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Collision prevention of ship towing operation under environmental disturbance

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ABSTRACT

Towing operations are highly reliant on the experience of the towing operators. Safety concerns arise when towing operations are subjected to environmental disturbances and dynamic traffic conditions. However, a systematic framework and approaches to enhance the safety and automation of towing operations remain lacking. This work proposes a framework of collision prevention of ship towing operations under environmental disturbance in near port waters. The focus is to prevent internal collisions between tug and assisted ship and provide early warning of possible collisions with other surrounding ships. A cooperative multi-agent control strategy is employed to specify the direction and magnitude of the towing force of the two tugs in real-time. Therefore, in the presence of environmental disturbance, the assisted ship can sail along the planned trajectory, and the acceptable safe geometric distance between each ship pair in the towing system is guaranteed. Further, a COLREGs-compliant collision alert system is designed to promptly remind the towing operators of a collision hazard with nearby ships, and different alert levels indicate different action obligations of towing operators. This proposed framework and developed methods are applied to a tandem towing system consisting of two tugs and one assisted ship to test its feasibility.

1. Introduction

Ship towing operation is an important component of maritime transportation and has been increasingly applied for a variety of purposes, including towing drilling platforms (Zhao et al., 2016), rescuing disabled vessels (Shigunov and Schellin, 2015; Ismail et al., 2021), supporting ship escort and convoy operations in ice conditions (Valdez Banda et al., 2016; Goerlandt et al., 2017; Zhang et al., 2020), and assisting ships to berth automatically (Du et al., 2021).

Ship towing operations are usually characterized by long operating hours and long towing distances. Therefore, safety concerns arise in towing operations, especially in changeable weather conditions and dynamic traffic conditions. Moreover, the limited maneuverability of the ships conducting towing operations decreases their capability of risk resolution. Under the influence of external environmental disturbances and inherent limitations, any improper operations can lead to deviations between the actual towing trajectory and the planned trajectory, and even to accidents such as ship-ship collisions especially in the restricted waters (Li and Zhou, 2021). Ensuring the safety of towing operations is therefore important to enhance maritime safety and ensure smooth transport.

Many studies have been conducted to achieve safe towing operations and these studies basically focus on the dynamic modelling (Bernitsas and Chung, 1990; Fang and Ju, 2009; Nam, 2020), the cooperation and coordination of tugs (Ardito et al., 2012; Bruzzone et al., 2017; Wu et al., 2021), and trajectory track and control (Tao et al., 2019; Li and Zhou, 2021; Ismail et al., 2021). Some work also considers the impact of weather conditions, such as wind, current and wave, on the performance of towing operations, see Fitriadhy et al. (2013) and Sinibaldi and Bulian (2014). These contribute to the design of the towing strategy before

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initiating the towing operation (including the towing method, tugs allocation and their horsepower, towline strength and length, and towing speed in different environments) and the implementation of the towing plan (covering aspects such as course stability control and trajectory tracking).

However, the collision during the towing process has not received much specific attention. For a towing operation, two possible ship-ship collision scenarios are of concern: i) the internal collision between a tug and the assisted object, and ii) the external collision between the towing system and other ships nearby. The occurrence of ship collisions during towing operations can lead to serious consequences. This is evidenced by the internal collision between a tug and assisted tanker (Mikhail, 2021) and the external collision described in Marine Accident Investigation Branch (2015), Mariners' Alerting and Reporting Scheme (2020) and National Transportation Safety Board (2020). In practice, the internal collision is usually avoided by ensuring a sufficient length of the towline and controlling the amplitude and speed of maneuvers (such as rate of turn) (Qi et al., 1995; Yan and Huang, 2001). The towing operators keeps monitoring and controlling the relative distance between tugs and assisted ship (Cao, 2016). To avoid external collisions, the surrounding waters of the towing system are usually restricted to other ship from passing (Tao et al., 2019) during the towing operation. However, all these strategies rely heavily on expert knowledge (Wu et al., 2021). Furthermore, excessively long towlines, slow maneuvering and restrictions on surrounding vessels' passage will increase the workload of the operators, and can reduce the utilization of a channel in which the operation may take place. However, achieving intelligent and automated towing operations to improve the efficiency of ship transportation in busy waters and maintain the safety of towing operations remains a challenge.

