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A Modest Numerical Simulation for Automatic Ship Collision Avoidance System to Support Green and Autonomous Shipping Concept

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ABSTRACT

The development of autonomous ship is being pursued massively and significantly, either industrially, regulatory, or academic. The autonomous ship is considered to be able to significantly reduce challenges caused by unexpected errors of manual navigation (manned ship). One of the challenges for autonomous ship development is constructing an automatic ship collision avoidance system as a basic system for identifying and avoiding an obstacle object around the ship. The collision avoidance system must consider not only the position of the ship and the obstacle but also the maneuvering characteristic (ship dynamics) and control system of the ship, thereby making its numerical system more complex. This research presents a modest numerical simulation for designing an automatic ship collision avoidance system. However, the numerical model still considers the main necessary elements of the system. The numerical model includes a set of automatic guidance system, collision avoidance system, ship dynamics, and control system. Head on head, overtaking, and crossing collision scenarios are performed to investigate the numerical model. The simulation results show that the modest numerical simulation can be used to perform an automatic ship collision avoidance system in which the ship can automatically avoid a target ship considered as the ship's obstacle in those three collision scenarios.

Keywords: *Autonomous ship, Ship collision avoidance, Fuzzy logic.*

1. INTRODUCTION

Nowadays, technological developments have become an exceedingly natural thing. Technological developments commonly happen and grow fast, especially in this industry 4.0 era. In this era, people are starting to compete to create or develop technology with various innovations. Technological innovation is growing rapidly along with the demands of technology that are really needed at this time. One of the technological innovations that is currently being intensively developed is unmanned or autonomous ship. Unmanned or autonomous ship is a ship that is driven without humans' interference, or in simple words, it is driven by using a computer program that has been created and installed on a ship's system. A computer program is built and developed by a model-based process according to the real situation solved by a mathematical model. The numerical or mathematical model has various kinds which can be selected according to necessity.

An autonomous ship is essential in implementing a future shipping concept, namely, the green and autonomous shipping concept. At least, there are two essential advantages of an autonomous vessel in shipping, pollution reduction and human error reduction [1]. Reducing the number of crew as well as technology used in an autonomous ship can decrease marine pollution, including marine debris [2], plastics into the oceans [3], and marine noise [4]. Moreover, due to advanced technology used in autonomous ships, the emission of gases and oil tends to be lower since autonomous ships commonly use a battery as their propulsion plant or other systems [5], and thereby air and atmospheric pollution can be significantly diminished [1].

The development of autonomous ship in several countries is being pursued massively and significantly, either industrially, regulatory or academic [6]. This significant development aligns with the increasing demand for autonomous marine vehicles (including autonomous ships) in maritime activities [7]. Chen et al. [8] mentioned that autonomous ships could significantly reduce the challenges caused by unforeseen errors of manual navigation (manned ships), thereby lowering labour costs, improving navigation safety, and increasing related profit margins.

The development of autonomous ships does not only focus on the ship's ability to run and sail automatically following a predetermined shipping route line, but also the development of the ship's ability to detect and avoid objects in front of the ship automatically to avoid ship collisions. The ability to avoid collision automatically becomes strongly important, along with the fact that 89-96% of accidents at sea that occur are ship collisions, [9] where human error contributes more than 80% to the occurrence of ship collisions [10]. Therefore, the development of

automatic ship collision avoidance becomes important and needs to be developed using appropriate mathematical models to represent the dynamic behavior of the autonomous ship.

The challenge for developing an automatic ship collision avoidance system is selecting and arranging mathematical or numerical models for each sub-system of the automatic collision avoidance system, including the ship positioning system, track guidance system, maneuvering motions (ship dynamics), control system, collision risk assessment, and decision making for determining collision avoidance solution. Accordingly, the numerical model for developing automatic collision avoidance systems is complicated. The automatic collision avoidance system needs to be built and developed using mathematical modelling, with an adapted approach to simplify the complexity of its mathematical model.

