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Araştırma Makalesi

Otonom Su Üstü Araçları için COLREG Kurallarını İçeren Çarpışma Önleyici Sistem

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ÖZET

Bu çalışmada önerilen matematiksel model, MMG (Matematiksel Model Grubu) manevra modeli ve geleneksel PD kontrol sistemine dayalı bir kontrol algoritması olmak üzere iki bölümden oluşmaktadır. MMG modeli, geminin manevra karakteristiklerini hesaplamak için kullanılmaktadır. Kontrol sistemi ise manevra modeliyle birlikte geminin seyir halindeyken herhangi bir engelle karşılaşması durumunda güvenli bir rotanın oluşturulmasını sağlamaktadır. Matlab-Simulink yazılım programında oluşturulan matematiksel model sayesinde COLREG kurallarına uygun olarak rota belirlenebilmektedir. Gemiye ait bilinen hidrodinamik katsayıların MMG modele uygun olması ve geminin seyir test sonuçlarının mevcut olması sebebiyle Esso Osaka gemisi seçilerek bir dizi simülasyon gerçekleştirilmiştir. Öncelikle geminin farklı hızları için dönme ve zigzag testleri yapılarak geminin manevra özellikleri belirlenmiştir. Elde edilen sonuçlar Esso Osaka gemisinin seyir testi sonuçları ile karşılaştırılarak önerilen model doğrulanmıştır. İkinci olarak, belirlenen bir hedef koordinat için geminin rotası elde edilmiştir. Üçüncü olarak ise geminin başlangıç noktası ile önceki simülasyon için belirlenen hedef koordinat arasında farklı büyüklüklerde engel olması durumu düşünülerek simülasyonlar gerçekleştirilmiştir. Sonuç olarak COLREG kurallarına uygun olarak belirlenen sanal koordinatlar sayesinde güvenli yeni rotalar oluşturulmuştur. Geminin manevra karakteristik değerleri kontrol algoritmasına dahil edildiği için sanal koordinatların belirlenmesini doğrudan etkilemektedir. Bu nedenle, doğru manevra özelliklerini bulmak önem arz etmektedir. Önerilen matematiksel modelden elde edilen simülasyon sonuçları değerlendirildiğinde, Esso Osaka gemisi için belirlenen koordinatlar arasında güvenli bir rota oluşturulduğu sonucuna varılmıştır.

Anahtar kelimeler: MMG model, Çarpışma önleme, COLREG, Güvenli Taşımacılık

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A Collision Avoidance System Based on COLREGs Rules for Autonomous Surface Vessels

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ABSTRACT

The proposed mathematical model in this study consists of two parts, one is the maneuvering model, called MMG (Mathematical Model Group), and the other is a control algorithm based on traditional PD control system. The MMG model is used to compute the ship's maneuvering characteristics, and a ship can safely reach target coordinates with the help of a control algorithm if it encounters any obstacles along the way. Because of the suitable hydrodynamic coefficients of Esso Osaka, the proposed mathematical model is evaluated using trial test data from Esso Osaka. Firstly, the maneuvering characteristics of the ship were determined by performing the turning and zigzag tests for different velocity of the ship. By comparing the results obtained with the trial test results of the Esso Osaka, the suggested model was verified. Secondly, the ship's route was obtained for a determined target coordinate. Thirdly, a new route is automatically obtained by assuming that there is an obstacle between the starting point of the ship and the target coordinate determined for the previous simulation. As a result, this new route is created thanks to the virtual coordinates determined in accordance with the COLREGs rules. Since the maneuvering characteristic values of the ship are included in the written algorithm, it directly affects the determination of the virtual coordinates. Therefore, it is very important to find accurate maneuvering characteristics. Evaluating the simulation results obtained from the proposed mathematical model, it is concluded that a safe route has been created between the coordinates determined for the Esso Osaka ship. Moreover, the ship reaches the target coordinate without any collision.