Given the above, the primary aim of this work is to promote the automation and safety of towing operations by proposing a framework for collision prevention of ship towing operations under environmental disturbances. This proposed framework is designed for a towing system that consists of an assisted ship and two tugs. The framework specifically focuses on guiding the modelling of the following three aspects. First, a trajectory tracking algorithm is employed to keep the towing operation following the planned trajectory under environmental disturbances. Second, a cooperative multi-agent control strategy based on the model predictive control (MPC) algorithm is designed to ensure the safe distance between tugs and an assisted ship, thereby preventing the internal ship collision. Third, a COLREGs-compliant collision alert system is constructed to detect the external collision and then alert the towing operators to prepare maneuvering strategies for collision avoidance.

The remainder of this paper is arranged as follows. Section 2 is the review and analysis of related works. Section 3 focuses on the design of the framework to follow the planned trajectory and how to prevent internal and external collisions in ship towing operations under environmental disturbances. Section 4 presents the development of methodologies associated with various aspects of the framework. A case study is simulated in Section 5 to demonstrate the feasibility of this proposed method. Some advantages and limitations of this work are discussed in Section 6. Section 7 concludes.

2. Review and analysis of related works

Trajectory tracking and collision prevention during the towing process are critical to enhancing automation and safety in towing operations, and several typical studies are listed in Table 1. Fitriadhy et al. (2013) presented a method to analyze the course stability of tugboats under wind disturbance, and reveals that ship collisions may lead to tugboat instability. Sinibaldi and Bulian (2014) constructed a four-degrees-of-freedom (surge/swing/yaw/roll) nonlinear dynamics model to study the dynamics of the stable/unstable equilibrium, and the effects of wind and towing speed on the equilibrium of the system and their stability were investigated. Hajieghrary et al. (2018) used a distributed feedback control strategy to control a fleet of autonomous surface vehicles (ASVs) towing a single buoy, which enables the towed buoy asymptotically to approach the reference trajectory. Tao et al. (2019) modelled the ship towing system based on maneuvering modeling group model and a catenary model. The control objective is to manipulate the towed cylindrical drilling platform to track the desired trajectory under the environmental disturbance, and therefore a linear active disturbance rejection control-based path following controller is designed. With the backstepping control strategy, Lee et al. (2020) utilized the rudder on the towed vessel to ensure that the towed vessel keeps a good track of the course generated by the tugboat. The application of this proposed method to the harsh weather is the next step of the authors. In the work done by Li and Zhou (2021), two robust torque controllers were designed by a dynamically tracking target for the precise trajectory tracking control of ship towing systems. Zheng et al. (2021) applied an intelligent course keeping active disturbance rejection controller based on double deep Q-network into towing operations of a tug towing an unpowered cylindrical drilling platform. The towed object can maintain the designed heading well under wind disturbance. Du et al. (2021) proposed a multi-agent cooperative control algorithm based on a model predictive control strategy to enable the towed vessel to more accurately approach the desired position at the desired velocity even under environmental disturbances. Ismail et al. (2021) focused on the dynamics and control of two-ship towing system. Two control strategies are combined to guarantee this two-ship ensemble to track its prescribed heading angle and surge speed. Du et al. (2022) formulated a COLREGs-compliant reference trajectory for a ship towing system avoid collisions with surrounding ships in near port waters. The distributed MPC-based strategy is adopted to determine the towing force and towing angle of two tugs to further ensure this towing system follow this reference trajectory. The environmental disturbance is not considered in this work. The external collision is also measured in a simplified way and the dynamic nature of other ships are ignored.