This research presents a simple numerical approach to be used for automatic collision avoidance system. The numerical model includes an automatic guidance system, collision risk assessment, decision-making of collision avoidance solution, ship dynamics for maneuvering motions, and a ship control system, even though in modest form. The numerical simulation on three collision scenarios: head on head, overtaking, and crossing situations are conducted to examine the proposed numerical model. The component of each sub-system for the automatic ship collision avoidance system is discussed. The numerical simulation results for the three scenarios, including the ship's trajectory, heading, and rudder angle, are analyzed.

2. MATHEMATICAL MODEL FOR SHIP DYNAMICS

The ship dynamics model used in this research is derived from Newton's Second Law, in which the general equation used for modelling ship dynamics with 6 DOF (degree of freedom) is shown in Equation (1) [6],

$$M\dot{v} + C(v)v + D(v)v + g(\eta) = \tau \,, \tag{1}$$

where,

M : inertia matrix (including added mass)
$C(v)$: matrix of Coriolis and centripetal term (including added mass)
$D(v)$: damping matrix,
$g(\eta)$: vector of gravitational forces and moments,
τ : vector of control inputs.

Equation (1) is then derived to be the following forms (Equation (2)) for horizontal plane motion by applying Euler's first and second axioms, rewritten in components according to [12].

$$\left.\begin{aligned} m[\dot{u} - vr + wq - x_G(q^2 + r^2) + y_G(pq - \dot{r}) \\ + z_G(pr + \dot{q})] = X, \\ m[\dot{v} - wp + ur - y_G(r^2 + p^2) + z_G(qr - \dot{p}) \\ + x_G(qp + \dot{r})] = Y, \\ I_z\dot{r} + (I_y - I_x)pq + m[x_G(\dot{v} - wp + ur) \\ - y_G(\dot{u} - vr + wq)] = N. \end{aligned}\right\} \tag{2}$$

in which,

X, Y, N : external surge and sway forces, and yaw moment,
m : mass of ship,
I_x, I_y, I_z : moment inertia of ship in surge (x), sway (y), and heave (z) directions,
u, v, w : surge, sway, and heave motion velocity,
p, q, r : roll, pitch, and yaw motion velocity,
$\dot{u}, \dot{v}$: surge, and sway motion acceleration,
$\dot{p}, \dot{q}, \dot{r}$: roll, pitch, and yaw motion acceleration,
x_G, y_G, z_G : ships' center of gravity.

By assuming the ship's mass is homogeny, and the ship is symmetric in xz-plan $(I_x = I_y)$, the dynamic motion equation of the ship can be simplified as follow,

$$\left.\begin{aligned} m(\dot{u} - vr - x_G r^2) = X, \\ m(\dot{v} + ur + x_G\dot{r}) = Y, \\ I_z\dot{r} + mx_G(\dot{v} + ur) = N. \end{aligned}\right\} \tag{3}$$

X, Y, N in Equation (3) represent the total external force and moment components acting on the ship. The forces and moment consist of hydrodynamic force and moment in calm water conditions and exciting force and moment due to environmental loads, including current, wind, and waves. Since this research focuses on developing a preliminary model for automatic ship collision avoidance system which only deals with calm water, it neglects the environmental exciting force and moment.

Expressing hydrodynamic force and moment by using Taylor expansion as proposed by Abkowitz [13], the Equation (3) can be rewritten for ship maneuvering motion equations consisting of linear hydrodynamic derivatives components known as "whole ship model" as follows.

$$\left.\begin{aligned} (m - X_{\dot{u}})\dot{u} - X_{\dot{u}}(u - U) = 0, \\ (m - Y_{\dot{v}})v - Y_v v + (\dot{m}x_G - Y_{\dot{r}})\dot{r} \\ + (mU - Y_r)r = Y_\delta\delta, \\ (mx_G - N_{\dot{v}})\dot{v} - N_v v + (I_z - N_{\dot{r}})\dot{r} \\ + (mx_G U - N_r)r = N_\delta\delta. \end{aligned}\right\} \tag{4}$$

