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Research Article

Modeling and Simulation of Environmental Disturbances for Six degrees of Freedom Ocean Surface Vehicle

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Abstract

In this paper we focused on Modeling and Simulation of environmental disturbances for ocean Surface Vehicle. We developed ship simulation system for simulating ship motion in a virtual environment with respect to environment disturbances such as sea wave, wind and sea currents. This system simulates ship motions in six degrees of freedom, pitch, heave, roll, surge, sway, and yaw. This system is simple and responds in real-time to interactions and it is based on a mathematical ship model. The mathematical ship model is derived from the non-linear speed equations, Newton's laws, fluid dynamics and other basic physics. We use multivariable functions to model the ocean surface with superposition of sinusoid functions and the ship model requires fewer amounts of ship data and the mathematical ship model can be used with different types of ships and it can be used in real time virtual reality applications.

1. INTRODUCTION

Modeling and Simulation of environmental disturbances for ocean Surface vehicle have been used in ship simulators for naval training, ship hull designing, simulates military science and entertainment activities such as computer games. There are commercial ship simulation systems with six degrees of freedom such as *Transas and Oceaniccorp* simulation systems [1,2]**.** These systems use six degrees of freedom ship motion prediction algorithms with environmental disturbance simulations but those systems extremely expensive, too complicated and proprietary.

There are many real-time and none real-time ship motion prediction algorithms proposed by various researches around the world. Most of them are three to four degrees of freedom ship motion prediction algorithms [3 – 6]. There are few six degrees of freedom (6DOF) ship motion prediction algorithms proposed my researchers [7,8]. However those six degrees of freedom ship motion prediction algorithms are not capable

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of predicting real-time 6DOF ship motions with respect to environmental disturbances. Some those algorithms have large number of model parameters or over simplified and some real world scenarios cannot be simulated.

2. RELATED WORK

Some numerical algorithms are based on strip [6, 9]. *Salvesen et al.*. presented strip theory based method for predict heave, pitch, sway, roll and yaw motion as well as wave-induced vertical and horizontal forces blending moments and moments in regular waves [6]. Comparison between computed motions and experimental motions show satisfactory agreement in general. However this numerical procedure is impractical for real time simulation because these strip theory based ship motion predictions need hours to produce a set of accurate solutions for just one or two motions by using modern computers. *Journée* present Quick Strip Theory Calculations for ship motion prediction [9]. This approach describes a strip theory based calculation method which delivers information on ship motions and added resistance within a very short computation time. A comparative validation is done but it is more suited for ship hull design and cannot be used for real-time ship motion simulations. *Fossen and Smogeli* presented strip theory formulation for dynamic ship motion prediction [10]. In their approach, a computer effective nonlinear time-domain strip theory formulation for low-speed applications has been presented. The proposed model can be used to simulate real-time ship motion prediction and it is possible to incorporate the effect of varying sea states. However, the model is suited for low speed maneuvers and model parameters were evaluated by using a proprietary product.

Some other studies have been carried out for predict ship motion utilizing the Kalman Filter approach [11]. *Triantafyllou et al.* utilized Kalman filter techniques with simplified computational ship models for ship motion prediction. In this study, the equations of motion as derived from hydrodynamics and approximations used with Kalman filter technique. The influence of the various parameters are evaluated. However, their method requires specific model parameters, and if the ship parameters are unavailable their method is not applicable.

Xiufeng et al. developed a mathematical models for realtime ship motion simulation [12]. They estimate the total forces acting on the ship first, then based on Newton's law, they deduce first order differential equations to model the relation between forces and accelerations. The equations are solved by using Runge– Kutta method. Their applications focus on handling ships in selected area such as inside or near harbor areas, only the physics models for surge, sway, and yaw are given and they haven't discussed the possibility to simulate existing real ships with their simulation system.

Another work is presented by *Cieutat et al.* [13] and they proposed wave models based on the work of *Alain Fournier and William T Reeves* [14]. This approach describes a new efficient real-time model of wave propagation and shows its integration in a real maritime simulator. They determine heave, pitch, and roll of a ship by using sea surface height under the ship. For estimating pitch and roll, the tangent plane of sea surface is computed first. Then the ship is rotated such that its orientation is aligned with the tangent plane. Their ship motion prediction algorithms are too simple and ships of different shapes will produce the same behavior if the wave condition is the same. Consequently their method is not flexible enough to simulate the behaviors of different ship models.

X Zhao et al. presented development of a high performance ship-motion prediction method [15]. Simulation results show that this method can predict ship motion with good accuracy. This is suitable for short-term motion prediction but not suitable for longer time real-time ship motion predictions.

Ching-Tang Chou, and Li-Chen Fu presented a 6 degree-of-freedom real-time ship motion simulation system [7]. They focused on the construction of the physical dynamics of the ship on virtual reality environment. The real force and torque of ship are modeled according to Newton-Euler Formula according to the calculation of the volume below the ocean surface. They presented a new algorithm which can approach the dynamics of the ship in real-time. They introduced their real-time ship motion prediction algorithms only for Deep Ocean. They have not represented the excess drag force due to combination of yaw and sway and they did not discuss the possibility of simulating existing real ship with their virtual environment.

Gatis Barauskis and Peter Friis-Hansen presented 3 degrees of freedom ship dynamic response model [3] which can predict surge, sway and yaw. They focused on CPU time required for ship motion prediction, ability of simulating complex non-linear models and availability of determine ship model parameters for the different type of existing ships. The model consists of non-linear speed equation; linear first order steering equation called *Nomoto* model [16, 17] and linear sway equation. The model response in real-time for rudder and throttle commands. This ship model is able to operate on a limited number of model parameters. Apart from ship main data, which can be determined rather easily from databases such as Lloyd's register [18] or those ship model parameters can be estimated by using standers maneuvering tests [16]. This model represents the added mass /excess drag force due to combined yaw and sway motion.

Ueng et al. presented efficient computational models for ship motions simulation [8]. These models are used to simulate ship movements in real time. Six degrees freedom ship motions (pitch, heave, roll, surge, sway, and yaw) are divided into two categories. The first three movements are induced by sea waves, and the last three are caused by propellers, rudders and other environment disturbances. Newtonian dynamics, fluid dynamics and other theories in physics are used to develop algorithms. This method can be used to predict real time ship motions with high CPU effectiveness. The model does not represent the added mass / excess drag force due to combined yaw and sway motion. It is a considerable deviation from the real world scenario. They haven't discussed the mechanism to determine unknown model parameters and they have not done validation with respect to real world ship scenarios.