Table 1
Typical research regarding the safety and automation of ship towing operations.

Research work	Environmental disturbance	Trajectory tracking		Internal collision	External collision
		heading	position		
Fitriadhy et al. (2013)	+	+	−	−	−
Sinibaldi and Bulian (2014)	+	−	−	−	−
Li and Zheng (2018)	+	−	+	+/−	−
Hajieghrary et al. (2018)	−	−	−	+/−	−
Tao et al. (2019)	+	−	+	−	−
Lee et al. (2020)	−	−	+	−	−
Li and Zhou (2021)	−	−	+	−	−
Zheng et al. (2021)	+	+	−	−	−
Du et al. (2021)	+	+	+	+/−	−
Ismail et al. (2021)	+	+	−	−	−
Du et al. (2022)	−	+	+	+/−	+
This paper	+	+	+	+	+

Note: + means this content is included in this study; - means this content is excluded in this study; ± means ambiguous or not mentioned.

These studies mainly focus on trajectory tracking and environmental disturbance is often considered during the towing process. These enable the towing system to accurately execute the towing plan even under various weather conditions. However, the dense traffic in near port waters also threatens the safety of towing operations. When the collision risk with surrounding ships exists, the towing system is usually regarded as stand-on ships only if their maneuverability is severely restricted, as specified in CORLEGs. Such a maneuverability-limited ship towing system needs to maneuver when the risk of collision becomes severe. Otherwise, they are normal motor ships and may need to take evasive maneuver from the outset. It is critical for the towing system to maneuver properly to avoid serious encounters with surrounding ships. Besides, the collision between tugs and assisted objects also happens during towing operations, especially under severe weather conditions. However, there is a lack of focus on how to prevent internal collision and external collision during the towing process. It is necessary to research collision prevention of ship towing operations under environmental disturbances. Therefore, this paper aims to enhance the safety and automation of towing operations in various weather and water traffic conditions. Specifically, trajectory tracking and collision prevention under environmental disturbance during the towing process are the focus of this paper.

3. Framework design for collision prevention of towing operations under environmental disturbance

In this work, a tandem towing system consisting of two tugs and one assisted ship is selected to illustrate its feasibility and effectiveness, as shown in Fig. 1. From the figure, $Y_nO_nX_n$ is the earth-fixed coordinate system, $x_bo_by_b$ is the ship-fixed coordinate system; α_1 and α_2 are the towing angles; (x_S, y_S) is the position of the assisted ship, ψ_S is the heading angle of the assisted ship.

This configuration of the towing system is the basic number of fully manipulating a floating object in towing operation. The assisted ship is assumed to be unpowered, which is connected to a forward tug 1 and aft tug 2 by towlines: the fore tug (Tug 1) is to increase the speed and steer the heading of the ship, the aft tug (Tug 2) is to decrease the speed and stabilize the heading of the ship.

The towing operations in this paper are carried out near port areas, where the wind effects are dominant in environmental disturbances (Kepaptsoglou et al., 2015). Thus, during the towing process, the towing system is mainly influenced by wind disturbances. Considering the wind effects can cause other environmental effects, like currents and waves, trigonometric functions is used to represent other environmental disturbances.

Fig. 2 shows the framework to achieve the safe towing operation with environmental disturbance. This proposed framework consists of four main modules. The first module is data collection. The attributes of the towing system (including ship dimension and ship maneuverability), environmental disturbance information, the planned trajectory and traffic information of surrounding ships are collected.

The second is the ship motion control and prediction module. By the utilization of the 3-DoF (degree of freedom) hydrodynamic model and model predictive control (MPC) strategy, the ship trajectory of this towing system can be predicted and regulated. The predicted ship trajectory is then utilized for the analysis of internal and external collision, introduced next.