Keywords: MMG model, Collision avoidance, COLREGs rules, Safety transportation

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1. Introduction

There are internationally accepted rules for marine traffic to be able to navigate safely at sea in accordance with ships' purpose of usage. One of the international rules applied for navigational safety is the COLREGs (Regulations for the Prevention of Collisions at Sea) rules (IMO, 1972). These rules, which are crucial in terms of avoiding collisions of the ship and obtaining a safer route, ensure the regulation of ship traffic. For this reason, it is very significant to include these rules in the algorithm in studies on autonomous ships. The researchers have studied to obtain a safe route for the ships in the marine traffic. For example, Liu et al. (2017) suggested a collision avoidance system-based control algorithm with COLREGs rules. The authors used the Nomoto model to determine the transfer function. Furthermore, the ship maintains a constant speed and maintains more than one nautical mile distance from other vessels. In some studies, hybrid collision avoidance systems have been developed for a safe navigation. Eriksen et al. (2020) proposed the hybrid collision avoidance (COLAV) system for unmanned surface vessels compliant with COLREGs rules and performed the system for three different scenarios. Similarly, A hybrid technique consisting of velocity obstacles (VO) and rapidly exploring random trees (RRT) is proposed to determine the safe route for autonomous surface vessels based on COLREGs rules (Dubey and Louis, 2021). The fuzzy logic, traditional PID control and combined Fuzzy and PID control systems are widely preferred to develop a collision avoidance system by the researchers. Perera et al. (2009) have developed a new decision-making method for avoiding collisions in maritime navigation. The new DM system is built on fuzzy logic and expert knowledge from humans. To avoid collisions and establish the safe route, Li et al. (2019) devised a multi objective optimization approach based on fuzzy controller. Namgung (2021) investigated a local route planning method with a fuzzy inference system to avoid collisions that are compliant with COLREG guidelines. Another study focused on the development of a ship collision avoidance system that uses fuzzy logic systems to detect dangerous situations and quantify the amount of danger using a continuous value (Grinyak and Devyatisil'nyi, 2016). He et al. (2021) suggested a mathematical model including maneuvering model, namely MMG, and a fuzzy adaptive PID control system. In addition, the proposed model conforms to COLREG rules 13 to 17. Another study was about to develop a collision-avoidance system including a nonlinear Norrbin model based on traditional PID control and COLREGs rules (Zhou et al.,2021). Similarly, based on the traditional PID control system is widely used by the researchers to avoid the collision in the marine traffic, such as Zaccone and Martelli, (2020), Wang et al. (2021). As a result, the reason for using PD control as a control system in this study is that it is a frequently preferred controller in terms of ease of application.

Although the researchers indicate different methods for collision avoidance systems, the goal is to provide safe marine traffic. Huang et al. (2020) provides a complete overview of collision avoidance approaches based on three methods for determining solutions: motion prediction, conflict detection, and conflict resolution.

The proposed mathematical model has two purposes. One of the aims of this study is to obtain a ship trajectory for target coordinates. Another aim is to avoid a collision by automatically altering the ship's trajectory if it encounters any obstacles. First, turning and zigzag tests were simulated to determine Esso Osaka's maneuvering characteristics. Second, a course with obstacles was determined, and the path following simulation was performed using a Matlab-Simulink mathematical model. As a result, the mathematical model can be used to determine a ship's maneuvering characteristics as well as a safe new route under the COLREGs rules if the ship encounters obstacles of various sizes along the course.

2. Mathematical Model

In the event of a constant obstacle between two coordinates, a model is proposed for determining a new safe route under COLREGs rules. This proposed model is divided into two components. One is a maneuvering model that considers the ship's known hydrodynamic coefficients, and the other is a control method for following the route and, if necessary, determining a new one. The MMG model was selected since it was suitable for the known coefficients of the Esso Osaka ship. An algorithm was added to the mathematical model's control section to determine a safe route in compliance with the COLREG regulations to reach the target coordinates, safely.

2.1. Maneuvering Model

Ogawa and Kasai (1978) introduced the MMG model, which includes equations that can be calculated as modules such as hull, rudder, and propeller. Using the ship's axial coordinates, a mathematical model was created by combining three of the six freedom motions known as surge, sway, and yaw. The fixed and moving coordinates of ship are described and other relevant quantities are shown in Figure 1.