There are a number of proposed mathematical ship models such as *Tristan P´erez and Mogens Blanke* [4], *Tristan Perez and Thor I. Fossen* [19] and *Anna Witkowska et al.* [20] However possibility of integrating those mathematical ship models with real-time applications is not discussed.

After studying all these approaches we found out that the three degrees of real-time ship motion algorithms proposed by *Gatis Barauskis & Peter Friis-Hansen* [10] and the six degrees of real-time ship motion algorithms proposed by *Shyh-Kuang Ueng et al.* are very effective from different perspectives. Based on these two approaches we proposed more effective and productive real-time six degrees of freedom algorithms.

3. Description of the Model

The motion of a floating rigid body on calm fluid surface can be specified by Newton's laws, fluid dynamics and other basic physics, but the motion of a floating rigid body in ocean surface is extremely complicated and difficult to predict. All six possible degrees of freedom (6DOF) in a motion of a ship can be illustrated in Figure 1. Surge, heave, and sway are translational motions. Roll, yaw, and pitch are rotational motions [5, 21].

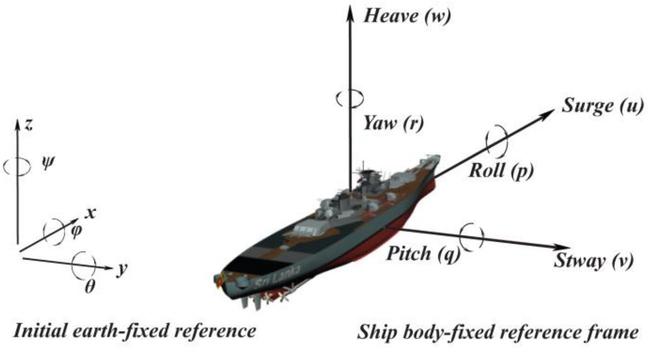

Figure 1: Six possible degrees of freedom coordinate systems [5]

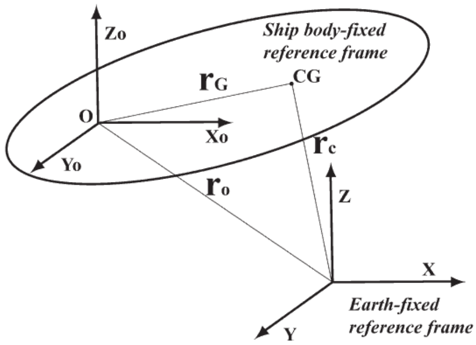

Figure 2: Reference frames and ship motions [21]

Following assumptions were made in order to simplify the mathematical ship model for real-time challenges.

- The pitch, heave and roll motions are caused by sea waves. Surge, sway, and yaw motions are induced by internal and external forces such as rudders, propellers and environment conditions such as wind and see currents.

- Figure 1 illustrate the initial earth-fixed reference frame with $[x\ y\ z]^T$ coordinate system and the ship body-fixed reference frame with $[x_o\ y_o\ z_o]^T$ coordinate system. Ship body-fixed axes coincide with the principal axes of inertia. Origin of the ship body-fixed frame coincide with the center of gravity of the ship ($r_G = [0\ 0\ 0\ ]^T$) [5].

- The ship is rigid and impossible to deform. The shape of the ship is identical to a cubical.

- Sea currents and wind acts two dimensionally and parallel to XY plane

- The sea waves consist of sinusoidal waves and waves can apply force and moments (Torque) on the ship. However ship cannot influence the wave. The variation of the sea surface is less than or equal to beaufort's sea state 4 [16].

- Sea surface currents can apply force on the ship. However deep sea currents cannot influence the ship.

The magnitudes of the position, orientation, forces, moments, liner velocities and angular velocities are respectively denoted by $[x\ y\ z]^T$, $[\psi\ \theta\ \varphi]^T$, $[X\ Y\ Z]^T$, $[K\ M\ N]^T$, $[u\ v\ w]^T$ and $[p\ q\ r]^T$ as shown by Table1. The position-orientation vector in the XY plane is expressed as $\eta = [x\ y\ \psi]^T$ and the linear-angular velocity vector is expressed as $v = [u\ v\ r]^T$. The rate change of Position-orientation vector is expressed as

$$\dot{\eta} = R(\psi)v \ [4] \qquad \text{where} \qquad R(\psi) = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix}. \qquad (1)$$

Table 1: Six possible degrees of freedom ship motion [5]

Degrees of freedom	Forces Moments	Linear/Angular Velocities	Positions Euler Angles
Surge	X	u	x
Sway	Y	v	y
Heave	Z	w	z
Yaw	N	r	ψ
Pitch	M	q	θ
Roll	K	p	φ

3.1 Wave Model

We use multivariable ocean wave model introduced by *Ching-Tang* [22] to model the sea surface and determine the height field of the sea surface. In that model,

$$h(xyt) = \sum_{i=1}^{n} A_i sink_i\,[(xcos\theta_i + ysin\theta_i) - \omega_i t + \varphi_i\,]\,. \tag{2}$$

Above function represents a water surface height on the Z axis direction. A is the wave amplitude, k is the wave number where this number is defined as 2π /λ by the wave length λ. ω is the pulsation which is defined as the 2πf *by* the frequency f. A , k , and f are time (t) dependent variables. θ is the angle between X axis and the direction of the wave. φ is the initial phase which can be selected randomly between 0 - 2π.

3.2 Wind Model

We derived simplified two dimensional wind model by using two mathematical wind models introduced by Thor I Fossen & Monika Bortnowska [5, 23] .The resultant wind force acting on a surface vessel is defined in terms of relative wind speeds u_{Wind} and v_{wind}

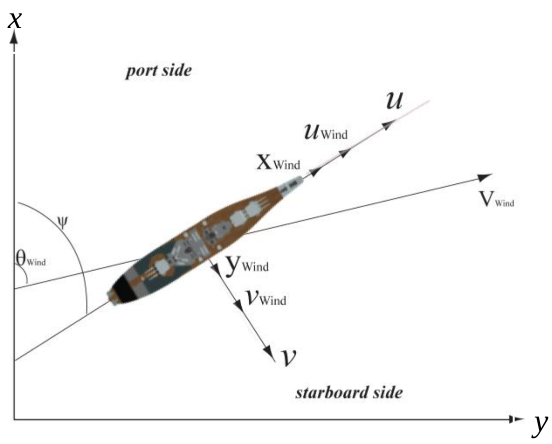

Figure 3: Two dimensional wind model

as illustrated in figure 3. θ_{wind} is the angle between X axis and the direction of the wind. Then u_{Wind} and v_{wind} determined as follows.