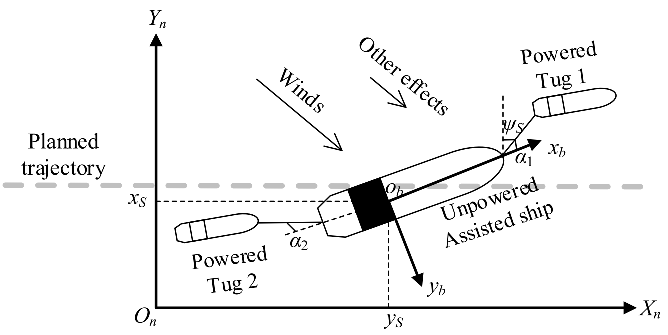

Fig. 1. The components of a tandem towing system.

The third is the internal collision prevention module. The distances between the assisted ship and two tugs are monitored to satisfy the safe distance limit. This safe distance limit indicates the minimum acceptable distance between each pair of ships. According to the geometric configuration of the towing system, the motion of the two tugs is controlled by MPC strategy to achieve the desired states that guarantee the safe distances between the assisted ship and the two tugs.

The fourth is the external collision alert module. When there are vessels in the vicinity of the towing system, the traffic information of these vessels is collected to check whether a collision may occur. If the collision exists, the alert level will be quantified based on the ship action obligation. The obligation of the towing system can be determined based on the understanding of Rule 16 and 17 in Convention on the International Regulations for Preventing Collisions at Sea (Conventions on the International Regulations for Preventing Collision at Sea, 1972). Rules 16 and 17 specify the obligation for collision avoidance of a ship being a give-way ship and a stand-on ship respectively. The collision alert can be activated to clarify the towing operators' action obligation, which contributes to the operators deciding on the appropriate collision avoidance strategy.

4. Methodologies for framework implement

Four critical modules in this proposed framework are elaborated in the following subsections: a mathematical model of ship towing operation, MPC-based ship trajectory control model, internal collision prevention, and external collision alert.

4.1. Dynamic model of towing system with environmental disturbance

A 3-degree of freedom (DoF) kinematics and kinetics model is employed to model the surge, sway and yaw motions of the towing system in the time domain (Fossen, 2011).

$$\begin{cases}\dot{\boldsymbol{\eta}}(t)=\boldsymbol{R}(\psi(t))\boldsymbol{\nu}(t)\\ \boldsymbol{M}\dot{\boldsymbol{\nu}}(t)+\boldsymbol{C}(\boldsymbol{\nu}(t))\boldsymbol{\nu}(t)+\mathrm{D}\nu(t)=\boldsymbol{\tau}(t)+\boldsymbol{\tau}_e(t)\end{cases}, \tag{1}$$

where the position vector $\boldsymbol{\eta}(t)=[x(t)\ y(t)\ \psi(t)]$ contains ship position (x, y) and heading ψ in earth-fixed coordinate system; $\boldsymbol{R}$ is the rotation matrix, which is a function of ψ; the velocity vector $\boldsymbol{\nu}(t)=[u(t)\ v(t)\ r(t)]^T$, and u, v, and r presents the velocity of surge, sway and yaw respectively in ship-fixed coordinate system; $\boldsymbol{M}$, $\boldsymbol{C}$ and $\boldsymbol{D}$ are the Mass (inertia), Coriolis Centripetal and Damping matrix, respectively; $\boldsymbol{\tau}(t)=[\tau_u(t)\ \tau_v(t)\ \tau_r(t)]^T$ indicates the controllable input referring to the forces and moment in ship-fixed coordinate system, which is expressed as:

$$\boldsymbol{\tau}_S(t)=\boldsymbol{B}_S(\alpha_1(t))F_1(t)-\boldsymbol{B}_S(\alpha_2(t))F_2(t), \tag{2}$$

