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AN AUTOMATIC COLLISION AVOIDANCE AND ROUTE GENERATING ALGORITHM FOR SHIPS BASED ON FIELD MODEL

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Key words: automatic collision avoidance, route generating, course-changing, track-keeping, velocity potential field, intelligent navigation, COLREGs.

ABSTRACT

This study used a velocity potential field approach to develop an automatic collision avoidance system and a route-generating algorithm for merchant ships. The system includes course-changing and track-keeping modes. The system based on the velocity potential of source/vortex and dipole flow theory in fluid dynamics. The course-changing mode creates a source/vortex flow vector to guide the ship away from various obstacles. The track-keeping mode generates a dipole flow field to steer the ship back to the desired course. An algorithm for collision avoidance maneuvers is implemented by using the real-time data of DCPA, TCPA, and bearing angle based on the results of maneuver simulation. Collision prevention regulations and international navigational rules are incorporated into the algorithm. The velocity potential field method is straightforward and very simple to implement; it avoids the problem of deadlock that hampers artificial potential methods and is suitable for the real-time path planning of complex static obstacles or ship encounter situations. The method has been applied to some typical test cases, including head-on, over-take, and crossing encounter situations with ships. The results prove that the proposed method is useful in finding safe paths for ships in encounter situations.

I. INTRODUCTION

Recently, marine traffic has been developing rapidly due to world shipping growth. This rapid growth has resulted in merchant vessels that are larger and faster than the merchant vessels of the past. Despite numerous advances in modern navigational equipment, ship collisions and groundings still frequently happen when ships navigate busy waterways; most collisions can be attributed to human decision failures. Intelligent navigation is one of the most effective approaches to minimize accidents due to human failures and to increase safety (Yang et al., 2007).

Collision avoidance and safe route finding are the most important problems for ship navigation in congested waterways and harbours. When ships are in an encounter situation, the navigator must find a safe route on which the ship can avoid collisions; this is traditionally assisted by automatic radar plotting aids (ARPA). The ship's ARPA system can process positional data, display the navigational situation on the radar screen, and allow the navigator to make reasonable decisions on what maneuver actions to be taken. Although ARPA has been used for many years, ARPA is not sufficient to eliminate marine accidents. Development of an intelligent ship navigation system to assist navigators is imperative, but such development is complex because of many limitations and constraints generated by ship maneuverability and the operating environment.

Traditional automatic ship navigation methods are mainly based on modern control theory; they model the dynamic behaviour of ships and the environment using mathematical or physical tools (Fossen, 1994). However, the uncertainties of the dynamic models and the complications of the operating environment limit the availability of such methods. Some approaches adopt evolutionary or heuristic algorithms to find an optimal global path (Ito et al., 1999; Smierzchalski and Michalewicz, 2000). These methods are useful for global route planning. It is difficult for these methods to produce appropriate results for localized route finding problems because of the real-time variations of local environmental situations.

To consider the influence of immediate environments, Lee et al. (2004) introduced a fuzzy logic autonomous navigation algorithm based on a potential field method. The artificial potential field (APF) method was first used by Khatib (1986) for robot path planning. The basic concept of APF is to fill the operating space with an artificial potential field such that the vehicle can be guided by the gradient of potential to avoid obstacles and move to its goal. The APF method allows real-time vehicle op-

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eration in complex environments and can indicate the behaviour of moving vehicles. However, the APF method manifests some problems such as deadlock, wandering in the vicinity of the target point, and low reliability of avoidance to mobile obstacles. Many solutions have been proposed to overcome the problems, for example, the solution of associating with other algorithms to eliminate the deadlock problem or the oscillation area, the solution of improving the basic function, and the solution of using a new potential field. Despite the problems and the high computational costs, the APF method has been widely used in automobiles and robots (Noto et al., 2012; Kovcs et al., 2016; Macktoobian and Shoorehdeli, 2016).

In recent years, some pioneer researchers, such as Xue et al. (2011), Xiao et al. (2012), Rong et al. (2015) have applied the APF concept to automatic trajectory planning and collision avoidance for marine vehicle traffic simulation. Marine vehicles usually must follow a predetermined course (e.g., the shortest path or the least risky path) as precisely as possible. Furthermore, COLREGs (International Regulations for Preventing Collisions at Sea) (IMO, 1972) guidelines must be followed to ensure collision avoidance. The original APF method that was developed for robots or automatic vehicles, however, fails to offer the flexibility and robustness needed by marine vehicles. Accordingly, the APF method must be modified or redesigned for marine vehicles.

Lee et al. (2004) proposed a modification to the potential field method, named Modified Virtual Force Field (MVFF) method, that reflected COLREGs guidelines and navigation rules. The MVFF method incorporates two behaviour parameters and a mode number to provide a certain level of flexibility in the selection of track maintenance or collision avoidance. Based on the artificial potential field method, Xue et al. (2011) proposed an algorithm to recognize the encounter situation of collision and a strategy for collision avoidance as well as a method of dynamic route generation that was implemented in an automatic simulation of ship navigation system. Xiao et al. (2012) described a microscopic nautical traffic simulation model with a new artificial force field function that resembled the function of charged particles moving through an electrical field, according to the rules of electrical forces. The APF method has also been used by Rong et al. (2015) in a preliminary study to simulate the marine traffic in the Tagus River Estuary. They developed a simulation model consisting of a ship collision avoidance algorithm based on the APF method; their algorithm incorporated the ship sizes, lateral distribution of traffic along the route, and speeds sampled from AIS data.

Two concepts have been used to develop the APF method for marine traffic (collision avoidance and route generating) systems. The first concept focuses on the APF model itself and uses the physical parameters of ship encounter situations and ship course information to modify the APF model (Xue et al., 2011). The second concept re-formulates the field model using some relevant physical rules or ship maneuvering behaviours (Lee et al., 2004; Xiao et al., 2012). The latter generates new force potentials based on navigation rules including COLREGs and the local operating rules of the congested waterway or inbound channel.

In the fields of automobile research and robotics research, many ideas for re-formulating the field function have been proposed. By using steady-state heat transfer theory, Wang and Chirikjian (2000) presented a new artificial potential field method for path planning of non-spherical single-body robots. Another artificial potential approach used the velocity potential of fluid mechanics to construct streamlines in a working space of a mobile robot moving around obstacles in a very natural way (Khosla and Volpe, 1988). The velocity potential field approach has the advantages of a very low computational cost and the capability of fast route generation without any deadlock, even in dynamic environments with moving obstacles. In addition, the method generates the desired velocity directly by finding the gradient of the potential function, which is an advantage from the autonomous navigation viewpoint. Shibata et al. (2014) proposed a collision avoidance algorithm with a velocity potential method that generated an obstacle-avoidance velocity vector for automobiles with local environmental recognition. Burgos and Bhandari (2016) presented a viable means for unmanned aerial systems to autonomously navigate and avoid obstacles with a combination of potential flow field and virtual force field methods. Hu et al. (2017) proposed an improved artificial potential field method based on potential flow theory; this method achieved a highly efficient mobile robot path planning. This study mainly focuses on an approach that avoids the local minimum and obstacles.

