Three-dimensional Simulation on Collision Response of Ships

Jun-sheng HU\textsuperscript{1,2,*}, Yao-jie CHEN\textsuperscript{1,2} and Xin YUAN\textsuperscript{1,2}

\textsuperscript{1}College of Computer Science and Technology, Wuhan University of Science and Technology, Wuhan 430065, China
\textsuperscript{2}Hubei Province Key Laboratory of Intelligent Information Processing and Real-time Industrial System, Wuhan 430065, China

*Corresponding author

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Abstract. In order to enhance the realism and fidelity of the navigation simulator in ship collision response simulation, a technical solution for adding the Bullet physics engine to the three-dimensional visual simulation of the navigation simulator is proposed. Using rigid body dynamics theory, collision dynamics and energy conservation law to establish a three-dimensional collision mechanics model of ships. In the collision response phase, the Gauss-Seidel iterative algorithm is used to solve the real-time six-degree-of-freedom position and attitude parameters of the ship during the collision process, and the rendering update is synchronized in the 3D view. Experiments show that the scheme is feasible, and it can render ship collision scenes in real time and stably, and the collision process conforms to objective physical laws, which effectively improves the realism and fidelity of ship collision simulation in navigation simulator.

Introduction

With the continuous development of international shipping industry and modern shipbuilding technology, the trend of large-scale and high-speed ships is obvious, the navigation density is also increasing, and the safety of navigation is attracted much attention. In order to improve the safety of maritime navigation and reduce the incidence of maritime accidents, seafarer simulators are usually used to train and evaluate seafarers. The Manila Amendments to the STCW Convention issued by the International Maritime Organization put forward higher equipment requirements for navigation simulators, and it is urgent to perfect the functions of navigation simulators [1]. Collision detection and collision response are one of the key technologies for navigation simulators. The current simulation system usually stops the ship after collision, and it lacks realistic feeling in the collision response visual simulation. If the realistic problem of ship collision response can be effectively solved, the performance of the navigation simulator can be further improved, and it can also improve the crew’s ability of operating simulator for emergency situation. Aiming at this problem, this paper proposes a technical solution that combines the OpenSceneGraph (OSG) 3D rendering engine with the Bullet physics engine, studies the 3D collision response algorithm [2,3]. Finally, the program is successfully applied to the navigation system of the navigation simulator.

Establishing a Three-dimensional Model of Ship Collision in Terms of Dynamics

Make the following assumptions for the three-dimensional model of ship collision in terms of dynamics [3]: Consideration of ship swaying, surging, yawing and rolling motions in ship collisions; Ship collision and damage deformation areas are extremely small and considered plastic collisions; The impact force at the moment of collision is transmitted synchronously on the collision ship; Considering the ship as a rigid body and ignores the structural properties of the untouched part [4].

Establish Coordinate System

In order to analyze the three-dimensional model of ship collision in terms of dynamics, two
coordinate systems are constructed as shown in the following figure. The \(O-xyz\) is a global coordinate system that does not change with the ship's position. At the initial moment, the \(x\)-axis is on the longitudinal section of the ship A, and the \(yOz\) plane is on the cross section of the ship A. The \(O'-uvw\) coordinate system is similar to the \(O-xyz\) coordinate system. The \(z'\)-axis and \(w'\)-axis pass through the center of gravity of ship A and ship B respectively, and it is parallel to \(z\) axis and \(w\) axis.

In figure 2, point \(C\) is the collision contact point, and the normal of the point \(C\) is \(\xi\) axis, tangent direction is \(\eta\) axis, taking the point \(C\) as the origin of the coordinate system. Remember that \(\alpha\) is the angle between the \(x\) axis and the \(\eta\) axis, and \(\beta\) is the angle between the \(x\) axis and the \(\mu\) axis.

![Diagram](image1)

![Diagram](image2)

**Figure 1. Coordinate system 1 in ship collision analysis.**

**Figure 2. Coordinate system 2 in ship collision analysis.**

### Establishing the Equation of Motion

When the ship collides, it can be analyzed about force at the contact point \(C\). Under the action of the collision force \(F_\xi\) in the \(\xi\) direction and the collision force \(F_\eta\) in the \(\eta\) direction, the equation of motion of the ship A can be expressed as follow [5]. A similar analysis can be performed on ship B.

\[
\begin{align*}
M_\alpha (1 + m_\alpha) v_\alpha = & -F_\xi \sin \alpha - F_\eta \cos \alpha \\
M_\alpha (1 + m_\alpha) v_\eta = & -F_\xi \cos \alpha - F_\eta \sin \alpha \\
M_\alpha R_\alpha^2 (1 + j_\alpha) = & -F_\xi [\gamma \sin \alpha (x_c - x) \cos \alpha] + F_\eta [\gamma \cos \alpha (x_c - x) \sin \alpha] \\
M_\alpha R_\alpha^2 (1 + j_\alpha) = & F_\xi h \cos \alpha - F_\eta h \sin \alpha
\end{align*}
\]