$$\boldsymbol{\tau}_i(t)=\boldsymbol{B}_i(\beta_i(t))F_i(t)+\boldsymbol{\tau}_{Ti}(t), i=1,2, \tag{3}$$

where $\boldsymbol{\tau}_S$ and $\boldsymbol{\tau}_i$ are the controllable inputs for the assisted ship and tugs; B_S and B_i are the configuration matrix; α_1 and α_2 are the towing angles; F_1 and F_2 are the towing forces; $\boldsymbol{\tau}_{Ti}$ is the forces and moment to move the tugs. Thus, the control outputs of the assisted ship are the towing forces and angles, and the control outputs of the tugboats are the thruster forces and moment.

The term $\boldsymbol{\tau}_e(t)$ in formula (1) stands for the environmental disturbance forces and moment, which consists of dominant wind effects $\boldsymbol{\tau}_w(t)$ and other effects $\boldsymbol{\tau}_o(t)$ $(\boldsymbol{\tau}_e(t)=\boldsymbol{\tau}_w(t)+\boldsymbol{\tau}_o(t))$. The wind effects can be expressed as follows (Fossen, 2011):

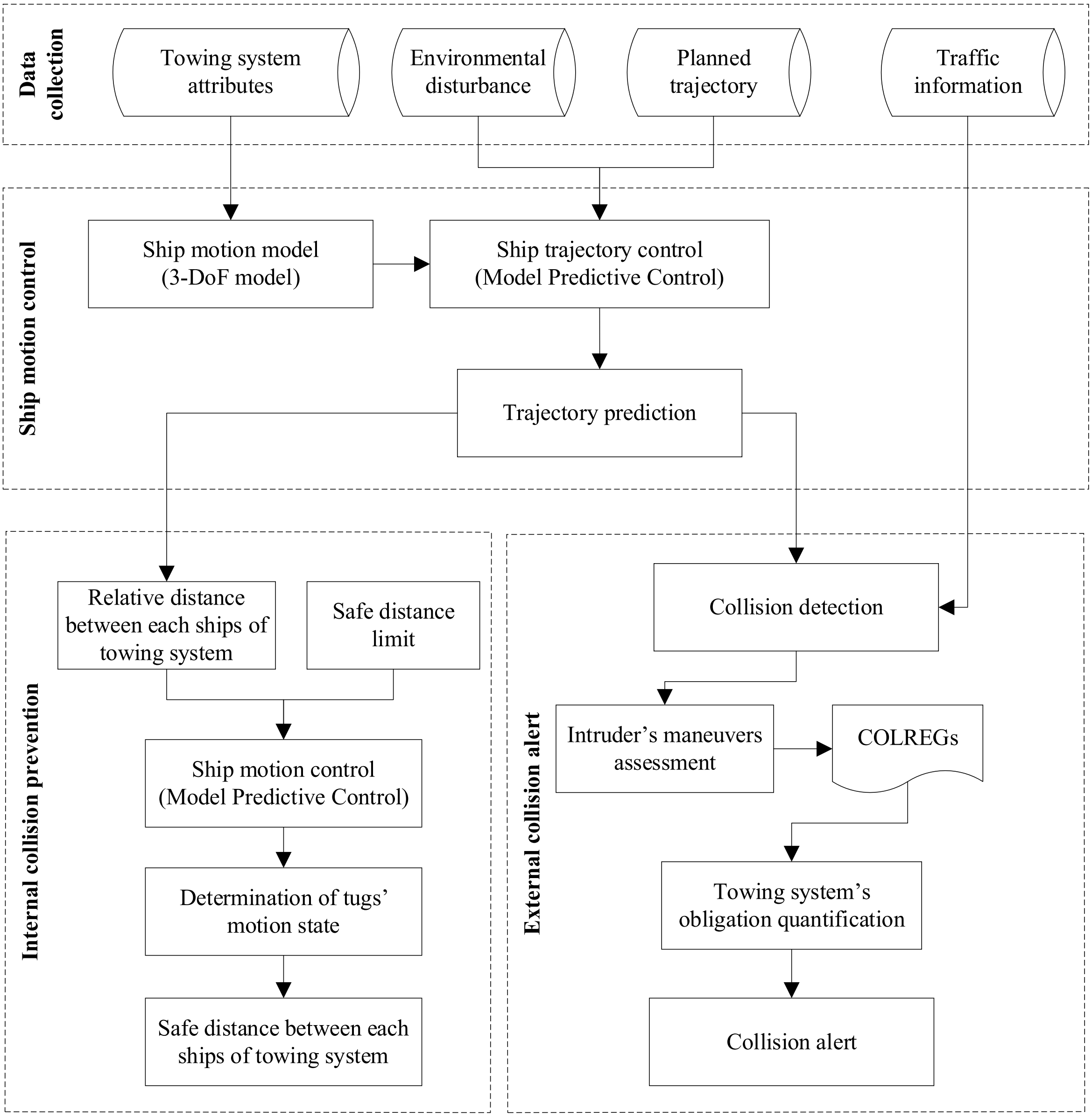

Fig. 2. Framework of collision prevention of ship towing operation under environmental disturbance.

$$\boldsymbol{\tau}_w(t) = \frac{1}{2}\rho_a V_{rw}^2(t)\begin{bmatrix} -c_x\cos(\gamma_{rw}(t))A_{Fw} \\ c_y\sin(\gamma_{rw}(t))A_{Lw} \\ c_n\sin(2\gamma_{rw}(t))A_{Lw}L_{oa} \end{bmatrix}, \tag{4}$$

where ρ_a denotes the air density; V_{rw} is relative wind speed; c_x, c_y and c_n are wind coefficients for horizontal plane motions; $\gamma_{rw}(t)$ is the wind angle of attack relative to ship bow; A_{Fw} and A_{Lw} denote the orthographic area and side projection area of the ship structure above the ship's waterline, respectively; L_{oa} is the ship overall length. The other effects (waves and currents) generated by winds (Cavaleri et al., 2012) are represented by using trigonometric functions and related to the wind speed $V_w(t)$ and direction $\beta_w(t)$ (Du et al., 2020):