In this paper, we describe an automatic collision avoidance and route generating algorithm for ships. We implemented the velocity potential of the ideal flow theory in fluid mechanics to serve as an artificial potential field for guiding marine vehicles; the velocity potential field is the linear combination of the fundamental solutions of potential flow theory. The automatic collision avoidance system consists of two modes, namely, course-changing and the track-keeping modes, which based on the velocity potentials of vortex and dipole flow theory, respectively. The course-changing mode creates a velocity vector field of the vortex; that field guides give-way ships to turn away from obstacles or to avoid stand-on ships according to the guidelines of the international regulations for preventing collisions at sea (COLREGs). The track-keeping potential creates a dipole flow vector field to bring the ship back to the desired course.

On the basis of real-time maneuvering simulation data, including the distance at the closest point of approach (DCPA), time to closest point of approach (TCPA), and bearing angle, a collision avoidance algorithm was devised and implemented. The velocity potential field method is suitable for the real-time path planning of complex static obstacles and ship encounter situations. The algorithm considers the factors of ship navigation behaviours and marine environments and allows for establishing a model similar to conventional ship navigation practices.

The structures of this paper are arranged as follows. In section 1, the objective and the scope of this study are introduced. Section 2 investigates a three-dimensional dynamical model for ship navigation. In section 3, the topic of encounter situation and collision avoidance is described. The potential field method based

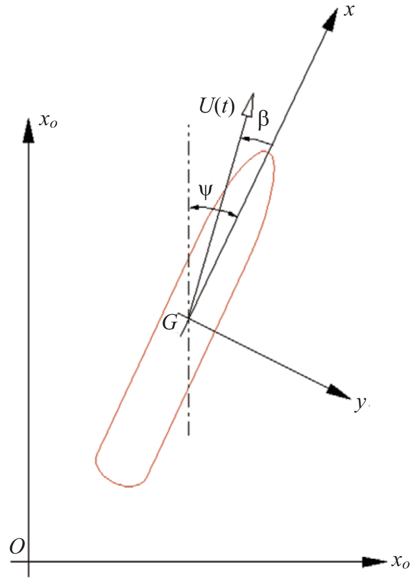


Fig. 1. Global and ship coordinate systems.

on the potential flow theory is explained in section 4. The vortex and dipole potential are used to model the course-changing and track-keeping operations. In section 5, the application of the proposed method to static obstacles and ships encounter problems are discussed to verify the effectiveness and feasibility of the algorithm. Finally, the conclusion is drawn in section 6.

II. THE DYNAMICAL MODEL FOR SHIP NAVIGATION

To fully represent a ship maneuvering on a water surface requires six-degree-of-freedom motion equations. It is customary assuming that the ship as a rigid body motion on the horizontal plane. Therefore, by neglecting the pitching, heaving and rolling degrees of motion, the mathematical model is simplified to the surging, swaying and yawing degrees of freedom. Let a ship navigate with the global and inertial (local) coordinate systems (see Fig. 1). The inertial coordinate system *G-xy* is attached to the ship; the *x*-axis is aligned along the ship's axis; the *y*-axis is taken in the starboard direction; and the origin is placed at the center of gravity *G*. The mathematical dynamical model of the planar motion of a ship maneuvering in inertial coordinates (*x, y*) is written as follows (Kijima, 1991; Yavin et al., 1995);

$$
\begin{aligned}
&m_1\left(\frac{L}{U^2}\right)\frac{d(U\cos\beta)}{dt}+m_2\left(\frac{L}{U}\right)r\sin\beta \;=X',\\
&m_2\left(\frac{L}{U^2}\right)\frac{d(U\sin\beta)}{dt}+m_1\left(\frac{L}{U}\right)r\cos\beta \;=Y',\qquad (1)\\
&I\left(\frac{L^2}{U^2}\right)\frac{dr}{dt}\;=N'.
\end{aligned}
$$

where t, L, U, β and r denote time (sec), the length between perpendicular (m), ship speed (m/sec), drift angle (*rad*) and yawing rate (rad/sec), respectively. The coefficients (m_1, m_2, I) represent the three components of the total mass/inertia coefficients. Also, X', Y' are the non-dimensional external forces along the *x* and *y*-axis, respectively, and N' is the non-dimensional yawing moment about the center of gravity of the ship.
with component building theory, the external hydrodynamic loads X', Y', and N' can be further decomposed into the following components:

$$
\begin{aligned}
X' &= X'_H + X'_P + X'_R,\\
Y' &= Y'_H + Y'_P + Y'_R,\qquad (2)\\
N' &= N'_H + N'_P + N'_R.
\end{aligned}
$$

The subscripts *H*, *P*, and *R* denote the contributions due to ship's hull, propeller, and rudder respectively. The hull-dependent terms can be expressed in terms of the various stability derivative coefficients, for examples, the typical terms $X'_0(Fn)$, $X'_{\beta n}$, X'_{uu}, Y'_β, Y'_r, Y'_{rr}, $Y'_{\beta\beta}$, $Y'_{\beta\beta r}$, $Y'_{\beta rr}$, N'_β, N'_r, N'_{rr}, $N'_{\beta\beta}$, $N'_{\beta\beta r}$, $N'_{\beta rr}$, and so forth. It is noted that all stability derivatives are considered as geometrical constants in the sense that they do not depend on the ship dynamics, i.e., on U, β, and r. They can be approximated by the parameters representing the ship geometry such as the ship slenderness ratio B/L where B is ship breadth, the hull aspect ratio $2d/L$ where d is ship draught, and the blockage coefficient C_B. The details of stability derivative coefficients and the models for propeller and rudder can be found in (Kijima, 1991; Yavin et al., 1995).

During the numerical study conducted here, we use a tanker as the test ship, the main particulars of the model ship were as follows: length L = 250 m, breadth B = 40.77 m, draught d = 16.96 m, with a block coefficient of C_B = 0.831.

III. ENCOUNTER SITUATION AND COLLISION AVOIDANCE

COLREGs are essential rules governing navigation and collision avoidance. The collision situations between two ships, defined in COLREGs, can be divided into head-on, crossing, and overtake encounters. The parameters used in the classification are the relative course angle (ψ_R) between the own ship (ψ_O) and a target ship (ψ_T), that is $\psi_R = \psi_O - \psi_T$ and the navigation speeds of the own ship and the target ship, V_O and V_T respectively. Table 1 lists the classification of the ship encounter types. The own ship should give way to all the ships which appear on its starboard side; it is not a stand-on ship until all other ships are on its port side. According to COLREGs, the navigator or an automatic collision avoidance system must decide whether a risk of collision exists and what maneuver actions must be taken for avoiding collisions. The operating procedures related to the permitted or required action from each vessel are described as follows.

Table 1. Classification of the ship encounter types (Xue et al., 2009).

Encounter type	Criteria
Heading-on	$\lvert\psi_R\rvert \geq 168.75^{\circ}$
Target ship being overtaken	$\lvert\psi_R\rvert < 68.75°$ and $V_O > V_T$
Target ship overtaking	$\lvert\psi_R\rvert < 68.75°$ and $V_O < V_T$
Target crossing starboard-to-port	$-168.75° < \psi_R < -68.75°$
Target crossing port-to-starboard	$68.75° < \psi_R < 168.75°$

Consider a scenario in which two ships navigate in open sea at long range: before any collision risk exists, both ships are free to take any actions. When two ships in sight of each other are approaching with no change of compass bearing, the two ships experience an encounter situation, and risk of collision first begins to apply. To minimize the possibility of uncoordinated ship maneuvers, COLREGs states that one ship, called the stand-on vessel, should maintain its course and speed, whereas the other, called the give-way vessel, is responsible for the avoidance maneuver (COLREGs rule 16 and 17). The give-way vessel is required to take early and substantial actions to achieve a safe passing distance.