$X_{\dot{u}}$, $Y_{\dot{v}}$, Y_v, $Y_{\dot{r}}$, Y_r, Y_δ, $N_{\dot{v}}$, N_v, $N_{\dot{r}}$, N_r, N_δ on Equation (4) are hydrodynamic derivatives that are constant to a particular ship and must be found by experiment or appropriate calculation. The maneuvering equations presented in Equation (4) can be expressed by using the Nomoto model proposed by Nomoto et al. [14] as follow [15],

$$T_1 T_2 \ddot{r} + (T_1 T_2)\dot{r} + r = K\left(\delta + T_3 \dot{\delta}\right). \quad (5)$$

The Nomoto model on Equation (5) is then can be stated into a transfer function in its Laplace form by the following model [11],

$$\frac{r}{\delta}(s) = \frac{K(1 + T_3 s)}{(1 + T_1 s)(1 + T_2 s)}. \quad (6)$$

Since $r(s) = s\,\psi(s)$, the relation between rudder angle, δ, and the ship's heading, ψ, the transfer function of Equation (6) can be expressed by the Nomoto's second order model as follow,

$$\frac{\psi}{\delta}(s) = \frac{K(1 + T_3 s)}{s(1 + T_1 s)(1 + T_2 s)}. \quad (7)$$

s denotes time, while the parameter of the transfer function, K, T_1, T_2, and T_3 can be expressed by considering linearized ship steering equations of motion proposed by Davidson and Schiff [16] and as reported by Fossen [11]. The transfer function parameter is related to hydrodynamic derrivatives of the ship, which can be expressed by the following formula.

$$\left.\begin{aligned} T_1 T_2 &= \frac{det(M)}{det(\boldsymbol{N})}, \\ T_1 + T_2 &= \frac{n_{11}m_{22} + n_{22}m_{11} - n_{12}m_{21} - n_{21}m_{12}}{det(\boldsymbol{N})}, \\ K &= \frac{n_{21}b_1 - n_{11}b_2}{det(\boldsymbol{N})}, \\ KT_3 &= \frac{m_{21}b_1 - m_{11}b_2}{det(\boldsymbol{N})}. \end{aligned}\right\} \quad (8)$$

$\boldsymbol{M}$ represents the inertia matrix, while $\boldsymbol{N}$ is the summation of linear damping, coriolis and centripetal term matrix. m_{ij}, n_{ij} and b_{ij} denote the element of matrix $\boldsymbol{M}$, $\boldsymbol{N}$, and $\boldsymbol{b}$, respectively, whereas $\boldsymbol{b}$ is a rudder control derivative matrix. The detail of matrix $\boldsymbol{M}$, $\boldsymbol{N}$, and $\boldsymbol{b}$ can be found on Fossen [11],

$$\left.\begin{aligned} \boldsymbol{M} &= \begin{bmatrix} m - Y_{\dot{v}} & mx_G - Y_{\dot{r}} \\ mx_G - N_{\dot{v}} & I_z - N_{\dot{r}} \end{bmatrix}, \\ \boldsymbol{N} &= \begin{bmatrix} -Y_v & mu - Y_r \\ -N_v & mx_G u - N_r \end{bmatrix}, \\ \boldsymbol{b} &= \begin{bmatrix} Y_\delta \\ N_\delta \end{bmatrix}. \end{aligned}\right\} \quad (9)$$

The dynamic maneuvering motion of the ship respecting to time can be obtained by using the transfer function presented on Equation (7) in relation between steering control input (rudder angle) δ and ship's heading, ψ.