(1)

Where, \(M_\alpha\) is the mass of the ship A; \(V_\alpha\), \(V_\eta\) are the line acceleration in \(x\), \(y\) direction; \(\omega_{az'}\) is the angular acceleration around the \(z'\) axis; \(\omega_{ax}\) is the angular acceleration around the \(x\) axis. The ship's center of mass coordinate is \((x_\alpha, 0)\); The coordinates of the collision point \(C\) is \((x_c, y_c, h_a)\); The additional mass factor for longitudinal motion is \(m_\alpha\); The additional mass coefficient for the traverse motion is \(m_\eta\); \(j_{az'}\) and \(j_{ax}\) are additional moment of inertia coefficients for rotation around the \(z'\) axis and the \(x\) axis; \(R_{az'}\) and \(R_{ax}\) are the radius of gyration that around \(z'\) and \(x\) axes. Similar assumptions are made on the ship B.

### The Speed of the Ship at the End of the Collision

According to the above analysis, the final line velocity and angular velocity of ship A can be obtained as follows:

\[
\begin{align*}
v_\alpha = & \frac{I_\alpha \sin \alpha + I_\gamma \cos \alpha}{M_\alpha (1 + m_\alpha)} \\
v_\eta = & \frac{I_\gamma \cos \alpha - I_\alpha \sin \alpha}{M_\alpha (1 + m_\alpha)} \\
\omega_{az'} = & \frac{I_\gamma [\gamma \sin \alpha (x_c - x) \cos \alpha] + I_\alpha [\gamma \cos \alpha (x_c - x) \sin \alpha]}{(M_\alpha R_\alpha^2 (1 + j_\alpha))} \\
\omega_{ax} = & \frac{I_\gamma h \cos \alpha - I_\alpha h \sin \alpha}{(M_\alpha R_\alpha^2 (1 + j_\alpha))}
\end{align*}
\]

(2)

Among them, \(v_{ax}\) and \(v_{ay}\) are the linear velocities of ship A along the \(x\) axis and \(y\) axis respectively, and \(\omega_{az'}\) and \(\omega_{ax}\) are the angular velocities of ship A around \(z'\) axis and \(x\) axis.

In the same way, for ship B:
\[
v_{bu} = V_{bu} - \frac{L_s \sin (\beta - \alpha) - L_s \cos (\beta - \alpha)}{M_s (1 + m_b)}
\]
\[
v_{bv} = V_{bv} + \frac{L_s \cos (\beta - \alpha) + L_s \sin (\beta - \alpha)}{M_b (1 + m_b)}
\]
\[
\omega_{bw} = \left\{ [L_s^2 \left( (y_s - y_b) \sin a + (x_s - x_b) \cos a \right) + L_s^2 \left( (y_s - y_b) \cos a + (x_s - x_b) \sin a \right)] / (M_b R_{bw}^2 (1 + f_{bw})) \right\}
\]
\[
\omega_{bu} = \frac{L_h \cos (\beta - \alpha) + L_h \sin (\beta - \alpha)}{M_b R_{bw}^2 (1 + f_{bw})}
\]

Among them, \( v_{bu} \) and \( v_{bv} \) are the linear velocities of ship B along the \( u \) axis and \( v \) axis respectively, and \( \omega_{bw} \) and \( \omega_{bu} \) are the angular velocities of ship B around \( w \) axis and \( u \) axis.

Collision Response Constraint Analysis

The Bullet physics engine calculates the collision object island based on the distribution of the overlapping pairs obtained during the collision detection fine measurement phase, and then performs constraint analysis on each island, that is, the collision response [6].

Contact Condition

The \( k \)th contact point can be analyzed by means of the projection matrix \( P_k \in R^{3k \times 3} \), which is defined as follows [7-9].

\[
P_k^T = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ \end{bmatrix}
\]

The \( k \)th \( 3 \times 3 \) submatrix is an identity matrix. The normal force component corresponding to the velocity of the \( k \)th contact point is expressed as follows [10].

\[
n_k^T P_k^T C^T u = n_k^T \left( v_{jk} + \omega_{jk} \times r_{k,jk} \right) - n_k^T \left( v_{ik} + \omega_{ik} \times r_{k,ik} \right)
\]

If the contact point vector of object \( B_i \) and \( B_j \) at time \( t \) is \( P_k \). When one of the contact conditions of the two objects is non-zero and the other is zero or negative, or the potential collision point of the vector \( P_k \) is not collided at time \( t \), it is necessary to compensate the speed so that \( f_k \geq 0 \) [11].