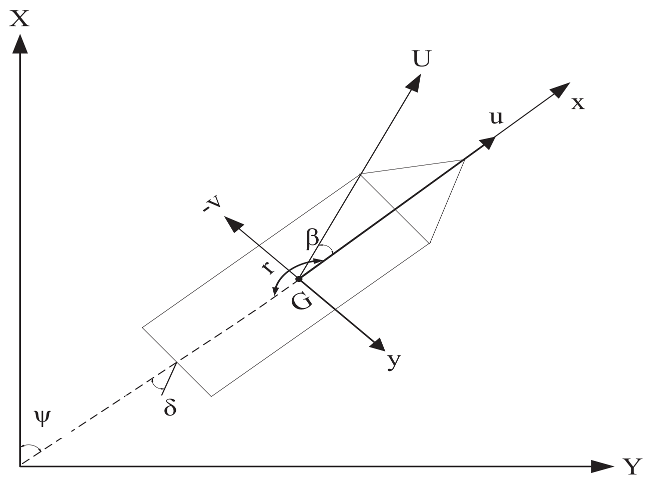

Figure 1. Fixed and ship coordinates

The mathematical expression of the surge, sway and yaw motions is given by Equation. 1.

$$
\begin{aligned}
&(m + m_x)\dot{u} - (m + m_y)vr - mx_G r^2 = X \\
&(m + m_y)\dot{v} + (m + m_x)ur + mx_G \dot{r} = Y \\
&(I_{zz} + mx_G^2 + J_{zz})\dot{r} + mx_G(\dot{v} + ur) = N
\end{aligned}
\tag{1}
$$

The total forces and moments are expressed as in Equation. 2. Subscripts H, P, and R denote hull, propeller, and rudder, respectively.

$$
\begin{aligned}
&X = X_H + X_P + X_R \\
&Y = Y_H + Y_P + Y_R \\
&N = N_H + N_P + N_R
\end{aligned}
\tag{2}
$$

The forces and moment acting on the ship are calculated with Equation 3.

$$X_H = -R_0 + X_{vv}v^2 + X_{vr}vr + X_{rr}r^2 + X_{vvvv}v^4$$
$$Y_H = Y_v v + Y_r r + Y_{vvv}v^3 + Y_{vvr}v^2 r + Y_{vrr}vr^2 + Y_{rrr}r^3 \quad (3)$$
$$N_H = N_v v + N_r r + N_{vvv}v^3 + N_{vvr}v^2 r + N_{vrr}vr^2 + N_{rrr}r^3$$

where X_{vv}, X_{vr}, X_{rr}, X_{vvvv}, Y_v, Y_r, Y_{vvv}, Y_{vvr}, Y_{vrr}, Y_{rrr}, N_v, N_r, N_{vvv}, N_{vvr}, N_{vrr} and N_{rrr} are known as hydrodynamic derivatives.

While calculating the propeller-induced forces and moment, Equation 4 is written assuming that a force acts in the direction of the ship's surge motion.

$$X_P = (1-t)T$$
$$Y_P = 0 \quad (4)$$
$$N_P = 0$$

Equation 5 expresses propeller-induced forces and moment depending on the rudder angle.

$$X_R = -(1-t_R)F_N sin\delta$$
$$Y_R = -(1-a_H)F_N cos\delta \quad (5)$$
$$N_R = -(x_R + a_H x_H)F_N cos\delta$$

The equation $F_N = (1/2)\rho A_R {U_R}^2 f_\alpha \sin\alpha_R$ can be used to calculate the rudder normal force F_N. ρ water density, A_R profile area of movable part of mariner rudder, U_R resultant inflow velocity to rudder, f_α gradient of the normal force coefficient, and α_R effective inflow angle to rudder. The studies by Yasukawa and Yoshimura (2015), Aksu and Köse (2017), and Budak and Beji (2021) were provided detailed information about the MMG model on how to calculate forces and moments. Hydrodynamic coefficient and main characteristics of Esso Osaka can be found in Rhee and Kim (1999), McTaggart (2005), and The Specialist Committee on Esso Osaka (2002).