$$\boldsymbol{\tau}_u(t) = \begin{bmatrix} k_X V_w(t)\cos(\beta_w(t) - \psi(t))A_{FD} \\ k_Y V_w(t)\sin(\beta_w(t) - \psi(t))A_{LD} \\ k_N V_w(t)\sin(\beta_w(t) - \psi(t))A_{LD}L_{oa} \end{bmatrix}, \tag{5}$$

where k_X, k_Y and c_n are the disturbance gains; A_{FD} and A_{LD} are the transverse and lateral projected area of vessel under the water, respectively.

4.2. *Trajectory control of towing system*

Considering (i) the control problem in this research has multiple control inputs; (ii) there are also multiple control constraints; (iii) the collision avoidance for such a low maneuverability system requires to take actions in advance., the MPC strategy is used for trajectory tracking. The core of the MPC is the design of the cost function. Since the assisted ship and two tugs have the same control objectives, the cost function designs of all ships are the same:

$$J = w_1(\boldsymbol{\eta} - \boldsymbol{\eta}_{\mathrm{d}})^T(\boldsymbol{\eta} - \boldsymbol{\eta}_{\mathrm{d}}) + w_2\boldsymbol{\nu}^T\boldsymbol{\nu}, \tag{6}$$

where $\boldsymbol{\eta}_{\mathrm{d}}$ is the desired position, w_1 and w_2 are the weight coefficients expressed by:

$$\begin{aligned} w_1 &= k_{\mathrm{w}1} \\ w_2 &= k_{\mathrm{w}2}(1 + V_{\mathrm{w}}) \end{aligned} \tag{7}$$

where $k_{\mathrm{w}1}$ and $k_{\mathrm{w}2}$ are the constant, satisfying $k_{\mathrm{w}1} < k_{\mathrm{w}2}$; V_{w} is wind speed.