Even though the COLREGs rules and regulations give priority to all the sailing ships' obedience to prevent collision accidents, they do not provide specific operating instructions, especially for the critical distance at which the collision avoidance operation first becomes a responsibility. Traditionally the navigator adopts empirical collision avoidance actions according to personal experience. This practice depends on a navigator using individual intuition to make decisions. An empirically critical distance will be much greater for high-speed vessels involved in a fine head-on or fine crossing situation. In a crossing situation involving two power-driven vessels in open sea, it is suggested that the distance at which avoidance maneuvers should be taken might be on the order of 5 to 8 nautical miles.

According to COLREGs, an automatic collision avoidance algorithm must decide whether a risk of collision exists and what maneuver should be taken to avoid collisions. Because no clear criteria exist for determining when the risk of collision is high enough to cause concern, a collision detection algorithm must be formulized.

IV. THE AUTOMATIC COLLISION AVOIDANCE SYSTEM

1. Conceptual Basis

A new artificial potential field model based on flow velocity potential was proposed and applied to generate a safe route for the give-way ship that performs collision avoidance and then turns back to its original course after passing clear of the stand-on ship and completing collision avoidance. The velocity potential field model is consonant with the concept of ship handling. Generally, the principle of ship handling is to know and anticipate how a ship behaves under all circumstances and what operations should be given to make the ship behave and move exactly along its route. Course-changing and track-keeping are two commonly used operation modes for seafarers.

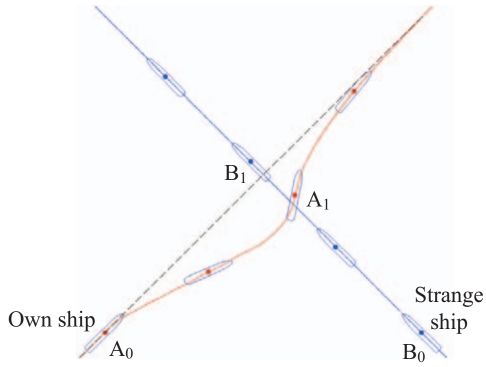


Fig. 2. Two ship encounter situation of target crossing starboard-to-port.

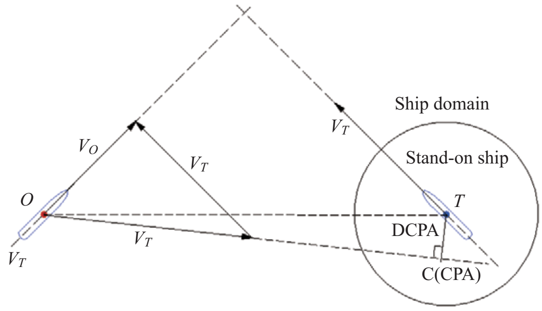
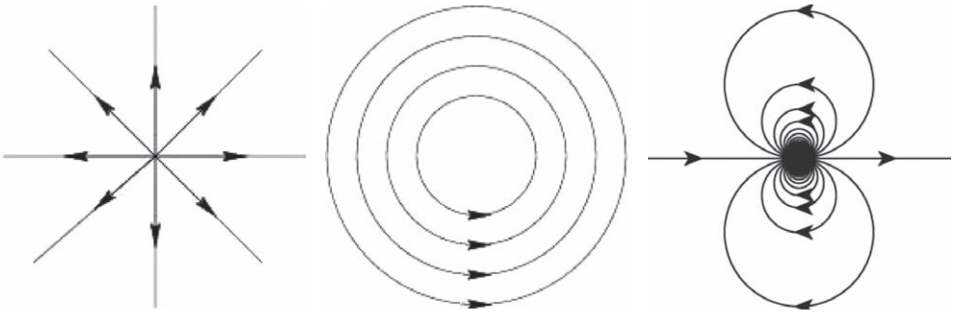


Fig. 3. Two-ship encounter situation and navigating parameters.

Consider the encounter situation illustrated in Fig. 2, in which the target crosses starboard-to-port. Suppose at the time t_0, the own ship in the position of A_0 sights a strange ship at B_0; the navigating courses for the two ships to follow are depicted by the corresponding straight line. The collision avoidance algorithm begins to work while the distance between the two ships is less than the one specified to begin the collision avoidance operation. The own and strange ships are identified as the give-way and the stand-on ships in the crossing situation, respectively, according to the COLREGs. The give-way ship performs a course-changing operation to avoid collision, by changing its heading; the give-way ship maneuvers to the starboard side to avoid collision. This maneuver strictly follows COLREGs in terms of avoiding crossing the path of a stand-on ship. The stand-on ship maintains its course and speed, and thus allows a port-to-port safe passing maneuver. The actual safe route for the give-way ship is similar to a course depicted in Fig. 2. At time t_1, the give-way ship at position A_1 passes clear of the stand-on ship (at B_1) and then begins to maneuver back to its desired route.

Fig. 3 illustrates the navigating parameters used in the collision avoidance operation in a two-ship crossing encounter. The own ship at position O is sailing with a velocity of $\mathbf{V}_O$, and the strange ship at position T is sailing with a velocity of $\mathbf{V}_T$. Also, $\mathbf{V}_{OT} = \mathbf{V}_O - \mathbf{V}_T$ is the relative velocity of the own ship



(a) (b) (c)

Fig. 4. Streamlines of a source, vortex, and dipole.

with respect to that of the strange ship. The circle around the strange ship is a dangerous region of collision of which the radius is the safe passing distance R_S. Point C is the closest point of approaching (CPA), the distance between C and T is the distance to the closest point of approaching (DCPA), and the time of the own ship sailing from O to C is the time to closest point of approaching (TCPA).

In this study, the algorithm adopted for an automatic collision avoidance system can be written as follows.

(1) The algorithm examines whether the strange ship is within the collision checking range, that is, if the distance between the own ship and strange ship D_{OT} is less than the distance specified for beginning the collision avoidance operation D_B, i.e., $D_{OT} < D_B$, then the own ship begins to check for the existence of collision risks.

(2) The encounter type, as well as the give-way and stand-on ships, are also specified. The necessary conditions to begin a collision avoidance operation include a DCPA less than the safe passing distance and a positive TCPA, that is, DCPA < R_S and TCPA > 0, respectively.

(3) The collision avoidance operation is adopted by changing courses to generate a safe route that is to be used as a primary means of avoiding a collision in normal circumstances. In this study, the course-changing mode was used to guide the give-way ship to alter course and navigating along a route that satisfies COLREGs.

(4) The effectiveness of the action is continuously investigated until the strange ship has passed and is well clear. An acceptable well clear is determined by the non-existence of collision risks, and the necessary conditions for finished collision avoidance operation involve a DCPA greater than the minimum safe passing distance, a negative TCPA, and abaft the beam, that is, DCPA > R_S, TCPA < 0, and bearing angle $\lambda > 90°$, respectively.

(5) Finally, after the give-way ship has kept well clear of the ship to be passed, the automatic collision avoidance algorithm performs a maneuver of the track-keeping mode; that maneuver guides the give-way ship as it alters course and sails back to its original track.