3. TRACK KEEPING GUIDANCE AND RUDDER CONTROL SYSTEMS

In order to provide autopilot control of a ship, a track keeping guidance system must be considered and attached in the autopilot control system. A track keeping guidance system is used for attempting an accurate and rapid course changing automatically to follow and move to the next track. In this research, Line of Sight (LOS) waypoint guidance system presented by Fossen [11] is used as the track keeping guidance system which can be defined in terms of a desired heading angle [17] presented in Equation (10), while the schematic of LOS guidance system is shown in Figure 1.

$$\psi_d(t) = \tan^{-1}\left(\frac{y_d(k) - y(t)}{x_d(k) - x(t)}\right) \quad (10)$$

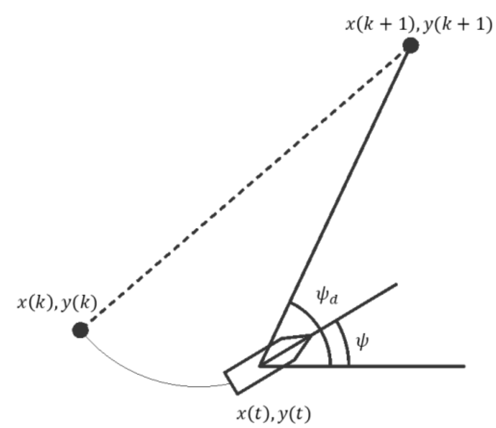

Figure 1. Schematic of Waypoint Guidance System by LOS

The desired point $\left(x_d(k), y_d(k)\right)$ indicates the coordinates point of the position to be headed while the point $\left(x(t), y(t)\right)$ is the current ship's position at the time t. The next waypoint can be selected based on whether the ship is located in the circle of acceptance with a radius R around the desired waypoint $\left(x_d(k), y_d(k)\right)$. If the ship reaches the desired point $\left(x_d(k), y_d(k)\right)$, the next desired waypoint $\left(x_d(k+1), y_d(k+1)\right)$ must be selected. The cross track error between desired heading and current heading can be calculated by following track keeping error formula given by Choe and Furukawa [18] which can be presented in Figure 2. The detailed formula is presented in Equation (11,12).

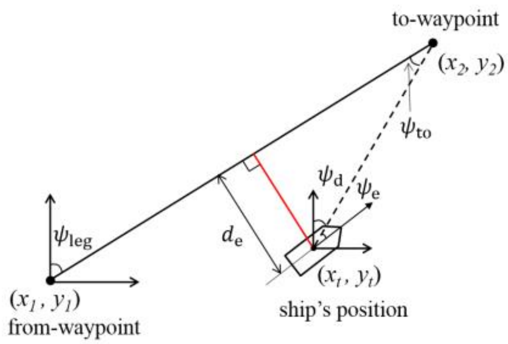

Figure 2. Parameter for Calculating Track Keeping Error [19]

$$d_e = \sqrt{(x_2 - x_t)^2 + (y_2 - y_t)^2}.\sin\psi_{to} \tag{11}$$

$$\left.\begin{aligned} \psi_{leg} &= \tan^{-1}\left(\frac{x_2 - x_1}{y_2 - y_1}\right), \\ \psi_d &= \tan^{-1}\left(\frac{x_2 - x_t}{y_2 - y_t}\right), \\ \psi_{to} &= \psi_{leg} - \psi_d. \end{aligned}\right\} \tag{12}$$

Moreover, the automatic rudder control system can be conducted by introducing the concept of fuzzy rudder control proposed by Kijima and Furukawa [20].

4. COLLISION RISK

In this study, evaluation parameters for deciding which ship to avoid when one's own ship discovers another ship in the vicinity and evaluation parameters for judging whether to activate the emergency avoidance system when a ship to avoid approaching one's own ship is determined by considering the collision risk (C.R.) assessment between the own ship and the other ship as an evaluation parameter. The ship's collision risk assessment by using fuzzy inference introduced by Ota et al. [21] is used in this paper. This method considers the closest distance DCPA (Distance to Closest Point of Approach) and the closest approach time TCPA (Time to Closest Point of Approach) as the parameter to calculate collision risk. DCPA is the distance of the closest approach when two ships maintain their speed and course from their current positions, and TCPA is the distance when two ships maintain their speed and course from their current positions. In this case, it represents the time until the two ships come closest to each other. DCPA and TCPA can be calculated by the following formulae (Equation (13)) in the coordinate system shown in Figure 3.