Thus, the MPC-based trajectory tracking strategy is expressed as:

$$J^* = \min_{\alpha_1,\alpha_2,F_1,F_2,\tau_{T1},\tau_{T2}} \sum_{j=1}^{H_P} \left(w_S J_S(k+j|k) + w_{T1} J_{T1}(k+j|k) + w_{T2} J_{T2}(k+j|k) \right), \tag{8}$$

$$\begin{aligned} &\text{s.t.} \forall j \in H_P, i = 1,2: -90^\circ \le \alpha_i(k+j|k) < 90^\circ, \\ &\quad 0 \le F_i(k+j|k) \le F_{i\ \max}, -\tau_{i\ \max} \le \tau_i(k+j|k) \le \tau_{i\ \max}, \\ &\quad |\alpha_i(k+j|k) - \alpha_i(k+j-1|k)| \le \overline{\alpha}_i, \\ &\quad |F_i(k+j|k) - F_i(k+j-1|k)| \le \overline{F}_i, \\ &\quad \text{Dynamics by } (1)-(4), \end{aligned} \tag{9}$$

where J represents the cost of different ships, and the subscripts s, $T1$, and $T2$ presents the assisted ship, Tug 1 and Tug 2 respectively; w is the weight coefficients; H_P is the length of the prediction horizon; j is the jth time step in the prediction horizon; $J_S(k+j|k)$, $J_{T1}(k+j|k)$ and $J_{T2}(k+j|k)$ are the prediction made at k about the cost of the assisted ship, Tug 1 and Tug 2 at $k+j$, respectively; $F_{i\ \max}$ is the maximum value of towing force that the two towing lines withstand; $\boldsymbol{\tau}_{i\ \max}$ is the maximum value of the thruster forces and moment; $\overline{\alpha}_i$ and $\overline{F}_i$ are the maximum change rate value of towing angle and force, respectively..

4.3. Internal collision prevention

4.3.1. Determination of safe distance limit

The failure of the tug's main engine and steering gear, leading to loss of control of the vessel, is one of the most dangerous situations during towing operations. When the main engine stops, the ship's speed will gradually slow down until the movement on the water stops due to the water resistance. During this period, from the start of the main engine stop to the stop of ship movement against water, the distance of a ship moving forward is called the ship stopping inertia stroke. The collision between the tug and the assisted ship could occur if the initial distance between the tug and the assisted vessel is less than the difference in their stopping inertia stroke.

Therefore, the stopping inertia stroke of a ship is introduced to calculate the safety distance limit.

$$\begin{cases} LimDis = |dis_1 - dis_2| \\ dis_i = \sqrt{(x_i(t_1) - x_i(t_0))^2 + (y_i(t_1) - y_i(t_0))^2}, i = 1,2 \\ \boldsymbol{\eta}_i(t_1) = [x_i(t_1)\ y_i(t_1)\ \psi_i(t_1)] = \int_0^{t_1} \left\{ \boldsymbol{R}\left(\psi\left(t\right)\right) \int_0^{t_1} \boldsymbol{M}^{-1}[-\boldsymbol{C}(\boldsymbol{v}(t))\boldsymbol{v}(t) - \boldsymbol{D}\boldsymbol{v}(t)]dt \right\} dt \end{cases}, \tag{10}$$

where $LimDis$ presents the safety distance limit. dis_i presents the stopping inertia stroke of ship i. t_0 is the starting time when the main engine of a tug stops and t_1 is the ending time when the ship's speed drops to zero. $\boldsymbol{\eta}_i(t) = [x_i(t)\ y_i(t)\ \psi_i(t)]$ is calculated based on formula (1) by setting the force and moment of the tug's main engine $\boldsymbol{\tau}(t)$ and environmental disturbance $\boldsymbol{\tau}_e(t)$ to zero.