2. The Velocity Potential for Path Planning

In fluid dynamics, potential flow theory describes the velocity field as the gradient of a scalar function, namely, the velocity potential function, which can be defined for various simple flows, for example, source, sink, vortex, and dipole flow. The source flow is a purely radial flow with no component of circumferential velocity. The flow goes away from the origin at a velocity of $v_r = m/r$ and $v_\theta = 0$, where m is the volumetric flow rate (also called the strength of the source). (v_r, v_θ) is the flow velocity vector in the polar coordinate system. The velocity potential for this flow can be derived as $\phi_s = \pm m \ln r$, where the positive sign stands for a source flow, and the negative sign stands for a sink flow that flows inwards.

A free vortex is a flow that goes in a circumferential direction with no radial flow. The flow velocity $(v_r, v_\theta) = (0, K/r)$, where K is the strength of vortex with which the circumferential velocity v_θ is infinite at the origin, decreases as r increases and becomes zero as r approaches infinity. The velocity potential can be derived as $\phi_v = K\theta$.

These potential functions can also be superimposed with other potential functions to create more complex flows. A dipole is the superposition of an infinitely close pair of a sink and a source with mass flow rates that have the same absolute value. The flow velocity potential and the velocity components in polar coordinates are

$$\phi_d = \mu \frac{\cos(\theta - \alpha)}{r^2}, \tag{3}$$

$$(v_r, v_\theta) = (\frac{\mu \cos(\theta - \alpha)}{r^2}, \frac{\mu \sin(\theta - \alpha)}{r^2}), \tag{4}$$

where μ is the strength of dipole, and α is the angle of the dipole axis to the positive x-axis, with which the dipole axis is defined as the direction from source to sink. The streamlines are the circles tangent to the dipole axis; the equipotential lines are also circles. The streamlines for a source, vortex, and dipole are sketched in Fig. 4.

This actual course can be determined using the artificial

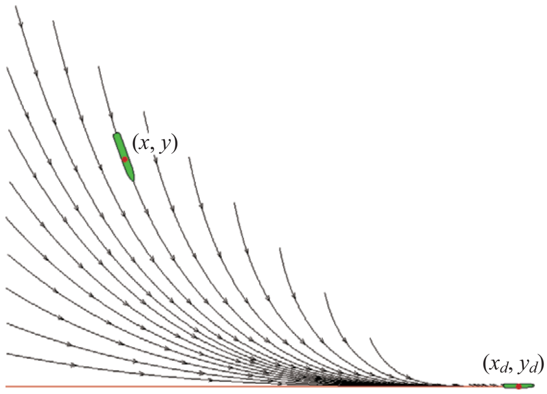


Fig. 5. Streamlines generated by track-keeping potential.

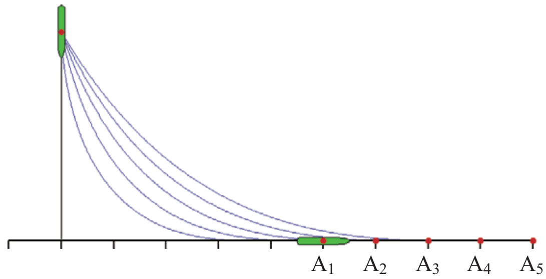


Fig. 6. Streamlines generated by track-keeping potential.

potential field method. The artificial potential field acts in a way reminiscent of flow velocity potential, especially for the source, vortex, and dipole potentials. Accordingly, the premise of the path planning method proposed in this study is to use potential flow theory to create a velocity vector field from simple potential flow elements and adopt the resulting velocity vector direction angle as the course angle command to steer the own ship. Figs. 5 and 7 illustrate the potential flow field created from various simple flows, dipoles, and vortexes respectively, depicting how a ship could use the velocity field vector direction angle to navigate around and avoid collisions with obstacles.

3. The Track-keeping Mode

The objective of the track-keeping mode is to steer the vessel back to the predefined track presuming that the vessel has involuntarily deviated from this track, or has completed a collision avoidance operation. The concept of the proposed algorithm is to introduce a virtual vessel (the leadership) that moves along the predefined track and is in front of the own ship. The virtual vessel acts as a transient destination that provides a proper return mode for the own ship to correct its course from a deviated position. Moreover, the return mode is determined by the position and speed of the virtual vessel.

The track-keeping mode supposes that the virtual vessel carries a dipole with its axis reverse to the track direction. Fig. 5 illustrates the streamlines generated by track-keeping potential. Consider a scenario in which the own ship is located at the position of (x, y) that deviates from this predefined track. A virtual vessel located at (x_d, y_d), the track-keeping potential can be defined as follows.

$$\phi = \phi_d = \mu \frac{\cos(\theta - \alpha)}{r^2}, \quad |\theta - \alpha| \le \frac{\pi}{4} \tag{5}$$

where $r = \sqrt{(x - x_d)^2 + (y - y_d)^2}$ is the distance between the own ship and the virtual ship, $\theta = \tan^{-1}(y - y_d)/(x - x_d)$ is the angle between the position vector of own ship and x-axis, (r, θ) are the coordinates of a polar system originated at (x_d, y_d), and α is the direction angle of the dipole axis.

The velocity components of $\mathbf{v} = (v_x, v_y)$ are

$$\begin{aligned} v_x &= v_r \cos\theta + v_\theta \cos(\theta + \pi/2) \\ v_y &= v_r \sin\theta + v_\theta \sin(\theta + \pi/2) \end{aligned} \tag{6}$$

and the desired course angle is $\psi = \tan^{-1}(v_y/v_x)$,

For simplicity, the speed of the virtual vessel is equal to that of the own ship for all points in time, hence, the initial position of the virtual vessel gives the parameters of return mode to determine the desired track. Fig. 6 illustrates the path line created by track-keeping potential with various mode parameters. The shorter the distance is between the virtual vessel and the own ship, the greater emphasis is set on a quick return to the desired track. The tracks from left to right correspond to a virtual vessel at the locations ranging from A_1 to A_5.

4. The Course-changing Mode

The objective of the course-changing mode generates a direction to guide the ship as it turns away from obstacles and leads the give-way ship in a collision avoidance operation following the COLREGs guidelines. The direction is evaluated by the course-changing potential based on the assumption that a vortex and a source are carried on the stand-on ship. The effective range of the vortex is the distance that the give-way ship begins to perform the avoidance collision operation R_V; the effective range of the source is the safe passing distance R_S. In this study, we specified the ship domain of give-way ship as the safe passing distance and commonly specified 5 to 8 nautical miles to R_V according to the relative speed of the ships in an encounter situation, ensuring that the avoidance operating time was greater than 20 minutes.

