac{p(\boldsymbol{\zeta})\max(\mathbf{v}\bullet\mathbf{f}, 0)H(\mathbf{l}\bullet\mathbf{f})}{(1+\Lambda(a_v)+\Lambda(a_l))f_z\cos\theta_v}d^2\zeta \quad (13)$$

$$\mathbf{f}(\boldsymbol{\zeta}) = \begin{bmatrix} fx \\ fy \\ fz \end{bmatrix} = \frac{1}{\sqrt{1+\zeta_x^2+\zeta_y^2}}\begin{bmatrix} -\zeta_x \\ -\zeta_y \\ 1 \end{bmatrix} \quad (14)$$

$$p(\boldsymbol{\zeta}) = \frac{1}{2\pi\sigma_x\sigma_y}\exp\left(-\frac{1}{2}\left(\frac{\zeta_x^2}{\sigma_x^2}+\frac{\zeta_y^2}{\sigma_y^2}\right)\right) \quad (15)$$

$$\Lambda(a_i) = \frac{\exp(-a_i^2) - a_i\sqrt{\pi}\,\mathrm{erfc}(a_i)}{2a_i\sqrt{\pi}}, i \in \{v, l\} \quad (16)$$

$$a_i = (2(\sigma_x^2\cos^2\phi_i + \sigma_y^2\sin^2\phi_i)\tan\theta_i)^{-1/2} \quad (17)$$

where, f is the normal of micro-surface element which slope is ζ, p is the Gaussian distribution of the slope, $\Lambda$is the Smith shading parameters, σ_x^2 and σ_y^2 is the slope variance along the x and y direction. H is the Heaviside function, defined as:

$$H(x) = \begin{cases} 0, & x \le 0 \\ 1, & x > 0 \end{cases} \quad (18)$$

erfc (x) is the error function, where to simplify only get the approximation form:

$$\mathrm{erfc}(x) = \frac{2e^{-x^2}}{2.319x + \sqrt{4+1.52x^2}} \quad (19)$$

In case of no light, Eq. 13 to calculate the visible probability can be simplified as:

$$q_{vn}^e(\boldsymbol{\zeta}, \mathbf{v}) = \frac{p(\boldsymbol{\zeta})\max(\mathbf{v}\bullet\mathbf{f}, 0)}{(1+\Lambda(a_v))f_z\cos\theta_v}d^2\zeta \quad (20)$$

By a normalization factor $1+\Lambda(a_v)$, can get the following conclusions (Cook and Torrance, 1982):

$$\iint_{-\infty}^{\infty} q_{vn}^e(\boldsymbol{\zeta}, \mathbf{v})d^2\zeta = 1 \quad (21)$$

The above formula indicates that at least can be able to see a micro-surface element with probability 1. If ignoring the multiple reflections and assuming that each element is a perfect micro-surface mirror, then the BRDF model can be described as the visible probability of a micro-surface element of slope ζ multiplies the Fresnel coefficients.

$$\mathrm{BRDF}(\mathbf{v}, \mathbf{l}) = \frac{q_{vn}(\boldsymbol{\zeta}_h, \mathbf{v}, \mathbf{l})F(\mathbf{v}\bullet\mathbf{h})}{4h_z^3\cos\theta_l\,\mathbf{v}\bullet\mathbf{h}} \quad (22)$$

Where:

$$d^2\boldsymbol{\zeta} = \frac{\sin\theta_l d\theta_l d\phi_l}{4h_z^3\mathbf{v}\bullet\mathbf{h}} = \frac{d^2\boldsymbol{\omega}_l}{4h_z^3\mathbf{v}\bullet\mathbf{h}} \quad (23)$$

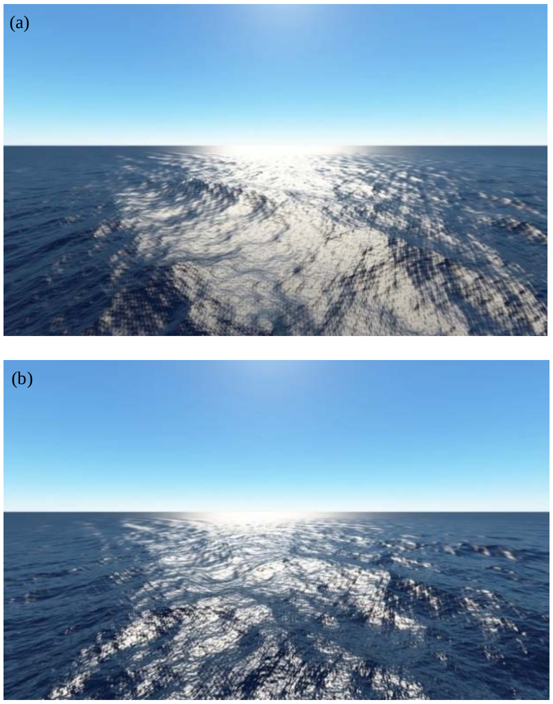

Fig. 4(a-b): Ocean simulation effects with and without BRDF, (a)Without BRDF and (b)With BRDF

In the Eq. 22 and 23, h is the half normal vector (also known as half size vector, which is the half angle between the incident direction and the reflection direction), can be calculated by the following equation (where norm means normalization):

$$\mathbf{h}=\text{norm}(\mathbf{v}+\mathbf{l}) \tag{24}$$

The Fresnel coefficient in Eq. 22 can be calculated by the following formula:

$$F(\mathbf{v}\bullet\mathbf{h}) \approx R + (1-R)(1-\mathbf{v}\bullet\mathbf{h})^5 \tag{25}$$

Where:

$$R = \frac{(n_2 - n_1)^2}{(n_2 + n_1)^2}$$

the refraction coefficients of water and air are respectively 1.333 and 1.0, so we can get R≈0.02.

The slope of Gerstner waveform, which is formed by a plurality of trochoid function, can meet the Gaussian distribution (Cook and Torrance, 1982). For a point P (x, y) on the sea surface, the simplified method of slope calculation is adding slopes of all trocchoidal waveform passing the point:

$$\begin{bmatrix} \sigma_x^2 \\ \sigma_y^2 \end{bmatrix} = \sum_1^n \frac{\begin{bmatrix} k_{i,x}^2 & k_{i,y}^2 \end{bmatrix}^T}{\|\mathbf{k}_i\|}(1-\sqrt{1-\|\mathbf{k}_i\| A_i^2}) \tag{26}$$

where, σ_x^2 and σ_y^2, respectively represent the slope variance along the x and y axes. In the calculating process, we use the wind direction and cross-wind direction to replace the x and y direction.

Figure 4 is a comparative simulation results with or without BRDF, 4(a) is the ocean surface effect which combined the Gerstner waveform with bump mapping texture, but without BRDF. 4(b) is the ocean surface simulating result with BRDF.

CONCLUSION

The program is based on Visual C++ 2005 and OpenGL, using GLSL language for GPU programming. Experimental machine is configured for Intel Core 2 Quad CPU Q9550 2.83GHz, 2GB RAM, Geforce GTX 285 graphics card, display resolution is 1920 * 1080 pixels.

The average frame rate of sea scenes is about 56/s. when loading the target ship, harbor buildings and other objects, the rendering frame rate can still be maintained at about 40/s, can satisfy the basic requirements of scene simulation.

Inspired from multiple levels of detail model, an ocean waves rendering method of multi-level details was introduced in this study. The Gerstner wave is set for the basic waveform at first. And then bump mapping is used for adding surface details, BRDF method is used to simulate the optical effects. With this method, the realistic wave modeling can be achieved via GPU rendering.

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