A Dynamic Three-dimensional Ship Domain Model for Vessels in Ports Waters

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Abstract. The study of three-dimensional ship domain may significantly benefit the vessels traffic service in ports waters and other restricted waterways. With the rapid development and increasing flourish of maritime transportation, the vessels traffic service by manual power may be too challengeable to handle the complex traffic situation in ports waters. This paper referenced some study on ship domain in the area of marine traffic engineering, then summarised the structure of ship domain and the learning ability of Intelligent Algorithm. A dynamic three-dimensional ship domain was constructed by inputting ship’s dynamic, static and environment information aiming at several influence factors in the system of “ship-environment-management”. The BP neural network was applied to make the three-dimensional ship domain dynamic by automatically change the dimension of ship domain basing on the inputting ship information. A calculating example which collected required vessels’ information in one VTS centre was shown to verify the reliability and practicability of this three-dimensional ship domain model.

Background

It has been over fifty years since the presenting of the concept “ship domain” which has been widely used in research on marine traffic engineering and ship behaviours and played a significant role especially in ship manoeuvring and collision prevention [1,2,3]. For ship domain in ports waters, it takes more complex factors into account than which outside the ports waters as a result of more complicated traffic situation, the limited navigable waters and more sensitive impact to vessel’s navigation. Therefore, the model of ship domain which proposed by Japanese scholar Fujii, British scholar Goodwin, P. A. Davis, Dutch scholar Van Ddr Tak is difficult to be generally applied to the limited waters like ports [1].

The “dynamic” referred in this paper means: By inputting the dynamics, statics and traffic environment information into the Vessel Traffic Service (VTS) systems, the data is gone through centralized processing to generate the adaptive three-dimensional ship domain model.

Dynamic three-dimensional Ship Domain Model

In order to determine the scope of the ship domain, scholars made a lot of research, and achieved a lot results: Fujii proposed an oval model of ship domain by taking a research and analyse on two-dimensional frequency distribution of the relative position of the ships in the coastal waters of Japan. Goodwin built a ship domain model with three sectors according to International Regulations for Preventing Collisions at Sea. Xu Zhouhua, Mou Junmin and others have built a three-dimensional ship domain model for collision avoidance in bridges zone basing on the characteristics of inland waterway [4].
This paper draws on the idea of Fujii, Goodwin, Xu Zhouhua and others [5, 6, 9, 10] to build the ship domain model regarding the ship domain in the ports waters as an elliptical column model inscribed in a cuboid (Figure 1). The major axis length of the elliptical column is the length of the ship domain. Where the minor axis length of the elliptical column is the beam of the ship domain. The height of the elliptical column is the depth below the free surface of the ship (the minimum safety depth).

![Figure 1. Three-dimensional Ship Domain Model.](image)

The construction of the domain is mainly determined by the characteristics of the ports waters themselves. Due to the numerous influence factors, the different natural conditions or various navigating states would make the dimension of the domain obviously dynamic changes even to the same ship. For example, when the ship is in the mooring, the dimension of the model should be an approximate cylinder due to the movement made by anchor chain. When the ship is in normal voyage in the inward and outward channel, the horizontal axis of the ship relating to another ship normally navigating in the channel should be reduced accordingly. In this paper, three-dimensional ship domain model is constructed from two directions—the horizontal plane and the vertical plane.

**Modeling in the Horizontal Plane**

According to the construction of three-dimensional ship domain model above, the horizontal plane is a standard elliptical shape, as shown in Figure 2.

![Figure 2. 3D Model in Horizontal Plane.](image)

The ellipse equation is:
According to figure2-2, the set of reference domain of the ship is:

\[
\frac{y^2}{a^2} + \frac{x^2}{b^2} = 1 \quad (a > b > 0)
\]  

(1)

According to figure2-2, the set of reference domain of the ship is:

\[a = m \cdot \text{LOA}, b = n \cdot \text{LOA}\]  

(2)

Where “m” is “the major axis coefficient of the ship's domain”, “n” is “the minor axis coefficient of the ship domain.”