$$\left.\begin{aligned} DCPA &= R\sin(\theta_{01} - \theta_r), \\ TCPA &= \frac{R\sin(\theta_{01} - \theta_r)}{V_r}. \end{aligned}\right\} \tag{13}$$

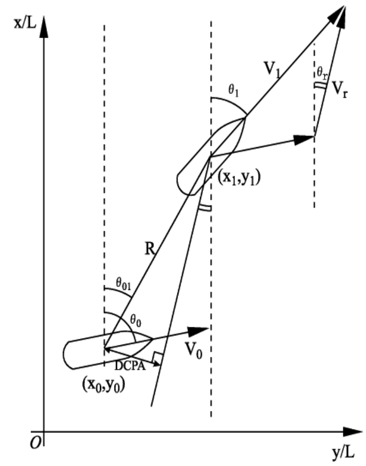

Figure 3. Schematic of The Relative Motion of Two Ships for Calculating TCPA and DCPA [21]

5. EVASIVE ROUTE SOLUTION

This paper uses a fuzzy logic control algorithm combined with the concept of blocking area introduced by Kijima and Furukawa [22] to determine evasive route selection to avoid collision. The concept of blocking area represents the amount of evaluation index related to the margin of distance, which is necessary for collision prevention between ships, which was obtained by the operator's estimation of the specifications and performance of the other ship when judging the avoidance action. The blocking area is defined by ship length L (m), ship width B (m), ship speed U (knot), tactical diameter D_T (m), and 90-degree turning time T_{90}(sec) which can be depicted in Figure 4. As shown in Figure 4, the longitudinal radius of the blocking area in fore and aft denote as R_{bf} and R_{ba}, respectively, while the transverse radius for both domains is S_b. The estimation formula for the blocking area parameters adopts the proposed formula by Arimura et al. [23] in Equation (14).

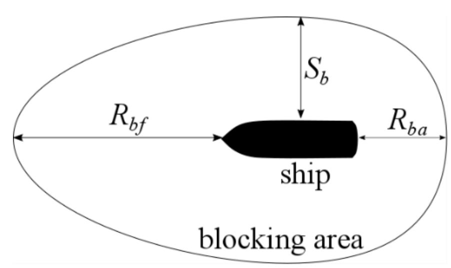

Figure 4. Definition of Blocking Area

$$\left.\begin{aligned} R_{bf} &= L + T_{90}.{}^{U}\!/_{2}, \\ R_{ba} &= L + T_{90}.{}^{U}\!/_{4}, \\ S_b &= B + D_T. \end{aligned}\right\} \tag{14}$$

Meanwhile, to conduct an evasive route, a fuzzy logic control algorithm based on the Mamdani method is adopted to control rudder angle. The input from the rudder control is in the form of yaw error values and yaw rate, while the output is in the form of rudder commands. The approach to selecting the membership function using the Mamdani method produces an output in the form of a definite value in the rudder command. The rudder actuator affects the direction of motion of the ship following the predetermined trajectory to follow the selected evasive route. The design of the rudder control using the fuzzy logic control based on Mamdani method is shown in Figure 5, while basic fuzzy rule used in this research is provided in Figure 6.