2.2. Control Algorithm

The ship arrives at the determined target coordinates thanks to the created control algorithm. The angle difference between the ship's instantaneous position and the target coordinate is used as a reference in Equation 6. To eliminate this angle difference, a control system that controls the required rudder angle has been established. The PD controller determines the required rudder angle (Equation 7) to reach the target coordinates.

$$\psi_d = atan\left(\frac{y_{dp} - y_{sp}}{x_{dp} - x_{sp}}\right) \quad (6)$$

where ψ_d desired heading angle, x_{dp} and y_{dp} destination points, x_{sp} and y_{sp} instantaneous ship position.

$$\delta(t) = K_p e(t) + K_d \frac{de(t)}{dt} \quad (7)$$

If the ship encounters an obstacle on its way to the target coordinate, a new safe route can be generated automatically under the COLREGs rules. Before the simulation, the coordinates and size of the obstacle must be manually entered into the mathematical model. The proposed control algorithm incorporates the ship's maneuvering characteristics into the calculations when determining the new route to avoid collision. In other words, the desired command must be sent to the rudder while the

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ship is a certain distance away from the obstacle for the ship to proceed safely without colliding with it. As a result, the ship's maneuvering characteristics are added as input information to the control system in the mathematical model. In short, the equation is determined by the virtual coordinates, given in Equation 8 and Equation 9, so that the ship can avoid collision according to the COLREGs rules in case of an obstacle.

$$\begin{aligned} SY_{pe1} &= Ycoore - y_{sp} \\ SX_{pe1} &= Xcoore - x_{sp} \\ S\psi_{pe1} &= atan\left(\frac{Sy_{pe1}}{Sx_{pe1}}\right) \end{aligned} \tag{8}$$

where SX_{pe1} and SY_{pe1} the first virtual coordinates for the obstacle, $Xcoore$ and $Ycoore$ obstacle's coordinates.

The D value in Equation 9 represents the minimum distance required to pass from the obstacle at a safe distance. SX_{pe2} and SY_{pe2} represents the second virtual coordinates for the obstacle.

$$\begin{aligned} SY_{pe2} &= Ycoore + D + D * \cos\left(\left(\frac{\pi}{2}\right) - s\psi_{pe1}\right) \\ SX_{pe2} &= Ycoore + D * \sin\left(s\psi_{pe1}\right) \\ S\psi_{pe2} &= \operatorname{atan}\left(\frac{SY_{pe2}}{SX_{pe2}}\right) \end{aligned} \tag{9}$$

3. Simulations

The mathematical model, which included the maneuver model and the control system, was used in Esso Osaka's validation simulations. These performed simulations are turning circle and zigzag tests at varying ship speeds. When the obtained results are compared to the Esso Osaka ship's trial results (Bhawsinka (2011)), the mathematical model produces reliable results. It should be noted that the ship maneuvering characteristics obtained through simulations are used as input data in the developed control algorithm. Table 1 shows the basic dimensions of the simulated Esso Osaka ship.

Table 1. Main characteristics of Esso Osaka ship.

L_{pp} (m)	325.0
B (m)	53.0
T (m)	22.05
C_B (-)	0.831
x_G (m)	10.3
V (m/s)	5.144
D_P (m)	9.10
H_R (m)	13.85
A_R (m^2)	119.82

3.1. Validation of the maneuvering model

The proposed model was used to execute turning and zigzag tests on the Esso Osaka ship, and the ship's maneuvering characteristics were identified. Figure 2-a and Figure 2-b, the simulation results of