$$u_{wind} = V_{wind}\cos(\theta_{wind} - \psi) - u$$
$$v_{wind} = V_{wind}\sin(\theta_{wind} - \psi) - v$$

X_{wind} and Y_{wind} the resultant wind forces acting on a surface vessel with respect to ship fixed reference frame.

$$X_{wind} = \frac{1}{2} R_{wx} \rho_{air} A_T (u_{wind})^2 \quad (3)$$

$$Y_{wind} = \frac{1}{2} R_{wy} \rho_{air} A_L (v_{wind})^2 \quad (4)$$

R_{wx} - wind resistant coefficients, ρ_{air} - density of air, A_T - transverse wind projected area *(l* x *d/2)*, A_L - lateral wind projected area *(w* x *d/2)*.

3.3 Sea Current Model

We derived a simplified two dimensional current model by using two mathematical wind models introduced by Thor I Fossen & Monika Bortnowska [5, 23].The resultant wind force acting on a surface vessel is defined in terms of relative current speeds $u_{current}$ and $v_{current}$ illustrated in Figure 4.

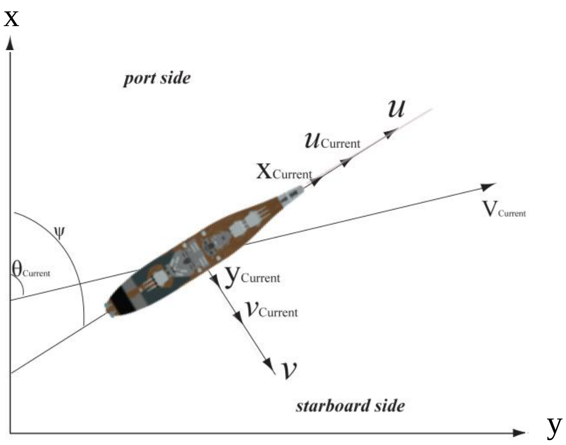

Figure 4: Two dimensional current model

$\theta_{current}$ is the angle between X axis and the direction of the wind. Then $u_{current}$ and $v_{current}$ determined as follows.

$$u_{current} = V_{Current}\cos(\theta_{current} - \psi) - u$$
$$v_{current} = V_{Current}\sin(\theta_{current} - \psi) - v$$

$X_{current}$ and $Y_{current}$ the resultant wind forces acting on a surface vessel with respect to ship fixed reference frame.

$$X_{current} = \frac{1}{2} R_{wx} \rho_{water} A_T (u_{water})^2 \quad (5)$$

$$Y_{current} = \frac{1}{2} R_{wy} \rho_{water} A_L (v_{water})^2 \quad (6)$$

R_{wx} - Current resistant coefficients, ρ_{water} - density of water, A_T - transverse current projected area *(l* x *d/2),* A_L - lateral current projected area *(w* x *d/2)*

4. Motions Induced by Propellers, Rudder, Wind and sea Current

4.1 Surge Motion

The surge motion of a ship is described by a simplification of the non-linear speed equation as follows [5] [24].

$$M\dot{u} = T_e - X_{u|u|}u|u| - (M + X_{vr})vr + X_{wind} + X_{current} \quad (7)$$

In equation (7) M and T_e respectively denote the ship's mass and single driving force (effective propeller thrust) that is transmitted from the ship engine by her propellers. The two terms $X_{u|u|}u|u|$ and $(M + X_{vr})vr$ can be regarded as damping forces, which depend on the instantaneous dynamics of the vessel. $(M + X_{vr})vr$ represents excess drag force due to combined yaw and sway motion. $X_{u|u|}u|u|$ correspond to the quadratic resistance force at the forward speed *u*. When the ship traveling a straight course and at a constant speed *u*, $(M + X_{vr})vr = 0$ and $0 = T_e - X_{u|u|}u|u|$. Then, if we know T_e and *u* then it is possible to calculate the $X_{u|u|}$. The force of the propeller is related to its revolution speed *n*, the diameter *D* and the thrust coefficient K_t . It is given by $T_e = K_t n^2 D^4$ [25]. $X_{vr} = 0.33\ M$ [4].

4.2 Sway Motion

Sway motion is considered based on the wind and sea current. Rudder movements can induce forces for sway motion but it is comparatively very small.

$$M\dot{v} = Y_{wind} + Y_{current} - Y_{v|v|}v|v| - (M + Y_{ur})ur \quad (8)$$

In equation (8) $Y_{v|v|}v|v|$ is correspond to the quadratic resistance force at the sway speed *u and* $(M + X_{ur})ur$ represents excess drag force due to combined yaw and surge motion. When the ship traveling in a calm sea at a constant speed *u* with a little rudder angle, $Y_{v|v|}v|v| = (M + Y_{ur})ur$. Then, if we know *v, r* and *u* then it is possible to calculate the $Y_{v|v|}$. $Y_{ur} \approx 0.36\ M$ [4].

4.3 Yaw Motion

Yaw motion is considered based on the rudder Moment and it is based on rudder angle, rudder area, and square of the fluid flow passing through the rudder. Development of computational rudder is extremely difficult, it is depend on lot of physical and mechanical variables. We considered simplified rudder model consist with rudder moment M_{rudder} and anti rudder moment M_{resist} [4, 25].

$$M_{\text{rudder}} = K_{rd} A_{rd} \left|V_{av}\right|^2 \theta_{rud} \qquad (9)$$

where θ_{rud} , A_{rd} and V_{av} represent rudder, rudder area angle and average fluid flow passing through the rudder. Approximately V_{av} can be assumed as a fraction of forward speed u . *i.e.* $(V_{av})^2 = K_f u^2$, K_f is a coefficient represent static condition between effective thrust and resistance .

$$\text{M}_{\text{ressist}} = B_y I_y r \quad \text{where } I_y = (1/12)\,(l^2 + w^2)$$

Then the net moment for yaw N, yaw angular acceleration ($\dot{r}$) and yaw angular velocity (r) is determined as follows [26]:

$$N = M_{rudder} - M_{ressist} \quad ; \quad N / M = \dot{r}\,; \quad \dot{r}\Delta t = \Delta r$$