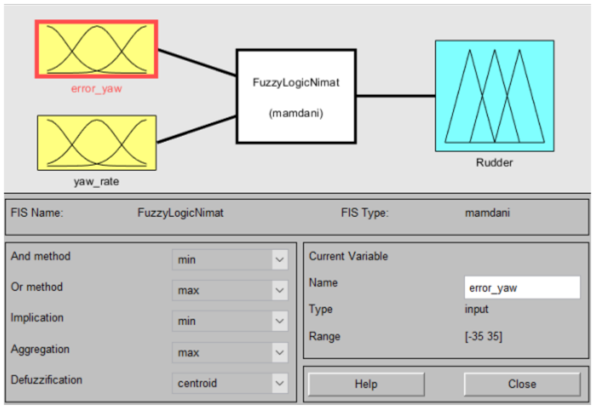

Figure 5. Fuzzy Logic Control Modelling based on Mamdani Method in Rudder Control System

r \ e	NB	NM	NS	Z	PS	PM	PB
NB	Z	PS	PM	PB	PB	PB	PB
NM	NS	Z	PS	PM	PB	PB	PB
NS	NM	NS	Z	PS	PM	PB	PB
Z	NB	NM	NS	Z	PS	PM	PB
PS	NB	NB	NM	NS	Z	PS	PM
PM	NB	NB	NB	NM	NS	Z	PS
PB	NB	NB	NB	NB	NM	NS	Z

Figure 6. Basic Fuzzy Rule for Rudder Control System in Evasive Route Solution

The evasive route solution can be provided by implementing an automatic collision avoidance system based on the concept of blocking area combined with the automatic rudder control based on fuzzy logic control described in advance.

6. SIMULATION RESULTS

6.1 Subject Ship and Scenario Variations

A container ship data, KRISSO Container Ship (KCS), is used as the subject ship to perform the simulation and verification of the proposed method for automatic ship collision avoidance. The specification data of KCS is shown in Table 1.

Table 1. KRISSO Container Ship (KCS) Specification Data

Main particulars	
L_{PP} (m)	230.0
B (m)	32.2
D (m)	19.0
T (m)	10.8
Displacement (m³)	52030
C_B	0.651
C_M	0.985
LCB (%), fwd+	-1.48

A numerical simulation is conducted to verify the effectiveness of the proposed method in avoiding ship collisions. Three collisions scenario referring Convention on the International Regulations for Preventing Collisions at Sea, 1972 (COLREGs) [24] are performed: head on head, crossing, and overtaking situations. The detail of the three scenarios is shown in Table 2. In this numerical simulation, the effect of environmental loads i.e. wind, wave, and current, is neglected.

Table 2. Condition for Collision Scenario

Scenario	Condition	Speed	Give away/ stand on ship
1	Head on head	Ship 1 and Ship 2: 5 knots	Ship 1 and Ship 2 : give-way
2	Crossing	Ship 1 and Ship 2: 5 knots	Ship 1: give-way ; Ship 2: stand-on
3	Overtaking	Ship 1: 15 knots Ship 2: 5 knots	Ship 1: give-way ; Ship 2: stand on

6.2 Head on Head Situation

Numerical simulation for head on head situation is conducted by considering two ships with opposite course directions. Ship 1 has 0.0 degree heading angle while -180 degree heading angle is set for ship 2. The initial position of both ships in terms of $(x_0/L, y_0/L)$ is (-20.0,0.0) and (20.0,0.0) respectively for ship 1 and ship 2, in which, x_0, y_0 are ships' center of gravity in x and y direction while L is ship's length. Both ships have the same speed, that is 5 knots, and must follow COLREG's rule for taking action to avoid a collision in head on head situation. Both ships must change their course to the starboard side direction. The trajectory of both ships is shown in Figure 7.