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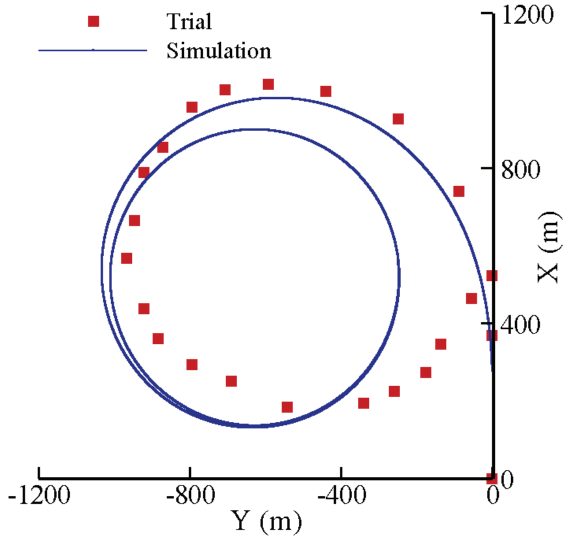
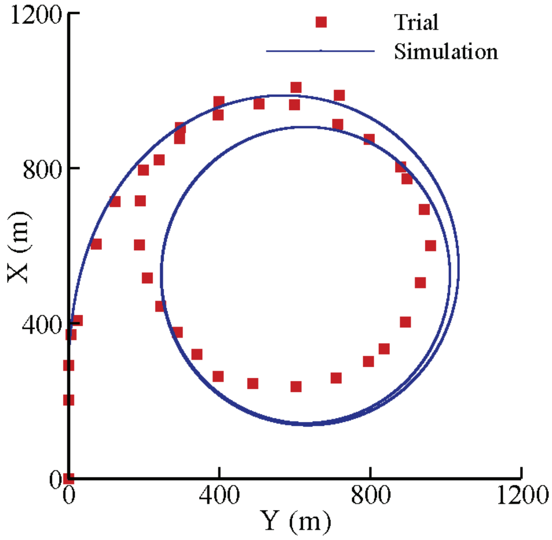
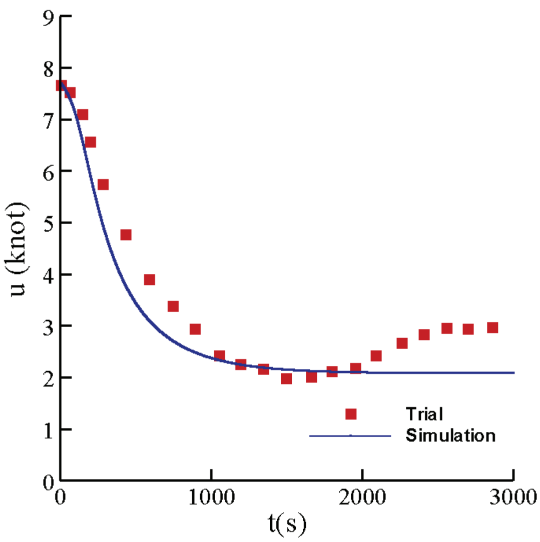
the turning tests at different speeds and the trial tests' results are given. Additionally, Figure 2-c and Figure 2-d depict graphs of the ship's velocity change during the turning test. When the simulation results are compared to the trial tests' results, it is determined that the mathematical model's results are compatible.



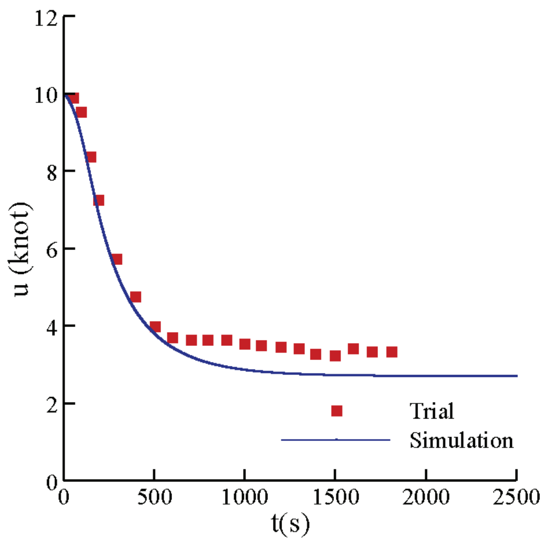
a) Turning circle for U= 7.7 knots.



b) Turning circle for U= 10 knots.