Typical streamlines of course-changing potential as depicted in Fig. 7 can be generated by a counter-clockwise vortex and a source are set to (x_v, y_v). Consider a crossing encounter in which the positions of the stand-on and give-way ships are (x_v, y_v) and (x, y). The course-changing potential can be defined as follows.

$$\phi = (1-\sigma)\phi_v + \sigma\phi_s = (1-\sigma)\tau\theta + \sigma m \ln r \tag{7}$$

where $r = \sqrt{(x - x_v)^2 + (y - y_v)^2}$ is the distance between the stand-on and the give-way ships and $\theta = \arctan(y - y_v)/(x - x_v)$

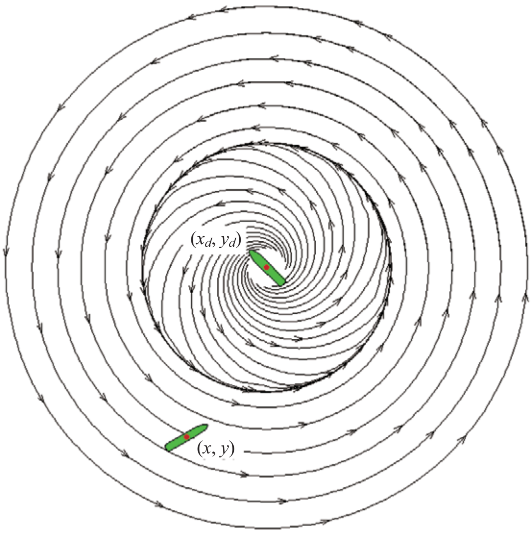


Fig. 7. Streamline of course-changing potential.

is the angle between the position vector of the own ship and the x-axis, (r, θ) are the coordinates of a polar system with its origin at (x_v, y_v) and σ is the linear interpolation factor. If $\sigma = 0$ we retain the vortex potential, if $\sigma = 1$ we receive the source potential. The velocity components in the polar coordinate system are depicted below.

$$v_r = \sigma \frac{m}{r}, \quad v_\theta = (1-\sigma)\frac{\tau}{r}. \tag{8}$$

The velocity components in Cartesian coordinate (v_x, v_y) can be obtained by the transformation equations, the Eqs. (6), and the desired course angle is $\psi_v = \arctan(v_y/v_x)$. In the present study, we specified $m = \tau = 1$ and

$$\sigma = \begin{cases} 1 & R_s < r \le R_V \\ 0 & 0 < r \le R_s \end{cases} \tag{9}$$

V. SIMULATION RESULTS

To validate the proposed method, we conducted a number of simulation studies regarding the performance of the velocity potential field model for the ship navigation and collision avoidance algorithm. A PID (Proportional-Integral-Derivative) steering control was used for the simulations. A variety of ship encounter situations, such as head-on, crossing, and over-take situations, were included. Unless additionally noted, all coordinate systems or distance units are expressed in nautical miles (nm), all times are in minutes (min), and all speeds are in knots (*kts*).

1. Static Obstacle

The first case considered an own ship proceeding to a static obstacle. Initially, the own ship was at (0,0); it navigated with a course of 090° and a speed of 15. An obstacle of diameter

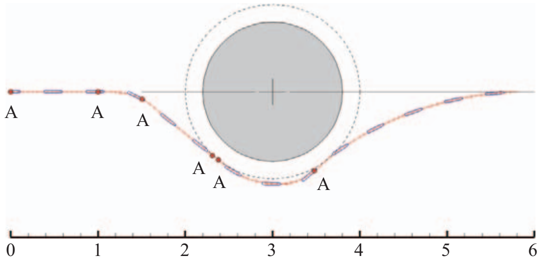


Fig. 8. Trajectory of the case of static obstacle avoidance.

1.6 was at the position (3, 0). It was assumed that the safe passing distance from the obstacle outer boundary was 0.2. The obstacle avoidance operation was activated when the distance between the ship and the obstacle boundary was less than 1.2. Fig. 8 illustrates the trajectory of the own ship sailing with the collision avoidance system. The maneuvering parameters are depicted against time in Figs. 9(a)-9(f), including the track-keeping and course-changing commands, the course over ground (COG), the bearing angle (λ), the distance to closest point of approach (DCPA), the time to closest point of approach (TCPA), and the degree of collision risk (CR).

From the trajectory (Fig. 8) and the output command history of the collision avoidance system (Fig. 9(a)), an explanation of the obstacle avoidance process is as follows. At time 0, the own ship was navigating along the designed track with the initial settings; the track-keeping mode was in operation. At time 4.0, the own ship arrived at position B (1.0,0.0), where the distance between the ship and the obstacle boundary was 1.2. Accordingly, the own ship commenced the avoidance operation; it activated its course-changing mode and de-activated its track-keeping mode. At the early stage of the avoidance operation from time 4 to time 6, corresponding to the ship track from position B to C, the automatic system steered the ship starboard and thus turned away from the obstacle until the criteria of the system were satisfied. At time 6.1, the own ship arrived at position C (1.51,-0.08); the DCPA was greater than 0.2 from the obstacle boundary. Because the DCPA was greater than the acquired safe passing distance, the automatic system enacted a steady-handling command to navigate on course 125°. The interchange of the course-changing mode and the steady-handling command occurred two times to maintain the course. No further actions were taken until the ship was closer to the obstacle. At time 10.4, the own ship navigated to position D (2.32,-0.74), the CPA, where the distance from the obstacle outer boundary to the own ship was equal to the DCPA and the TCPA was equal to zero. The ship firstly passes through the closest point of approach. After that, at time 10.7, the own ship reaches E(2.38,-0.78), where the bearing angle is greater than 90° on the port side. At position E, the DCPA > 0.2, TCPA < 0 and bearing angle $\lambda > 90°$, and the system criteria are all satisfied. Consequently, the automatic system stops the course-changing mode while the track-keeping mode is activated to navigate the ship back to the designed track. The output of the collision avoidance system is listed in Table 2 and the time histories of track-keeping and course-changing

Table 2. Responses of the collision avoidance system, where F(FALSE) and T(TRUE).

Time	DCPA > 0.2	TCPA < 0	$\lambda > 90°$	System Response mode
4.0	F	F	F	Changing-course
6.1	T	F	F	Steady-handling
10.7	T	T	T	Track-keeping
12.3	T	F	F	Steady-handling
12.8	T	F	T	Track-keeping

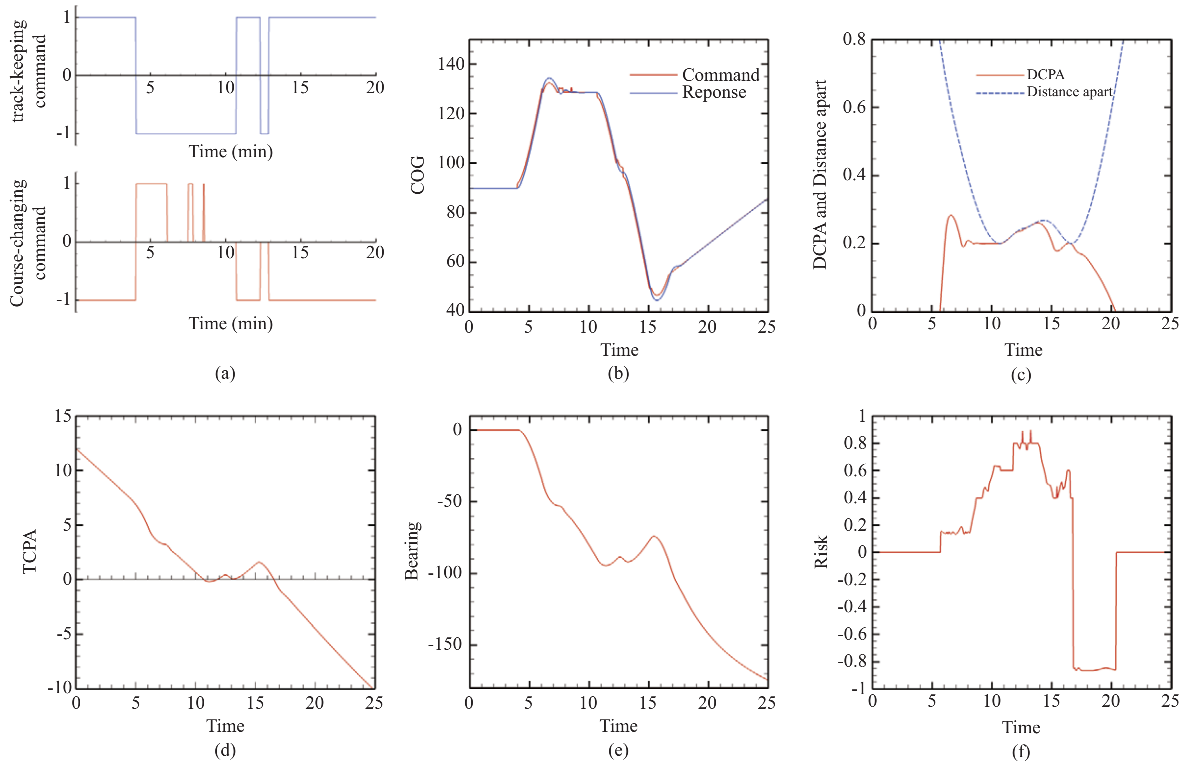


Fig. 9. Maneuvering parameters for avoiding a static obstacle.