Y-axis positive direction as the ship's course over ground, each target vessel is shown as rhombus graphics whose size (length and width) is in equal scale to the real ship dimension namely the Length Over All (LOA) and the Beam. The position of the ship's chart in the ship domain is defined as follows: From the lower end of the ellipse, the point B extends along the Major axis, with the scaled length of LOA then it is further extended a distance which is from the position where the antenna is to the position of the ship in GPS display. This is owing to the ship’s latitude and longitude obtained from AIS is the position of ship's GPS antenna on the bridge. In fact, because the AIS antenna and GPS antenna is very close, these two data can be equivalent. "A" is the distance from the bow to antenna where "B" is the distance from the stern to the antenna, and the value of A and B can be applied to calculate the distance between the ship DCPA, TCPA, the ship's graphical position, the bow Location and so on [9].

(1) Analysis of the Influencing Factors of Model

In this paper, the factors accounted which affect the dimension of the ship domain in the horizontal plane contain the speed, draught, type, visibility, wind scale, and LOA, are considered in this paper. The value of a and b is depend on the ship's LOA, speed, draught, ship type, visibility and wind scale.

(2) The Establishment of the Model

This paper chooses the BP neural network model of single hidden layer aiming at the characteristics of ship domain in ports waters. It selected the factors that affect the ship domain, including ship speed, draught, ship type, visibility and wind scale as the research object. Major axis coefficients and minor axis coefficients are the output. The network layer diagram is shown in Figure 3.

![Figure 3. BP Neural Network Layer Map.](image)

In this paper, Matlab software was applied. The variables such as speed, draught, ship type, visibility and wind scale were set as the input data while the ship domain dimension (major axis coefficient m and minor axis coefficient n) was set as the output empirical data which were learnt by the network. The mapping relationship between the dimension of ship domain and speed, draught, ship type, visibility, wind scale was obtained by network training into which the sample
data investigated from VTS center were substituted. After that, the major axis coefficients m and minor axis coefficients n of the ship domain can be derived from the real ship data input [7].

BP neural network algorithm steps are stated as follows:

1. Extraction of target characteristics
The data such as ship speed, ship drought, ship type, visibility and wind scale are selected as the characteristic factors of the target ship synthetically considering the traffic environment, ship static and dynamic parameters, basing on the knowledge of the current research of ship domain all over the world. The types of ship are divided into: dangerous goods ships, passenger ships and other types of ships, represented with the number of 3, 2, 1 to simplify the calculation of the model.

2. Set the input node
For the input nodes of the network, five factors are selected from the various factors affecting the ship domain in the “ship-environment” system: ship speed, ship draught, ship type, visibility and wind scale. The five input nodes consist of the input vector \( P = (Sp, Dr, Ty, Vi, Wi) \).

3. Normalize the input sample
In this paper, the premnmx function, namely Deviation standardization, is applied to normalize the sample matrix to the interval between \([-1,1]\). The functional expression is:

\[
y = \frac{2(x - \text{min})}{(\text{max} - \text{min})} - 1
\]  

Where “max” represents the maximum value of the measured data of the same index, and “min” represents the minimum value of it.

4. The number of the neuron nodes in the hidden layer
The number of hidden neuron nodes is significant to network training, and it will affect the property of network training if the nodes are larger or smaller, and even worse directly leading the network training to a failure. This paper intends to use empirical formula:

\[
s = \sqrt{n + m + a}
\]  

Where “n” refers to the number of input nodes, “m” refers to the number of output nodes, “s” refers to the number of hidden layer nodes. For the value of “a”, round it between 1 ~ 10 in general, and then change it according to the effect of network training. The network nodes in the hidden layer were dynamically adjusted using the program, and the situation of the network training was observed to determine the best number of nodes in the hidden layer.

5. Set the output nodes
The expected results of this paper are the major axis and minor axis of the ship domain, so that two output nodes are set.

6. Training network
The sample data selected includes speed, draught, ship type, visibility, wind scale, ship's major axis, minor axis and so on, which basically covers the most types of ship in ports. It makes the training network more completed to adapt to the needs of the ship domain model basically.

The network flow chart is shown as Figure 4.

In order to simplify the calculation, in the network training process, the premnmx function is applied to normalize the data, the logsig is applied as transfer function in the unit of hidden layer, the purelin function is applied as transfer function in the unit of output layer, the traingdx is applied to calculate in the study of network which is the training function learning adaptively with gradient decent.