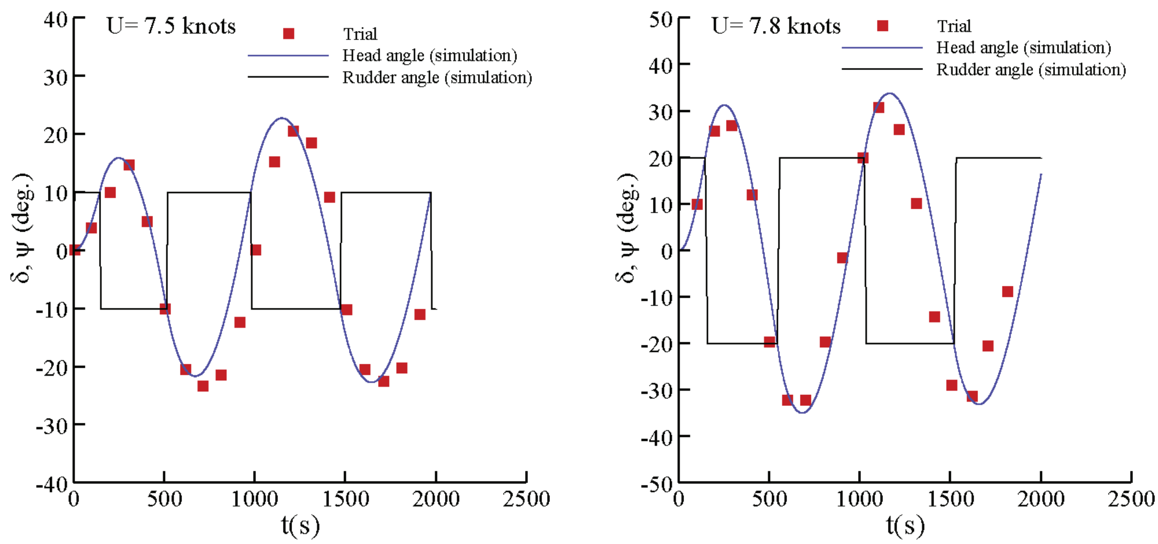
c) Surge velocity during turning circle for U=7.7 knots.



d) Surge velocity during turning circle for U=10 knots.

Figure 2. The comparison of the simulations results and the trial data for Esso Osaka ship. a) Turning circle for rudder angle -35°, b) Turning circle for rudder angle 35°, c) Reduction of surge velocity for rudder angle -35°, d) Reduction of surge velocity for rudder angle 35°

Figure 3-a shows the ship's 10/10 zigzag test result at 7.5 knots, and Figure 3-b depicts the ship's 20/20 zigzag test result at 7.8 knots. It can be shown that the trial tests and the simulation results are in near agreement. The findings of both the turning and zigzag tests will be used as data in the collision avoidance simulation that will be carried out as part of the study. As a result, it's critical whether the maneuvering model's outputs are accurate.



a) 10/10 zigzag test. b) 20/20 zigzag test.

Figure 3. The comparison of the zigzag tests results and the trial data for Esso Osaka ship

a) 10/10 zigzag tests, b) 20/20 zigzag tests

3.2. Simulation of collision avoidance system

Two different simulations were carried out depending on whether the ship encountered an obstacle in its movement towards the target coordinate. When there is no obstacle on the ship's route, the first obtained simulation result to reach the target coordinates is shown in Figure 4.