commands are depicted in Fig. 9(a). The track-keeping mode is implemented by a dipole which was carried by the virtual ship and creates a flow velocity field. In this case, the virtual ship is located at a fixed position (6, 0) at which the own ship would navigate back to the original track. At position E, the own ship begins to turn its head to port side based on the velocity potential of the dipole. Because of the port side steering which leads to the TCPA> 0 and the bearing angle $\lambda < 90°$ again at time 12.3. Therefore, A short period of steady-handling command was performed to keep the course. Finally, at time 12.8, the bearing is greater than 90°, the track-keeping mode activates to bring the own ship to fit the original track gradually. At time 27, the own ship arrives at the destination position with required course 090°.

The COG command generated by the collision avoidance system and the response COG of the own ship is compared in Fig. 9(b). In this case, a COG filter limits the COG command in a maximum of 2 degrees variation from the course of the ship. The result illustrates that the response COG followed the command well. The DCPA and the distance of the own ship from the obstacle boundary are depicted in Fig. 9(c). The collision avoidance system always keeps the distance from the obstacle boundary greater than the safe passing distance. The TCPA against time was depicted in Fig. 9(d). Besides the track from E to F, in the nearby region of the obstacle, the TCPA decreased monotonically as a result of the own ship proceeding to or depart from the obstacle. The interplay of the track-keeping mode and steady-handling command within the period of 10 to 15, leading to a different trend. Fig. 9(e) illustrates the time history of the bearing angle and it is similar to the TCPA.

The collision risk model proposed by Bukhari et al. (2013) is used in this paper. The system consists of three layers. The input layer acquires the input parameters including DCPA, TCPA and VCD (variance of compass degree) to calculate the collision risk. The fuzzy inference layer is responsible for applying fuzzy rules and generating an intelligent decision. The display layer pre-

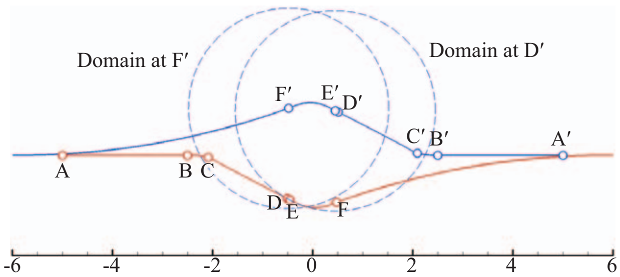


Fig. 10. Trajectories of ships in a head-on situation.

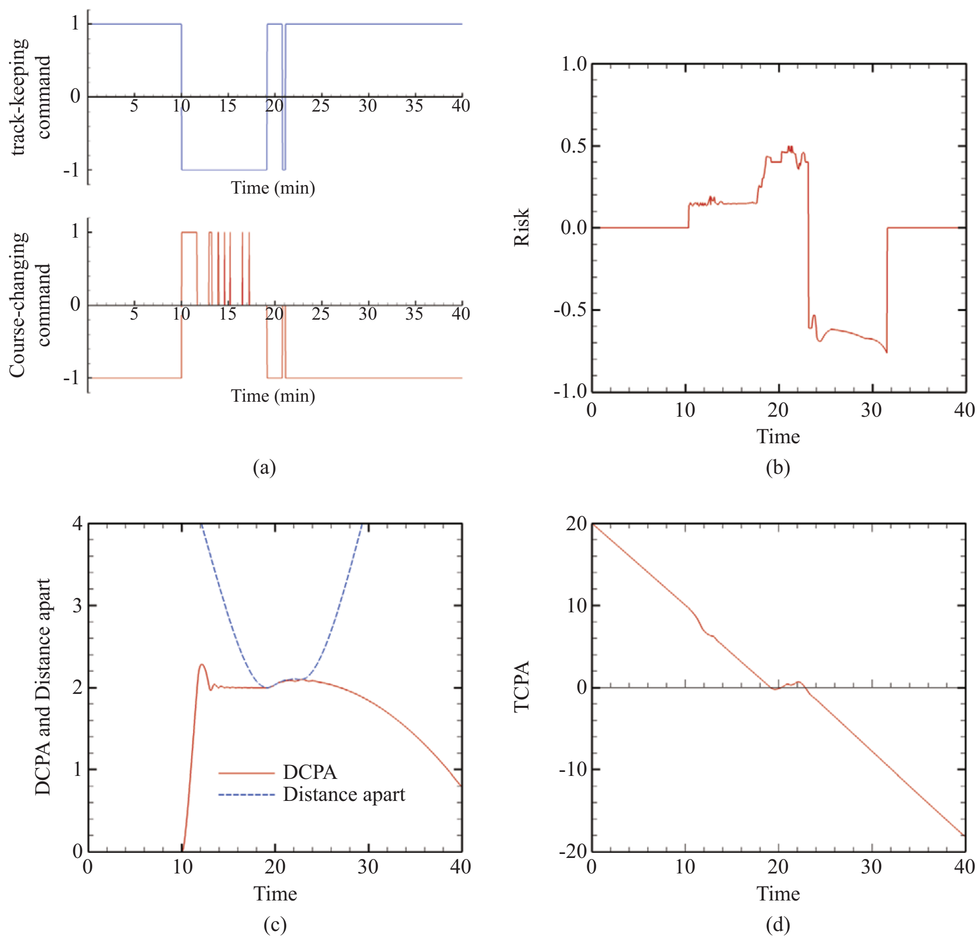


Fig. 11. Maneuvering parameters of own ship in a head-on situation.

sents the results in human readable format or builds the results in the automatic collision avoidance system. Fuzzy model of Mamdani type is built based on the fuzzy rules with linguistic variables. The collision risk model is established using the fuzzy logic approach employing the fuzzy IF-THEN rules from human knowledge and reasoning processes, followed by a concept mapping. It provides a tool for working directly with the linguistic terms commonly used in performing collision risk assessment. There are five linguistic values, including PS, PMS, PM, PMB, and PB, for DCPA, eight values, adding NB, NM and NS, for the variables VCD and CR (the degree of collision risk). The membership functions and fuzzy reasoning rule tables can be obtained from Bukhari et al. (2013). In this study, a fuzzy inference system is established for acquiring the degrees of collision risk that were subsequently adopted as one of the criteria for starting and terminating the collision avoidance operations. Fig. 9(f) illustrates the time history of the collision risk. At time 4, the system begins with the collision risk evaluation. The collision risk increases with the own ship approaching the obstacle, which results in the decrease of the TCPA, within the period of 4 to 11. A higher collision risk occurred later due to the decrease of a variance of compass degree (VCD) when the own ship navigates around the obstacle from E to F in the track. At the time of 16.6, the collision risk was eliminated, the track-keeping mode steered the own ship to the designed track.