5 Motions Caused by Sea Waves

By Using above nine equations we can compute the ship's position orientation vector in the XY-horizontal plane with respect to time. That means we can calculate x, y, u, v and ψ. Then according to Archimedes' principle we assume the translational motion (heave) and rotational motions (pitch, and roll) are generated by the swellness of water under the ship. It can be calculated by using the height variation of the sea surface. We assume that the shape of the ship is cubical as illustrated in Figure 5 and the ship body is vertically projected onto the sea surface to get the $l \times w$ bounding box. It is divided in to $1m \times 1m$ cells for mathematical convenience as illustrated in Figure 6**.** We evaluate the height fields at center points of each $1m \times 1m$ cells and we assume the ship is not actually presented when the height field is calculated. We can use *Ching-Tang's* wave model [22] to calculate height fields. We assume that the projected bounding box and its points move with the ship. Then, any time we can calculate height fields according to ship's orientation and the wave propagation. We can obtain forces and moments to generate the heave, pitch and roll motions by calculating the height fields for overall bounding box, calculating difference of height fields between the front and rear halves of the bounding box and calculating difference of height field between the Port and starboard halves of the bounding box respectively.

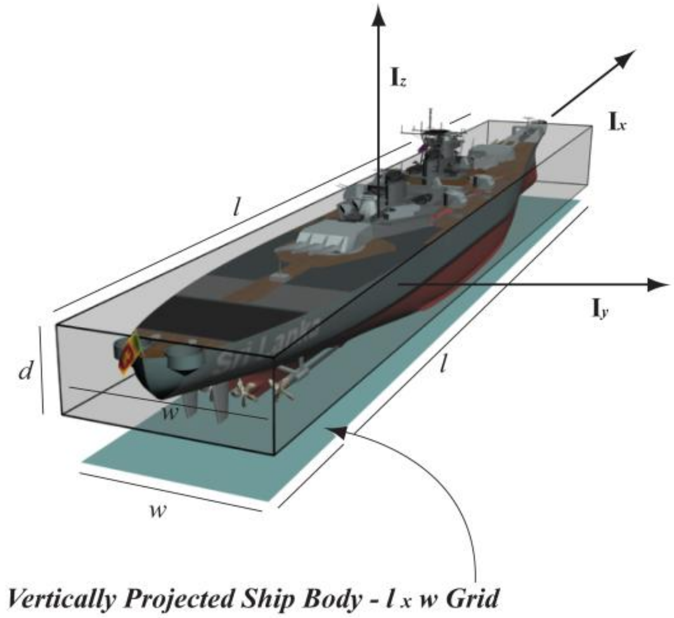

Figure 5: The shape of the ship is identical to a cubical

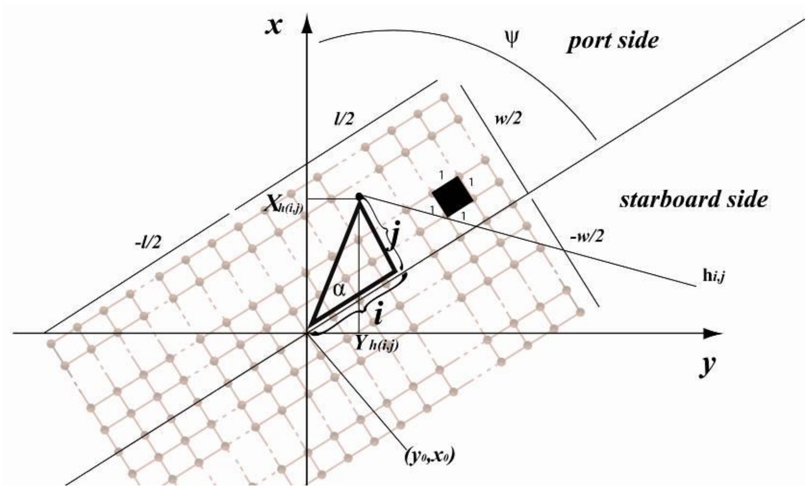

Figure 6: Vertically projected ship body ($l \times w$ grid)

5.1 Heave Motion

First we calculate the vertical variation (height fields) of each $1m \times 1m$ cells. If the some of height fields is not zero the swell of the sea surface generate the force to raise up or pull down the ship. The sum of height fields is H_a and $h_{i,j}$ denote the height field of (i,j) point with respect to vertically projected ship body ($l \times w$ grid).When we know the ship's position in YX plane $(y_{ox}x_o)$ and the heading (Euler Angle - ψ) with respect to positive X-axis , we can compute the earth fixed coordinate $(y_{hi,j}, x_{hi,j})$ for each and every ship fixed coordinate $h_{i,j}$ in vertically projected ship body ($l \times w$ grid) as illustrated in Figure 6. The height field of (i,j) point in the vertically projected ship body is equivalent to the height field of $(Y_{h(i,j)}, X_{h(i,j)})$ point in earth fixed coordinate system. Height fields of earth fixed coordinates can be calculated by using *Ching-Tang's* wave model [22]. i.e.

$h(i,j,t) = h(Y_{h(i,j)}, X_{h(i,j)}, t), Y_{h(i,j)} = \sqrt{i^2 + j^2}\ \sin(\psi - \alpha)$, $X_{h(i,j)} = \sqrt{i^2 + j^2}\ \cos(\psi - \alpha)$ and $\alpha = \tan^{-1} j/i$.

The sum of height fields in vertically projected ship body (l × *w* grid) $H_a = \sum_{i=\frac{-l}{2}}^{\frac{l}{2}} \sum_{j=\frac{-w}{2}}^{\frac{w}{2}} h_{i,j}$.