The BP neural network algorithm is used to train the sample data. When the dynamic and static information such as the speed, draught, ship type, visibility and wind scale of the ship are input again, the major axis coefficient “m” and the minor axis coefficient “n” of the horizontal plane of the target ship can be produced adaptively, and then the ship domain model dimension can be calculated according to the formula 1 and 2.
Modeling in the Vertical Plane

When ship navigating in the ports waters, it is necessary to avoid the occurrence of collision accidents, but also to prevent stranded accidents. Therefore, in this paper the mathematical model below the horizontal plane is built to provide a theoretical basis for warning the risk of stranding. According to the three-dimensional ship domain model built previously, the following model below the horizontal plane is determined as shown in Figure 5.

![Flow Chart of Network Training](image)

**Figure 4. Flow Chart of Network Training**

![3D Ship Domain Model Below the Horizontal Direction](image)

**Figure 5. 3D Ship Domain Model Below the Horizontal Direction.**

The three-dimensional ship domain below the horizontal plane is rectangular whose equation is:
The value of "c" is the depth below the surface of the ship domain. To determine the dimension of the model below the horizontal line, the value of "c" is required, namely the minimum safety depth.

The factors taken into account in the minimum safety depth of navigating ships include the value of draught and surplus depth. That is to say the minimum safety depth should be equal to the sum of the ship draught and the surplus depth. Draught (c_0) can be get directly from the ship's AIS information. In this paper, the main factors affecting the surplus depth are: hull squat value c_1, the minimum surplus depth under the keel of the navigation of ships c_2, the surplus depth of the waves c_3, and the surplus depth of trim C_4. The other changes of the minimum safety depth due to error or water density are not taken into account here [8].

According to the formulas given in the relevant references, the minimum safe depth is calculated as follows:

\[
c = c_0 + c_1 + c_2 + c_3 + c_4
\]

\[
c_0 = \text{ship draught}
\]

\[
c_1 = V^2 /100
\]

\[
c_2 = f(DWT,S_p)
\]

\[
c_3 = \begin{cases} 
0.0 \text{ (Full cover, Ports Waters)} \\
0.15 \text{ (Semi Cover, Ports Waters)} \\
0.30 \text{ (No cover, Ports Waters)} 
\end{cases}
\]

\[
c_4 = \begin{cases} 
0.30 \text{ (Ro Ro, DWT \leq 1000t, GT \leq 3000t)} \\
0.20 \text{ (Ro Ro, DWT > 1000t, GT > 3000t)} \\
0.15 \text{ (Oil tanker and Bulk Carrier)} \\
0 \text{ (Other vessels)} 
\end{cases}
\]

Where S_p means Soil property and Ro Ro means Roll-on Roll-off ships.

The information collected includes the draught, speed, dead weight ton, type of the ship, the cover condition of the ship navigating waters and the seabed soil property. The information would be taken into the formula 6, 7, then the three-dimensional ship domain model is obtained.

The two models above are spatially synthesized to obtain a three-dimensional ship model as shown in Fig. 6, and build a space cartesian coordinate system basing on it.

\[
-b \leq x \leq b
\]
\[
-c \leq z \leq 0
\]

The 3D ship domain model equation can be derived:
Calculation example of Three-dimensional Ship Domain

Calculation of 3D Ship Domain in Horizontal Plane

The sample data collected from Qingdao VTS centre would be input into the network training to construct a mapping relation between the input data and output data, then the ship domain in horizontal plane was acquired. Figure 7 below shows that the data reached the correlation standard after 392 times training.

![Figure 7. Network Training Result.](image)

After that, the real-time data from 20 vessels collected from VTS center would be put into the trained network. The range of the LOA of vessels is from 66.28m to 333m, the range of speed is 3.5 knots to 12.3 knots, the range of draught is 3m to 12m, the range of visibility is 2 nautical miles to 7 nautical miles, the range of wind scale is light breeze to fresh breeze, the vessel type includes normal vessels (1) and dangerous cargo vessels (3). Table 1 only shows 5 vessels data as examples.