Collision Response Algorithm

The collision response will generate many \( n \) dimensional sparse matrix equations in the program calculation phase, such as \( Ax = b \), where \( A \) has a larger order \( n \), but has more zero elements, which is generally solved by iterative method. When using the Gauss Seidel iterative method to solve the problem, first give the initial value \( x_0 \), assuming that \( x_1^{k+1}, x_2^{k+1}, \ldots, x_n^{k+1} \) has been obtained after the \( k+1 \) generation, the value of \( x_i^{k+1} \) can be substituted by these values. In general, the number of iterations is set before solving, and the corresponding algorithm is shown below [12].

\[
\text{Gauss-Seidel iterative algorithm, approximately solve } Ax = b \text{ given } x^0
\]

for \( iter = 1 \) to iteration limit do
    for \( i = 1 \) to \( n \) do
        \[
        \Delta x_i = \left[ b_i - \sum_{j=1}^{n} A_{ij} x_j \right] / A_{ii}
        \]
        \[
        x_i = x_i + \Delta x_i
        \]
    end for
end for
Simulation

Construction of the Experimental Environment

The experiment is based on the open source scene graphics engine OSG and the physics engine Bullet. It can render and draw three-dimensional scenes in real time, such as ship motion poses in collision simulation experiments.

The OSG engine and the Bullet engine are combined as shown below [13].

Experimental Parameters and Simulation Results

Based on the collision model of rigid body in the physics engine, combined with dynamic principle during ship collision, Perform 3D simulation on collision response. In the simulation experiment, set the offshore as the scene, and conducted two experiments named as on cross collision and rear-end collision respectively.

The basic parameters of the ship A and ship B in the experiment are shown in table 1. Let ship A and ship B have an initial velocity of 4.5 m/s and angular velocity set to zero. The initial settings of other parameters are shown in table 2.

The change of velocity and six-degree-of-freedom parameters of ship A and ship B before and after the collision in the three-dimensional view are shown in table 2, the three-dimensional simulation effect of the collision response is shown in figure 4 and figure 5.

Table 1. Basic parameters of ship A and ship B.

| Type    | Name               | Length/m | Width/m | Draft /m | Displacement /t |
|---------|--------------------|----------|---------|----------|-----------------|
| Ship A  | bulk cargo ship    | 288.1    | 44.0    | 10.5     | 170162          |
| Ship B  | container ship     | 208.2    | 29      | 10.1     | 27200           |
Table 2. Six degree of freedom parameter changes and velocity changes before and after collision between ship A and ship B in two experiments.

| Parameter | Cross collision | Rear-end collision |
|-----------|-----------------|--------------------|
|           | Before collision | After collision     | Before collision | After collision |
|           | Ship A | Ship B | Ship A | Ship B | Ship A | Ship B | Ship A | Ship B |
| $x$       | -338.21 | -435.67 | -351.04 | -446.02 | -338.21 | -435.67 | -523.34 | -562.31 |
| $y$       | 81.57   | 223.06  | 101.32  | 241.61  | 81.57   | 223.06  | 162.35  | 278.32  |
| $z$       | 0.0000  | 0.0000  | 0.1463  | -1.181  | 0.0000  | 0.0000  | 1.2034  | -2.0351 |
| $\theta$  | 0.1367  | -0.0772 | 0.2927  | -0.123  | 0.2608  | -0.0212 | 0.251   | 0.1312  |
| $\phi$    | -0.0063 | 0.0035  | -0.0122 | -0.008  | -0.0063 | 0.0035  | -0.0063 | 1.0256  |
| $r$       | -0.1427 | 0.0013  | 0.0049  | 0.0083  | -0.1427 | 0.0013  | -0.1427 | -2.154  |
| $v$       |          |         |         |         |          |         |         |         |
| $v_x$     | 3.182   | 3.182   | 1.5231  | 3.3561  | 3.182   | 3.182   | 1.1523  | 5.3011  |
| $v_y$     | 3.182   | 3.182   | 2.4782  | 3.4231  | 3.182   | 3.182   | 1.0403  | 5.1481  |
| $v_z$     | 0.0000  | 0.0000  | 0.0089  | -0.3131 | 0.0000  | 0.0000  | 0.0089  | -0.3131 |
| $w_x$     | 0.0000  | 0.0000  | 0.2213  | 0.2986  | 0.0000  | 0.0000  | -0.5025 | 0.2986  |
| $w_y$     | 0.0000  | 0.0000  | -0.0038 | -0.0131 | 0.0000  | 0.0000  | 0.0121  | -0.0519 |
| $w_z$     | 0.0000  | 0.0000  | 0.0314  | -0.0277 | 0.0000  | 0.0000  | -0.0733 | -0.0066 |

Figure 4. 3D visual simulation of cross collision.

Figure 5. 3D visual simulation of rear-end collision.

Summary

The experimental results show that the ship collision response simulation process conforms to the objective physical laws, effectively improves the realism and fidelity of the visual simulation, and it has certain guiding significance for the trainees to handle similar ship collision accidents. In addition, there are no considerations of complex environmental factors in the collision response phase, such as the constraints of weather, sea conditions, etc. These need to be further studied and improved.

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