The force for heave motion is can be calculated by multiplying the sum of the height fields and Sea water density (S_w). The net force for heave motion (F_h) can be calculated by subtracting the resistance force (R_h). K_h , $M, \dot{w}, w$ denote the resistance coefficient for heave motion, Mass of the ship, heave acceleration and heave velocity [16]. The equations are listed below.

$$R_h = K_h M\,|w|^2\ ;\ F_h = H_a S_w - R_h;\ \dot{w} = F_h/M\ ; \qquad \dot{w}\Delta t = \Delta w$$

5.2 Pitch Motion

Here we assume that pitch is determined by the difference of height field between front and rear halves of the ship. H_p is the height field deference between the front and rear halves of the ship.

$$H_p = \sum_{i=\frac{-l}{2}}^{\frac{l}{2}} \sum_{j=\frac{-w}{2}}^{\frac{w}{2}} h_{i,j} \frac{i}{|i|}$$

By using *Ching-Tang's* wave model [22], $h_{i,j}$ can be calculated. Then the net force for pitch (F_p), pitch angular acceleration ($\dot{q}$) and pitch angular velocity (q) is determined as follows:

$$R_p = K_p I_p q\ ;\ F_p = K'_p H_p S_w - R_p;\ \dot{q} = F_p/I_p\ ;\ \dot{q}\Delta t = \Delta q$$

where S_w, K_p, R_p, I_p, and K'_p denote the sea water density, resistance coefficient for pitch motion, resistance force against pitch motion, the ship's moment of inertia along Y-axis and coefficient for pitch motion respectively. For mathematical convenience we assumed the shape of the ship is cubical as shown in Figure 3; then $I_p = \frac{1}{12} M(l^2 + d^2)$.

5.3 Roll Motion

Here we assume that roll is determined by the difference of height field between the port side and starboard side halves of the ship. H_r is the height field deference between the port side and starboard side halves of the ship.

$$H_r = \sum_{i=\frac{-l}{2}}^{\frac{l}{2}} \sum_{j=\frac{-w}{2}}^{\frac{w}{2}} h_{i,j} \frac{j}{|j|}$$

Then as we did in the pitch motion calculations we can calculate net force for roll motion, roll angular acceleration and roll angular velocity.

6 System Overview

The system consists of two major stages. First stage is to compute ship's position and orientation in XY plane by using ship's physical data, user defined dynamic properties (Rudder, Engine RPM) and resistance forces due to motion. The second stage is compute heave, pitch and roll motion by using the out puts of the first stage and additionally considering the ocean wave model as illustrated in Figure 7. In this system, we use constraints, coefficients and parameters but those are can be evaluated by standers techniques [16] or we can figure out reasonable values for multipurpose naval vessel data published by various research institutes [4].

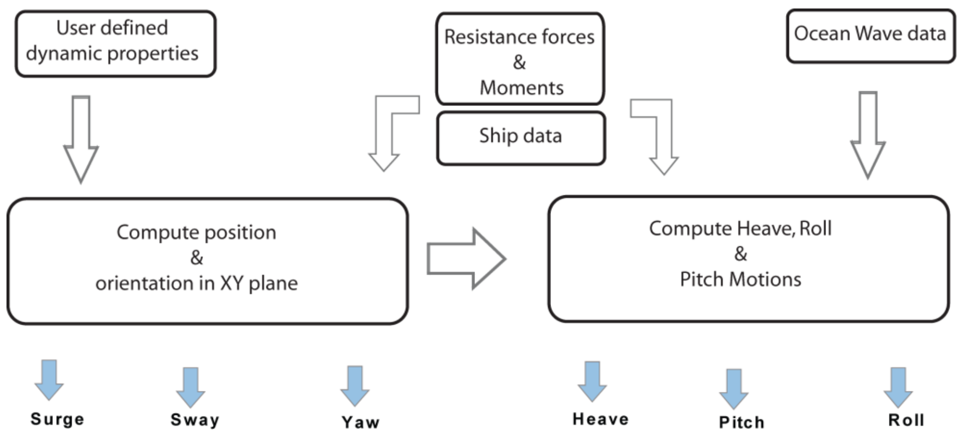

Figure 7: Structure of the motion prediction system

7. Experimental Simulation

We used multipurpose ship data published by Danish navel material command & Danish maritime institute [4]. Ship's length, beam, draft, mass and maximum effective thrust are respectively 48 m, 8.6 m, 2.2 m, 35.6 x 10^4 kg and 15.0 x 10^4 N. We implement the proposed ship motion prediction system with MATLAB Simulink **[27]** environment. All experiments were done with Intel Pentium computer equipped with 2.8 GHz CPU, 1 GB RAM. During the experiments reasonable and most responsive sinusoid ocean wave was considered (Amplitude - 2m, Wave length- 6m, Frequency - 0.4Hz, Initial phase - 0^0). We did Turning tests in order to compare our simulated ship and real world scenarios while observing the six degrees of freedom ship motion with respect to environment disturbances.

7.1 Simulation Results

Above mention wave condiions were simuated and rudder angle fixed at 0^0.In this first experement we assummed sea curent speed is zero ($V_{current} = 0$), rudder angle ($\theta_{rud} = 0$) *and* ship engine generate constant effective thrust (T_e =15.0 x 10^4 N) . θ_{wind} - the angle between X axis and the direction of the wind and V_{wind} – Speed of the wind were assumed as given below.

- θ_{wind} =-30^0, V_{wind} = 2.5 ms^{-1}, $V_{current}$ = 0, θ_{rud} = 0 and T_e =15.0 x 10^4 N
- θ_{wind} = 30^0, V_{wind} = 2.5 ms^{-1}, $V_{current}$ = 0, θ_{rud} = 0 and T_e =15.0 x 10^4 N
- θ_{wind} = 60^0, V_{wind} = 2.5 ms^{-1}, $V_{current}$ = 0, θ_{rud} = 0 and T_e =15.0 x 10^4 N
- θ_{wind} = 90^0, V_{wind} = 2.5 ms^{-1}, $V_{current}$ = 0, θ_{rud} = 0 and T_e =15.0 x 10^4 N
- θ_{wind} = 90^0, V_{wind} = 4.0 ms^{-1}, $V_{current}$ = 0, θ_{rud} = 0 and T_e =15.0 x 10^4 N