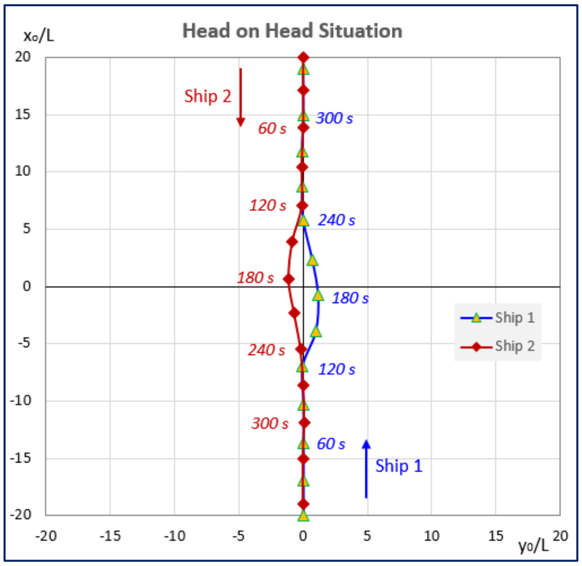

Figure 7. Trajectory Results in Head on Head Situation

As shown in Figure 7, after starting the calculation, the two ships proceeded straight along the course where they faced each other. At about 120 seconds, it became necessary to make avoidance decisions under normal avoidance conditions, and both ships started avoidance maneuvers by turning to starboard. After that, at about 180 seconds, the two ships are side by side, as shown in Figure 7. Currently, the distance between the two ships is about 2.0L, which is the closest. The size of the side blocking area, the ship is well beyond 0.7L to allow safe avoidance maneuvers. At this time, the rudder angle δ changes from a positive value to a negative value and begins to return to the initial course. After about 300 seconds, the distance from the initial route was 0.1L or less for both ships, and they returned to the initial route. Efficient avoidance maneuvers are being carried out because the two ships do not detour each other significantly.

6.3 Crossing Situation

A numerical simulation for the crossing situation is also conducted to verify the proposed method for the other possibility of collision, especially in crossing conditions. In this scenario, two ships that have perpendicular course directions are considered to represent the crossing condition. Ship 1 has 0.0 degree heading angle while -90 degree heading angle is set for ship 2. The initial position of both ships in terms of $(x_0/L, y_0/L)$ is (-20.0,0.0) and (0.0,20.0), respectively, for ship 1 and ship 2. Both ships have the same speed, which is 5 knots. Ship 1 is considered a give-way vessel, while ship 2 is a stand-on vessel. Ship 1 must change her course to starboard side direction whereas ship 2 must keep her course straight. The trajectory result of both ships in the crossing situation is shown in the Figure 8.

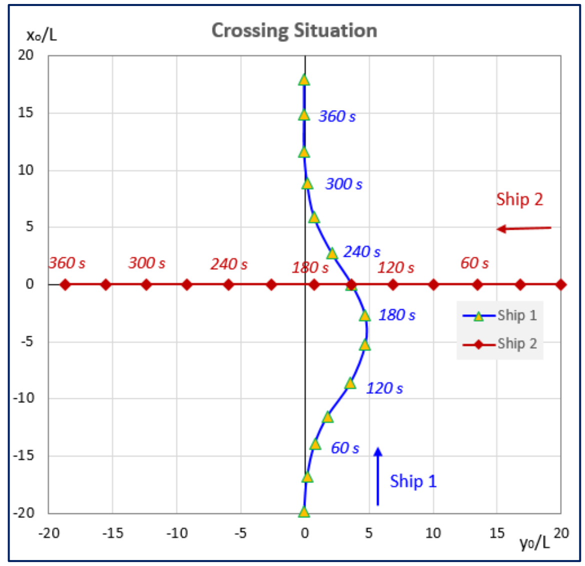

Figure 8. Trajectory Results in Crossing Situation

As shown in Figure 8, after starting the calculation, ship 1, which is obliged to give way, immediately needs to make a decision to give way and takes an avoidance route that turns sharply to the starboard direction. After that, considering the relative turning angles and distances of ship 1 and ship 2, ship 1 takes an avoidance route that approaches ship 2. The avoidance route of ship 1 intersects the route of ship 2 at about 210 seconds. At this time, ship 1 passes ship 2 in about 6.6L behind her, allowing safe avoidance maneuvers.