2. Head-On Encounter Situation

The second scenario is a head-on situation to demonstrate the performance of the proposed collision avoidance system. Initially, the own ship is set to A (-5, 0) and navigates with a course of 090° and a speed of 15. The target ship is set to A′(5, 0) and navigates with a course of 270° with speed same as the own ship. Both target and own ships are expected to deviate appropriately as the give-way ships, and later the two ships will expeditiously return to the planned track. Assume that the safe passing standoff distance between the own ship and the target ship is 2. The activation of the collision avoidance operation is set to perform when the distance between the ships is less than 5. Fig. 10 illustrates the trajectories of the own and target ships obtained by the collision avoidance operation.

At time 10, the own ship arrives at the position B (-2.5, 0.0) and the target ship reaches the position B′ (2.5, 0.0), both ships commence the collision avoidance operation, activate the course-changing mode and deactivate the track-keeping mode. The output command history of the collision avoidance system depicted in Fig. 11(a). A pair of co-rotating counterclockwise vortices, with centers fixed on both ships, is set to implement the avoidance operation. Both ships performed starboard turn maneuvers with the direction guided by the velocity field of the vortex pair. In compliance with the COLREGs rule, both ships passed port to port for a head-on encounter.

The output command history of the collision avoidance system is similar to the previous case of static obstacle. At time 11.7, the own ship arrives at the position C with a course of 118° and the target ship at C′ with a course of 298°. The DCPA is 2.0 and is greater than the acquired safe passing distance. Therefore, a steady-handling command is activated by the automatic system. The interplay of changing-coarse and steady-handling commands occurred several times to keep the DCPA greater than the safe passing distance. At time 19.1, the own ship keeps the course and navigates to the position D, the CPA where the distance between the two ships is equal to the DCPA and the TCPA is zero. The two ships passed through the closest point of approach. After that, the own ship reaches E and the target ship arrives at E′, where the bearing angle of the two ships is greater than 90° on port side. At position E and E′, the situation of the two ships, i.e., DCPA > 2.0, TCPA < 0 and bearing angle $\lambda > 90°$, satisfies the criteria so that the automatic system activates the track-keeping mode to navigate the ship back to the designed track. At time 23.2, the own ship arrives at the position F, the target ship at F′ where the collision risk vanished, the track-keeping mode directs both ships to the designed track. The time histories of DCPA and the distance of the own ship departing from the target ship are depicted in Fig. 11(c). The collision avoidance operation changes the ship course to preserve the DCPA and the distance is greater than the safe passing distance during the encounter. The collision risk and TCPA against time are depicted in Figs. 11(b) and 11(d), respectively.

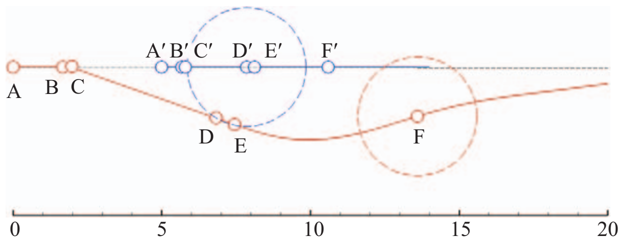


Fig. 12. Trajectories of ships in an over-take situation.

The comparison of the maneuvering parameters between the cases of static obstacle and head-on encounter, similar time histories pattern is attained. The case of head-on encounter is considered as a moving obstacle problem. It is successfully completed with the automatic collision avoidance system.

3. Over-Take Encounter Situation

The third scenario is an over-take encounter situation. Initially, the own ship is set to A(0,0) and navigates with a course of 090° and a speed of 15. The target ship is set to A′ (5,0) and proceeds with the same course as the own ship, however, using a speed of 5. The own ship overtakes the target ship from the stern and maneuvering according to the COLREGs rules such that the own ship should keep out of the way of the target ship. It is worth noting that the COLREGs rules do not explicitly specify which side the ship should overtake on. Hence, both the starboard and port turn maneuvers can be allowed in the algorithm. In this case, the own ship performed starboard turn maneuvers and passed on the starboard side of the target ship. We assume that the safe passing distance between the own ship and the target ship is 2. The activation of the collision avoidance operation is set to take place when the distance between the ships less than 4.

Fig. 12 illustrates the trajectories of the own and target ships obtained by the collision avoidance operation. The actuation points A, B, C, D, E and F are depicted on the track of the own ship, and the explanation is as follows. Point A is the initial position and the course-changing mode is activated at B. The steady-handling command is activated at C to keep the course and the DCPA greater than the acquired safe passing distance. Point D is the closest point of approach, the track- keeping mode is activated at E and the encounter well cleared at F. The actuation points A′, B′, C′, D′, E′ and F′ are depicted on the track of the target ship, which represent the corresponding points of A, B, C, D, E and F.

The maneuvering parameters against time are depicted in Figs. 13(a)-(d). The output command histories of the collision avoidance system are depicted in Fig. 11(a) and the patterns are similar to the case of head-on encounter. The time histories of DCPA and the distance of the own ship departing from the target ship are depicted in Fig. 11(c). The collision avoidance operation changes the ship course to preserve the DCPA and keep the distance greater than the safe passing distance during the encounter. The collision risk and TCPA against time are