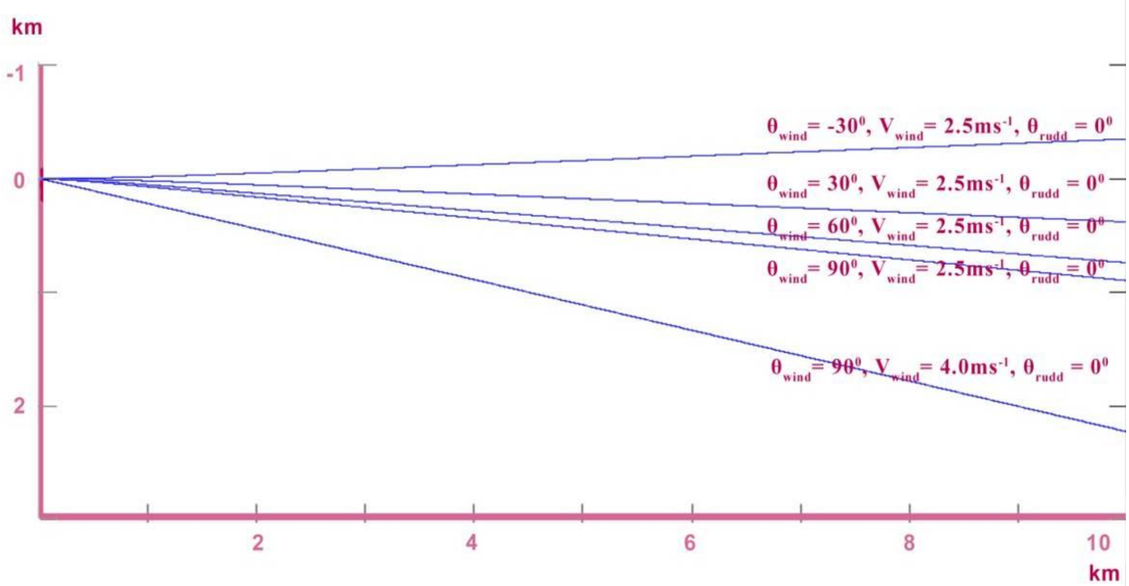

Figure 8: Predicted trajectories in earth fixed reference frame according to the given wind speed and directions

The Figure 8 illustrates the ship's position in the earth fixed reference frame and only first 30 minutes were considered. Similar experiment carried out with V_{wind} = 0, varying the sea current speed and sea current direction. The nature of the result is quite similar to the first experiment.

In the second experiment similar wave condition simulated as in the experiment 1. We assummed sea curent speed is zero ($V_{current}$ = 0), rudder angle constant (θ_{rud} *=10) and* ship engine generate constant effective thrust (T_e =15.0 x 10^4 N). θ_{wind} and V_{wind} were assumed as given below.

- θ_{wind} = 00^0, V_{wind} = 0 ms^{-1}, $V_{current}$ = 0, θ_{rud} = 10 and T_e =15.0 x 10^4 N
- θ_{wind} = 90^0, V_{wind} = 2.5 ms^{-1}, $V_{current}$ = 0, θ_{rud} = 00 and T_e =15.0 x 10^4 N
- θ_{wind} = -90^0, V_{wind} = 2.5 ms^{-1}, $V_{current}$ = 0, θ_{rud} = 00 and T_e =15.0 x 10^4 N

The Figure 9 illustrates the ship's position in the earth fixed reference frame and only first 30 minutes were considered. Similar experiment carried out with V_{wind} = 0, varying the sea current speed and sea current direction. The nature of the result is quite similar to the second experiment.

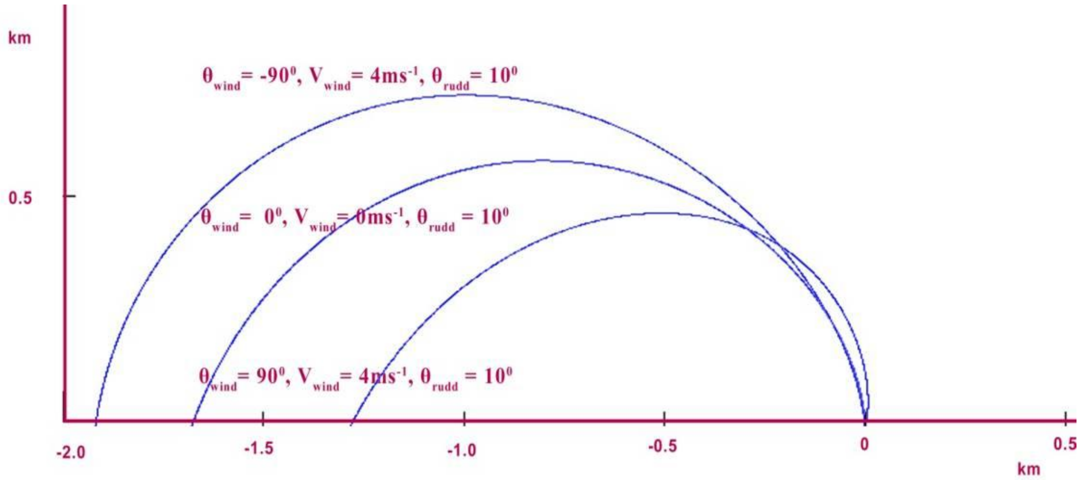

Figure 9: Predicted trajectories in earth fixed reference frame according to the given wind direction and rudder angle

In the third experiment similar wave condition simulated as in the experiment 1. We assummed sea curent speed is zero ($V_{current} = 0$), rudder angle constant ($\theta_{rud} = 10$) *and* ship engine generate constant effective thrust (T_e =15.0 x 10^4 N). Beginning of the simulation θ_{wind} and V_{wind} were assumed as given below.

$\theta_{wind} = -60^0$, $V_{wind} = 4\ ms^{-1}$, $V_{current} = 0$, $\theta_{rud} = 10$ and T_e =15.0 x 10^4 N

During the simulation θ_{wind} was gradually changed from -60^0 to $+60^0$. Figure 10 illustrates the ship's position in the earth fixed reference frame and only first 30 minutes were considered. Similar experiment carried out with initial conditions $V_{wind} = 0$, θ_{rud} = 10 and T_e =15.0 x 10^4 N and $\theta_{current} = -60^0$. During the simulation $\theta_{current}$ was changed from -60^0 to $+60^0$v. The nature of the result is quite similar to the third experiment.

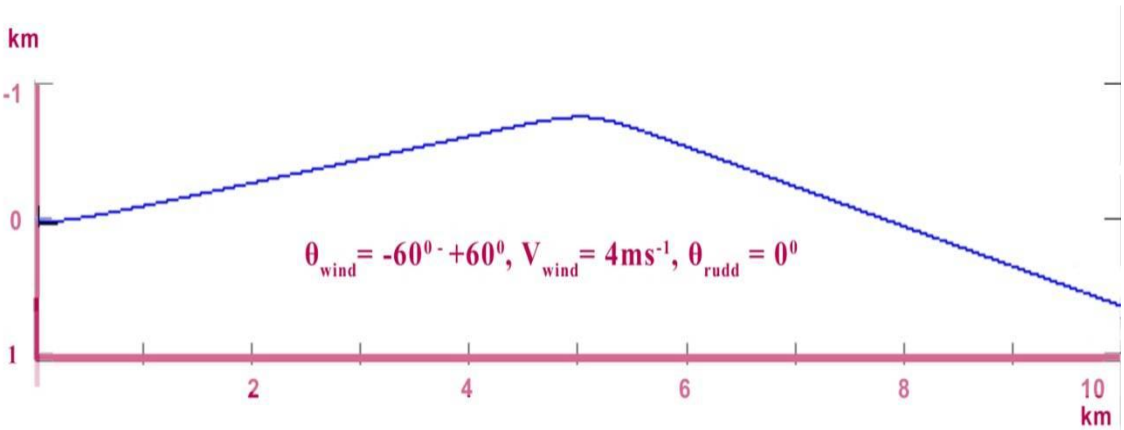

Figure 10: Predicted trajectory in earth fixed reference frame according to the given wind direction