6.3 Overtaking Situation

The last collision scenario is the overtaking situation when a ship approaches another ship in front of it and needs to overtake it. In this scenario conducted in this research, two ships are considered to have the same straight line courses with different speeds. The heading direction, initial position, and speed of both ships are 0.0 degree (both ships), ship 1: (-20.0,0.0) and ship 2: (-10.0,0.0), and ship 1: 15 knots, ship 2: 5 knots, respectively. Ship 1 is considered as a give-way vessel, while ship 2 is a stand-on vessel. Ship 1 must change its course to overtake ship 2 by portside direction whereas ship 2 must keep its course straight. The trajectory result of both ships in the crossing situation is shown in the Figure 9.

As figured in Figure 9, ship 1, which is obliged to give way vessel, must make a decision to give way immediately after the start of the calculation. According to the Act on Prevention of Collisions at Sea, it is preferable to overtake on the port side of the vessel to be avoided in overtaking navigation. As shown in Figure 7 and Figure 9, ship 1 is taking an avoidance route on the port side of ship 2.

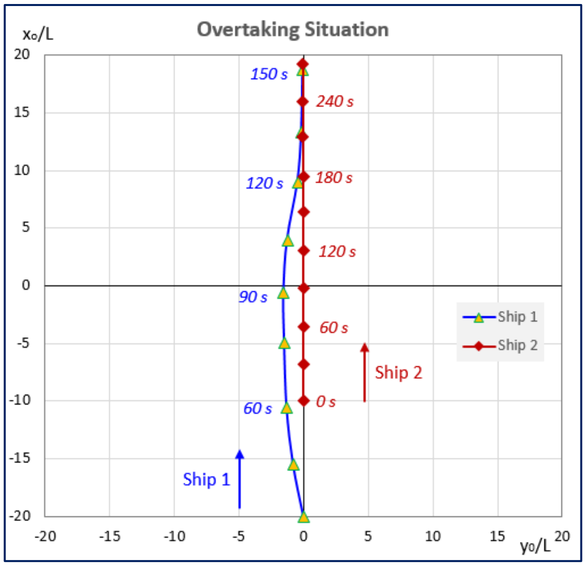

Figure 9. Trajectory Results in Overtaking Situation

Ship 1 takes avoidance maneuvers at about 30 seconds. At this point, ship 2, which is a course keeping vessel, needs to make a decision to avoid emergency avoidance. It can be seen that ship 2 does not steer blindly and continues to maintain its course and speed so that ship 1 can pass safely. As shown in Figure 9, at about 90 seconds, the two ships were side by side and closest to each other. At this time, the distance between the two ships is about 1.3L, and ship 1 overtakes ship 2 without entering the blocked area. After that, at about 120 seconds, the distance between ship 1's position and the initial route became less than 0.1L. Ship 1 has returned to its original course, but at this time, ship 1 is about 5.9L ahead of ship 2, so it can pass safely. These results verify that the proposed method can be used to avoid a collision in overtaking conditions.

7. CONCLUSION

A modest numerical approach for an automatic collision avoidance system algorithm is presented in this study. The model takes the simplification of ships' dynamics model adopting the Nomoto model, which combined with the important algorithm used for an automatic collision avoidance system that is an automatic guidance system, collision risk assessment, collision avoidance (evasive route selection) solution decision making, and ship control system. The LOS waypoint guidance system is used as the basis of the automatic guidance system, while the fuzzy inference system is applied for calculating the collision risk. The concept of blocking area combined with fuzzy logic control system is adopted to perform evasive route selection and automatic rudder control system when the ship needs to take an action to avoid a collision.

Three collision scenarios based on COLREGs are performed to assess and verify the proposed collision avoidance method. The collision scenarios consist of head on head, crossing, and overtaking condition. According to the simulation results, the proposed automatic collision avoidance system works well for the case according to COLREGs in either head on head, crossing, or overtaking situations. The ship (own ship) can avoid the other ship (target ship), and thereby ship can pass the target ship safely for those three collision scenario situations.
Furthermore, further study is expected to improve the proposed numerical model considering more dynamic model of maneuvering motions as well as environmental loads effect, such as wave, wind, and current.

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