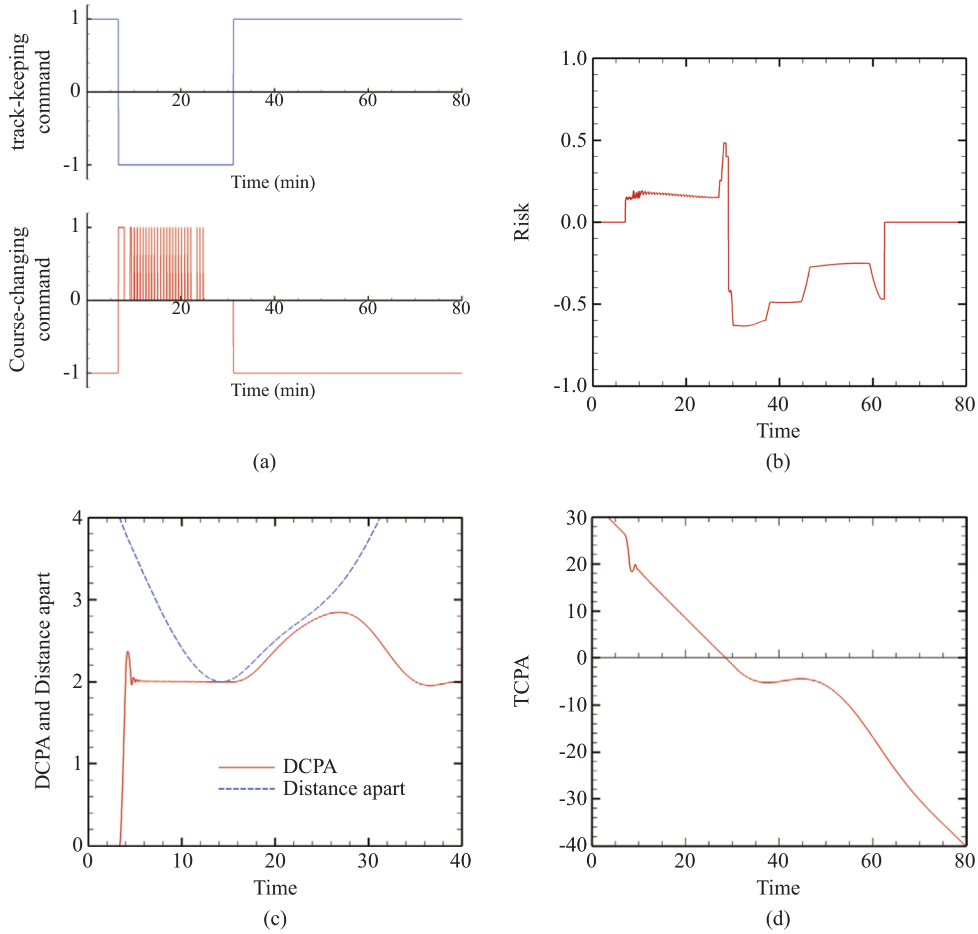


Fig. 13. Maneuvering parameters of own ship in an over-take situation.

depicted in Figs. 11(b) and 11(d), respectively. The proposed method provides successful maneuvers.

4. Crossing Encounter Situation

The fourth scenario is a crossing situation. Initially, the own ship is set to A(0, 0) and navigates with a course of 045° and a speed of 15. The target ship is set to A′(5, 0) and navigates with a course of 315° with the speed same as the own ship. Fig. 14 illustrates the crossing situation of the own and target ships. As COLREGs rule 15 states that the own ship which has a ship approaching from its starboard side should maneuver and avoid passing ahead of the target ship. In this case, we assume that the safe passing distance between the own ship and the target ship is 1. The activation of the collision avoidance operation is set to initiate when the distance between the ships is less than 4.

Fig. 14 illustrates the trajectory of the own and target ships obtained by the collision avoidance operation. The actuation points A, B, C, D, E and F are depicted on the track of the own ship, and the activations with respect to each point are same as the previous case of the over-take encounter. The maneuvering parameters against time are depicted in Figs. 15(a)-(d), from which it can be seen that the proposed system provides successful maneuvers. The output command histories of the collision avoidance system are depicted in Fig. 15(a) and the patterns are similar to the previous cases of the head-on and over-take encounters. It illustrates that the proposed method can ensure consistent results among the three fundamental encounter situations.

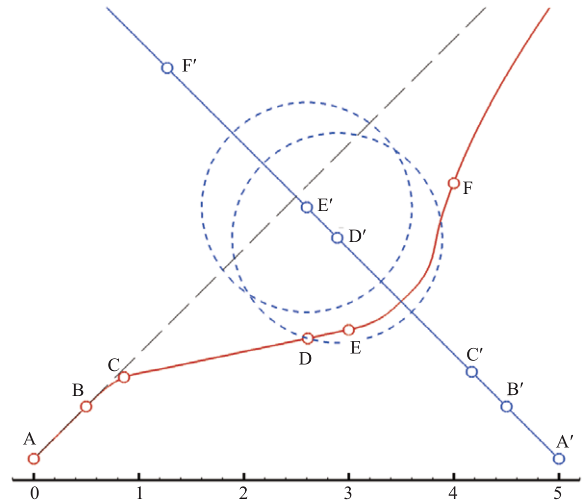


Fig. 14. Trajectories of ships in a crossing encounter situation.

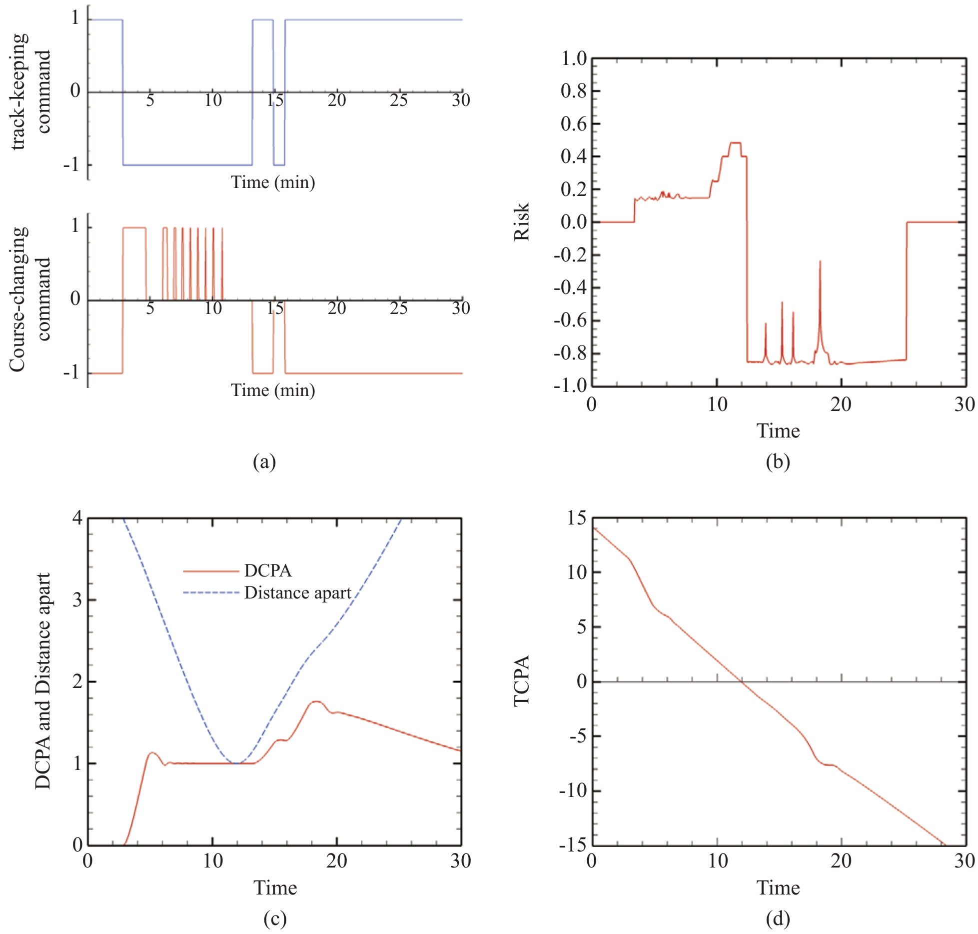


Fig. 15. Maneuvering parameters of own ship in a crossing encounter situation.

VI. CONCLUSIONS

The paper describes the design and primary application of an automatic collision avoidance system based on the approach of artificial potential fields to simulate ships in encounter situations. The field approach is based on the potential theory of source, vortex, and dipole in fluid dynamics; the velocity vector exhibits either course-changing or track-keeping behaviors. A maneuver algorithm for collision avoidance was implemented using real-time data of DCPA, TCPA, and bearing angle from ship navigation simulation. Furthermore, COLREGs rules were incorporated into the algorithm. The results of ships encounter simulations proved that collision avoidance was successfully realized using the proposed method. The case studies indicate that the velocity potential field model is consonant with the concept of ship handling and appears to be well-suited for the proposed automatic collision avoidance algorithm.

Much work remains to be done to improve this automatic collision avoidance system. For example, multiple-ship encounter situations and optimized path planning in crowded waters were not taken into consideration. Nevertheless, we believe that the current work has paved the way for future autonomous navigation systems.

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