In the fourth experiment similar wave condition simulated as in the experiment 1. We assummed rudder angle constant ($\theta_{rud} = 10$) *and* ship engine generate constant effective thrust (T_e =15.0 x 10^4 N). Beginning of the simulation θ_{wind}, V_{wind} and directions were assumed as given below.

θ_{wind} = -30^0, V_{wind} = 0ms^{-1}, $\theta_{current}$ = -30^0, V $_{current}$ = 2ms^{-1}, θ_{rud} = 10^0 and T_e =15 x 10^4 N , During the simulation V_{wind} was gradually changed from 0 to 4 ms^{-1}
θ_{wind} = 30^0, V_{wind} = 0ms^{-1}, $\theta_{current}$ = -30^0, V $_{current}$ = 2ms^{-1}, θ_{rud} = 10^0 and T_e =15 x 10^4 N , During the simulation V_{wind} was gradually changed from 0 to 4 ms^{-1}

The Figure 11 illustrates the ship's position in the earth fixed reference frame and only first 30 minutes were considered.

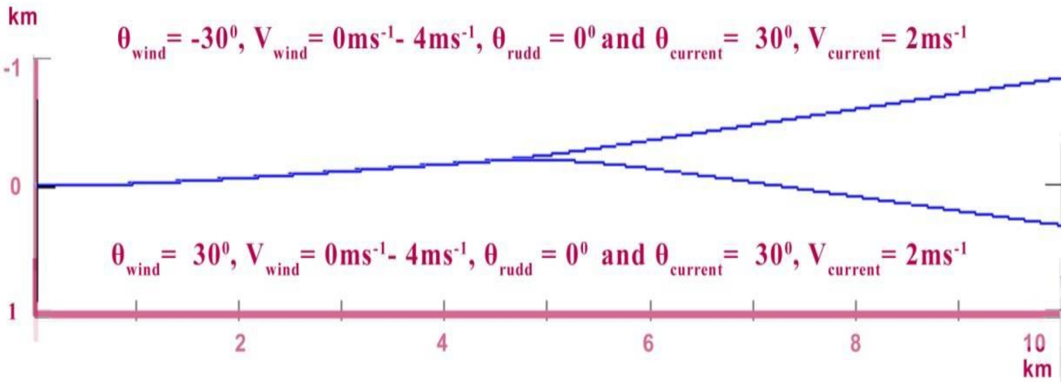

Figure 11: Predicted trajectory in earth fixed reference frame according to the given wind direction and wind speed

In the 5th experiment similar wave condition simulated as in the experiment 1. We assummed sea curent and wind speeds are zero rudder angle constant (θ_{rud} =0) *and* ship engine generate constant effective thrust (T_e =15.0 x 10^4 N). Under this condition ship gradually started to travel in a straight line with a constant speed. Heave, pitch and roll angular accelerations were recorded as shown in the figure 12. In higher level we observed angular accelerations have similar frequency but angular accelerations are varied as folows. Stable amplitude of angular accelerations of heave: 4 x 10^{-3}~ – 4 x 10^{-3}rads^{-2}, pitch: 4 x 10^{-4} ~ – 4 x 10^{-4} rads^{-2} and roll: 0.05 ~ – 0.05 rads^{-2}.

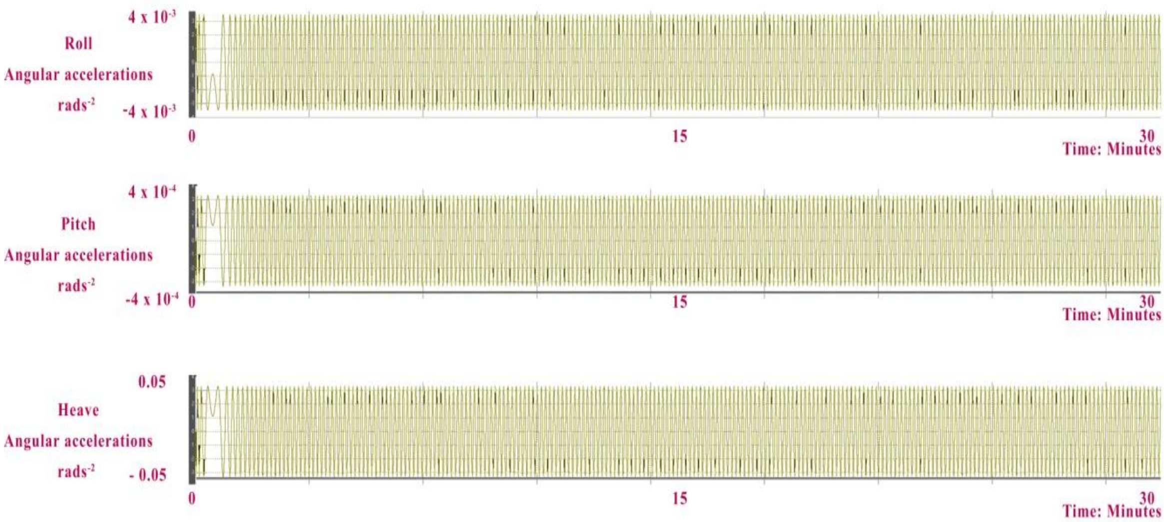

Figure 12: Variation of the heave, pitch and roll angular accelerations with time

According to experiments the proposed computational ship model response in real-time environmental disturbances wind, wave and sea currents. According to basic physics and redid body dynamics those real-time motion predictions are acceptable in higher level. Achieve the higher behavioral realism with six degrees of freedom computational ship model is a great challenge because accuracy of the ship motion prediction depends on the available computational power (CPU). In kinematics we can accurately predict position and orientation of a rigid body by solving several differential equations. If it is a non real-time computational ship model we can utilize available CPU power for a longer time to get accurate predictions. However, when we deal with real-time applications we have to get predictions very quickly. If we apply real Newtonian physics and fluid dramatics to predict ship motions then we can't get rapid motion predictions. On the other hand if you simplify your equations with assumptions then the accuracy level of the final prediction will be decreased.