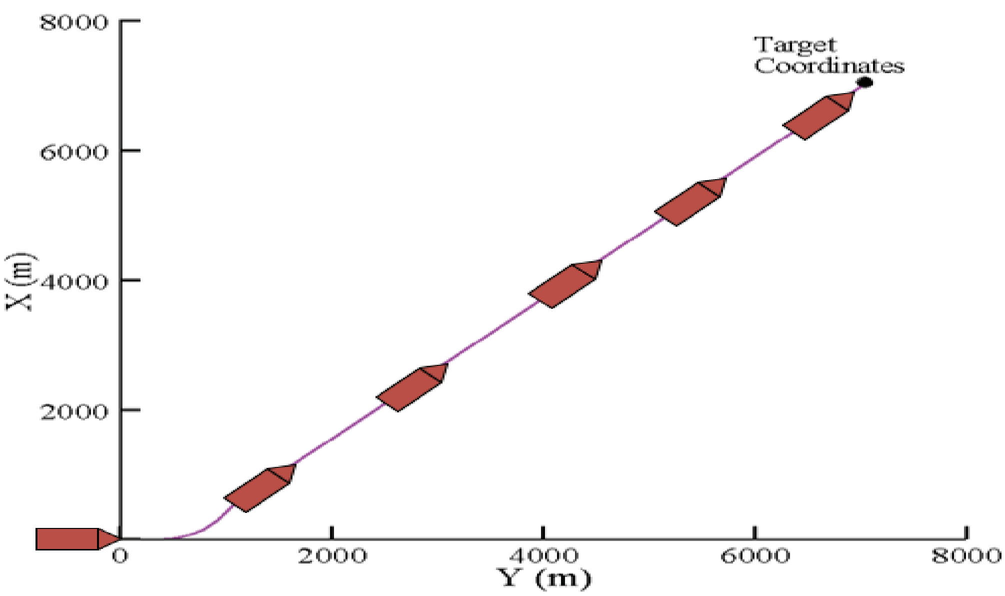


Figure 4. The obtained route for target coordinates without any obstacle

In the second simulations, firstly, two different sizes of the obstacle were defined, and these values were entered into the mathematical model as the initial data before the simulations were performed. The obtained routes were illustrated in Figure 5. The green line (Route 1) is for the obstacle's radius with 100 meters and the blue path (Route 2) is for obstacle's radius with 250 meters. These obtained ship's routes to the target destination are created according to the COLREGs rules. In terms of safe navigation, the size of the obstacle and the ship's maneuvering characteristics in the calculations are important to determine the virtual coordinates in the algorithm. As a result of simulation, the ship maintained a safe distance to the obstacle and arrived at the target coordinates without any colliding.

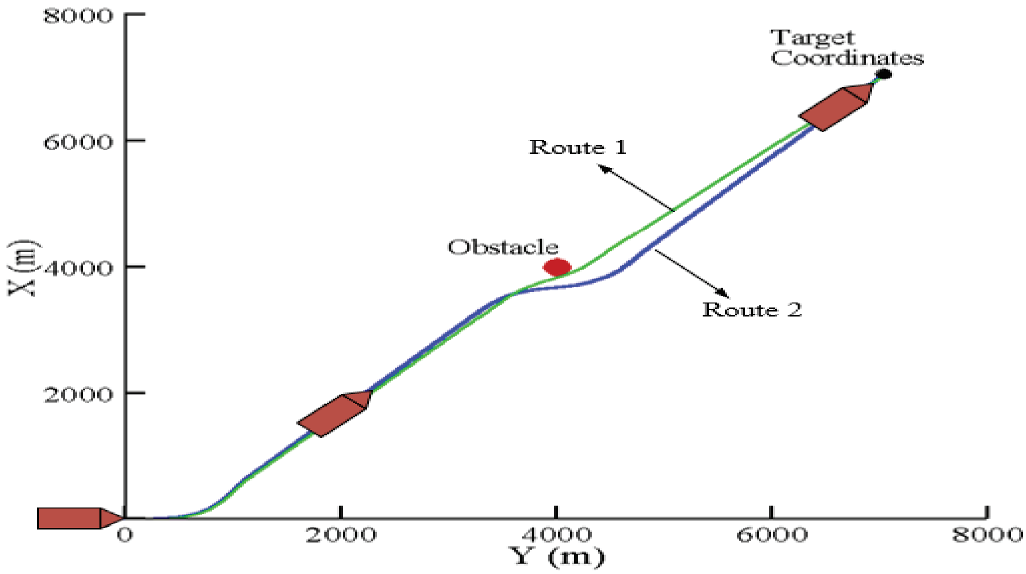


Figure 5. The obtained route for target coordinates with different obstacle sizes

4. Conclusion

The maneuvering model and control algorithm are included in the proposed collision avoidance system. The mathematical model is used to determine the ship's maneuvering characteristics as well as to determine a safe route to the target coordinates. Furthermore, under the COLREGs guidelines, a new path is developed so that the ship avoids colliding with an impediment on the trajectory. Simulations were used to determine the Esso Osaka ship's maneuvering characteristics, which were then compared to trial test results. Because the values of the maneuvering characteristics are used as data in the control algorithm to determine a safe route to avoid a collision, this validation is critical. In other words, the algorithm includes the maneuvering command that the ship begins to maneuver when it is within a certain distance of the obstacle. The size of the obstacle, on the other hand, is critical for safe passage. As a result, before running the simulation, the size of the obstacle should be employed into the mathematical model. The study used the COLREGs rules to find safe routes for two different-sized obstacles. Furthermore, the ship has been observed to reach the target coordinates both with and without obstructions. As a result, the collision avoidance system has determined that the ship arrives at the target coordinates safely and accurately. In the future study, the collision avoidance system will be developed for the situation of a ship colliding with one or more oncoming ships.

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