<table>
<thead>
<tr>
<th>Vessel</th>
<th>LOA (m)</th>
<th>Speed (Knots)</th>
<th>Draught (m)</th>
<th>Visibility (nmi)</th>
<th>Vessel Type</th>
<th>Wind Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vessel-1</td>
<td>212.6</td>
<td>9.8</td>
<td>11</td>
<td>7</td>
<td>1</td>
<td>Fresh breeze</td>
</tr>
<tr>
<td>Vessel-2</td>
<td>117.27</td>
<td>8.4</td>
<td>5.7</td>
<td>4</td>
<td>3</td>
<td>Moderate breeze</td>
</tr>
<tr>
<td>Vessel-3</td>
<td>182.5</td>
<td>9.9</td>
<td>12</td>
<td>5</td>
<td>3</td>
<td>Gentle breeze</td>
</tr>
<tr>
<td>Vessel-4</td>
<td>66.28</td>
<td>3.5</td>
<td>3</td>
<td>4</td>
<td>1</td>
<td>Moderate breeze</td>
</tr>
<tr>
<td>Vessel-5</td>
<td>243.8</td>
<td>6</td>
<td>8.2</td>
<td>4</td>
<td>3</td>
<td>Moderate breeze</td>
</tr>
</tbody>
</table>

Then the major axis coefficients and minor axis coefficients of those 20 vessels in the horizontal plane of ship domain can be obtained. Table 2 shows the calculated major axis and minor axis of the 5 vessels in table 1.
Table 2. Output Data.

<table>
<thead>
<tr>
<th></th>
<th>10.99337</th>
<th>9.152286</th>
<th>11.97245</th>
<th>1.392103</th>
<th>6.636645</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major axis</td>
<td>2.894229</td>
<td>2.326529</td>
<td>3.097194</td>
<td>0.447298</td>
<td>1.754169</td>
</tr>
</tbody>
</table>

The first line in Table 2 is the major axis \( m \) of ship domain, while the second line is the minor axis \( n \) of ship domain. The dimension of ship domain in horizontal plane can be derived from the function: \( a = m \text{LOA}; b = n \text{LOA} \).

**Calculation of the 3D Ship Domain in Vertical Plane**

Through the data collected in Chapter 3.1, the minimum safety depth \( c \) of 20 vessels can be calculated based on the speed, draught, deadweight tonnage, cover condition and soil property. The cover condition includes no-cover, semi-cover and full-cover; the soil property includes mud soil, dense sandy soil and median sandy soil. The deadweight tonnage ranges from 1323 tons to 150166 tons. Table 3 shows the specific required data of the 5 vessels in Table 1 as examples.

<table>
<thead>
<tr>
<th>Vessel</th>
<th>Speed (Knot)</th>
<th>Draught (m)</th>
<th>Deadweight ton</th>
<th>Cover Condition</th>
<th>Soil property</th>
<th>Minimum Safety Depth ( c ) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vessel-1</td>
<td>9.8</td>
<td>11</td>
<td>150166</td>
<td>No-cover</td>
<td>Median sandy soil</td>
<td>12.8104</td>
</tr>
<tr>
<td>Vessel-2</td>
<td>8.4</td>
<td>5.7</td>
<td>7864</td>
<td>Full-cover</td>
<td>Mud soil</td>
<td>6.9056</td>
</tr>
<tr>
<td>Vessel-3</td>
<td>9.9</td>
<td>12</td>
<td>95752</td>
<td>No-cover</td>
<td>Mud soil</td>
<td>13.6801</td>
</tr>
<tr>
<td>Vessel-4</td>
<td>3.5</td>
<td>3</td>
<td>1323</td>
<td>Full-cover</td>
<td>Dense sandy soil</td>
<td>3.5725</td>
</tr>
<tr>
<td>Vessel-5</td>
<td>6</td>
<td>8.2</td>
<td>95752</td>
<td>No-Cover</td>
<td>Mud soil</td>
<td>8.86</td>
</tr>
</tbody>
</table>

Eventually, the dimension of the three-dimensional ship domain of 20 vessels can be determined by the major axis \( a \), minor axis \( b \) and the Minimum Safety Depth \( c \) through equation 8.

**Conclusion**

In this paper, a dynamic three-dimensional ship domain was constructed by inputting ship’s dynamic, static and environment information aiming at several influence factors in the system of “ship-environment-management”. The BP neural network was applied to make the three-dimensional ship domain dynamic by automatically change the dimension of ship domain basing on the inputting ship information. A calculating example which collected required vessels’ information in one VTS centre was shown to verify the reliability and practicability of this three-dimensional ship domain model.

However, there are many other factors can be studied in the future work. For instance, the wave, currents, human effects and other factors which would made the model more completed if taken into accounts.

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**References**