7.2 Validation of Real-time Ship Motion Prediction

The proposed real-time computational ship model can easily predict more than 30 predictions per second with real-time environmental changes. The next major challenge was to validate the motion prediction algorithms and this kind of validation process can be done by using following methods.

(i) Validate against none real-time more accurate model: Ignore assumptions, limitation and constrains of algorithms and predict accurate non real-time ship motions then predict real-time ship motions with assumptions, limitations and constrains. Comparison of both results gives deviation of ship motion predictions due to assumptions and constrains.

(ii) Real world sea trials: Simulate the similar sea trial with the VR solution. Comparison of real sea trial and simulation results gives overall deviation with respect to real sea trial.

(iii) User tests: Incorporate this motion prediction system with the immersive VR solution and simulate known real world scenario such as vidusayura [28, 29]. Subsequently experienced real world users can be used to assess the ship motion prediction.

We mainly focused on first and third validation techniques and identified relevant strategies for validation process. We ignored the second method due to unavailability of properly recorded real sea trial data.

We used first technique to identify several deviations in our computational ship model. The relationship between ship motion and the ocean wave characteristics is commonly measured by using the Response Amplitude Operators (RAO) [30, 31]. In our computational ship model we assume the shape of the ship is identical to cuboids for mathematical convenience as illustrated in Figure 13 and perform real-time fluid dynamic calculations.

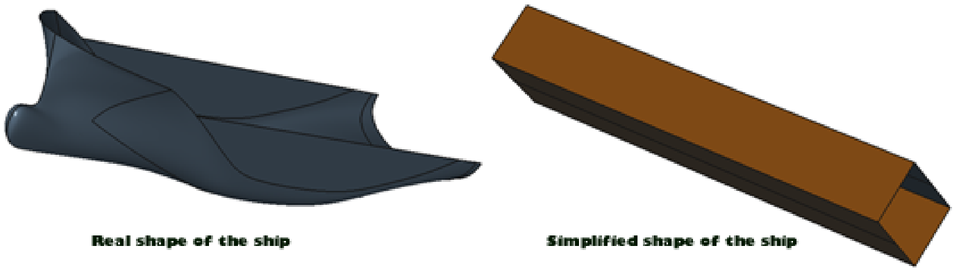

Figure 13: Real shape and simplified shape of the ship

We simulated above illustrated hull shapes under similar conditions by using a non real-time ship motion prediction application [32] and obtained deviated responses for same wave conditions as illustrated in Figure 14.

By using this mechanism we identified there is deviation of heave, pitch and roll responsiveness for wave conditions due to our assumptions. We used third validation method and incooperated proposed real-time six degrees of freedom ship motion prediction system with immersive virtual environment "*Vidusayura*" [29] and simulated ship. "*Vidusayura*" is a perception enhanced immersive virtual environment with pluggable architecture. Its ship motion prediction module was replaced with proposed ship motion prediction algorithms and we predicted real-time ship motions in immersive virtual reality environment.

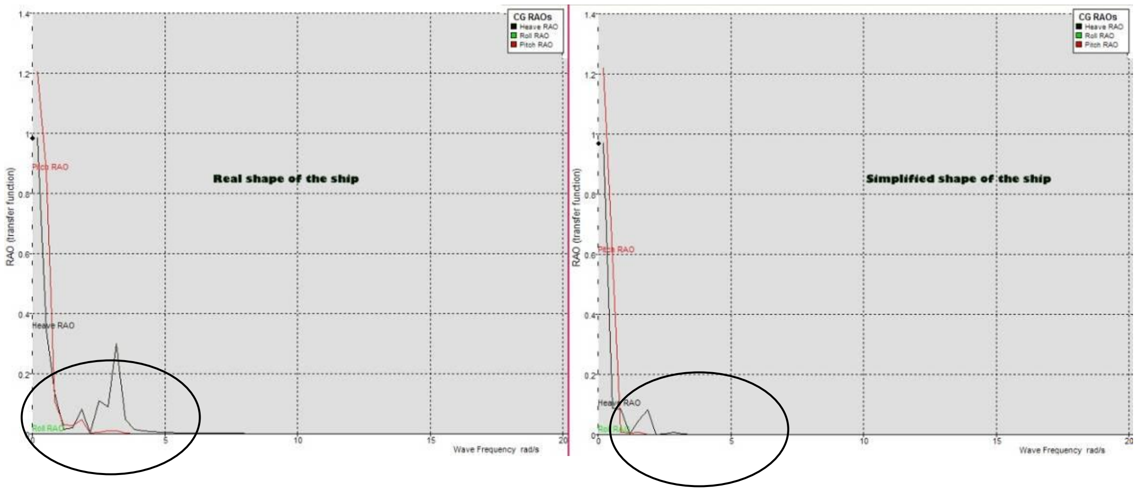

Figure 14: Variation of Response Amplitude Operator for real shape and simplified shape of the ship

We focused on subjective measurements and design user test with questionnaire. It targets experienced naval officers and still this is progressing but we did several fundamental test were conducted as shown in the Figure 15. Known scenarios were simulated and record experienced naval offices response. With respect to participant's response (feeling about the simulated scenario) and qualitative /quantitative properties of the simulated scenario, the participant's responses will be assigned to numerical scale as follows. Then the behavioral realism of the motion prediction can be reflected as percentage under predefined circumstances.

Figure 15 Naval officer test out ship motion prediction in immersive virtual environment

8 Conclusion and future work

The proposed six degrees of freedom ship motion prediction system works at a fraction of real-time with 2.8GHz CPU. This model can be used for long term motion prediction and it uses standard model parameters which are possible to evaluate with standers techniques. Wide range of ships can be simulated with proposed model and it has primitive realism with respect to real world scenario. Still we work on the validation of the proposed model but can be used to predict six degrees of freedom ship motion for real-time applications which need less accuracy. Based on above mention validation methods we have to complete the validation process and we have to discuss the factors affect on the ship's stability. Depending on the situation these motion predictions can be used to ship simulations for naval trainings, ship hull designing, simulate military scenes and entertainment activities such as computer games because it works at a fraction of real-time.

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