4.3.2. MPC-based reference trajectory tracking

The idea of internal collision prevention is to define the desired geometric configuration for the assisted ship and two tugs.

It is noticed that the position and heading of the ship can be determined by the trajectory control according to Section 4.2. Based on the ship position, heading and towing angles, the desired position and heading of the two tugs can also be determined by the following formulations (Du et al., 2020):

$$\boldsymbol{\eta}_{1d} = \begin{bmatrix} x_{1d} \\ y_{1d} \\ \psi_{1d} \end{bmatrix} = \begin{bmatrix} x_S \\ y_S \\ \psi_S \end{bmatrix} - l_1 \begin{bmatrix} \sin(\psi_S) \\ \cos(\psi_S) \\ 0 \end{bmatrix} - (l_{tow1} + l_{T1}) \cdot \begin{bmatrix} \sin(\psi_S + \alpha_1) \\ \cos(\psi_S + \alpha_1) \\ 0 \end{bmatrix} + \alpha_1 \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}, \tag{11}$$

$$\boldsymbol{\eta}_{2d} = \begin{bmatrix} x_{2d} \\ y_{2d} \\ \psi_{2d} \end{bmatrix} = \begin{bmatrix} x_S \\ y_S \\ \psi_S \end{bmatrix} - l_2 \begin{bmatrix} \sin(\psi_S) \\ \cos(\psi_S) \\ 0 \end{bmatrix} - (l_{tow2} + l_{T2}) \cdot \begin{bmatrix} \sin(\psi_S + \alpha_2) \\ \cos(\psi_S + \alpha_2) \\ 0 \end{bmatrix} + \alpha_2 \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}, \tag{12}$$

where $\boldsymbol{\eta}_{1d}$ and $\boldsymbol{\eta}_{2d}$ are the desired trajectories of the two tugs; l_1 and l_2 are the distance from the center of gravity of the ship to its bow and stern; l_{tow1} and l_{tow2} are the length of the towing line; l_{T1} and l_{T2} are the distance from the center of gravity of the Tug 1 and Tug 2 to its stern and bow, respectively.

Combining (8), (10) and (11) with the cost function in (5), the positions of the two tugs can be controlled to track their reference trajectory. Thus, the distance between the assisted ship and two tugs will keep the desired value, and the possibility of internal collision of the towing system can be effectively reduced.

4.4. External collision alert system

4.4.1. Collision identification

The collision is identified if one ship domain (SD) is projected to be violated within the specific time period, based on an extrapolation of the vessel trajectories. For a towing system, a ship collision happens if the SD of an intruder violates the SD of anyone ship of this towing system. A ship approaching the towing system is denoted as an intruder.

The non-linear velocity obstacle (NLVO) algorithm and SD theory are combined to detect the potential danger between this towing system and intruders, based on the predicted trajectories of towing system (Huang and Gelder, 2017).

$$\begin{cases} S_{NL\_VO}(t_0) = \bigcup_{\mathrm{t}}^{\infty} \left(\dfrac{P_{TS}(x,y,t) - P_{Intr}(x,y,t_0)}{(t-t_0)} \right) \oplus \dfrac{ConfP(O,R)}{(t-t_0)} \\ ConfP(O,R) = \{ \| P_{TS}(x,y,t) - P_{Intr}(x,y,t_0) \| \le R \} \end{cases}, \tag{13}$$

where $S_{NL\_VO}(t_0)$ is the conflicting velocity set of an intruder leading to a ship collision with this towing system at current moment t_0; $P_{TS}(x,y,t)$ is the predicted ship trajectory of the towing system based on MPC strategy and ship motion model, and $P_{Intr}(x,y,t_0)$ is the current position of the intruder; $P_{OS} \oplus ConfP(O,R)$ denotes the prohibited region around this towing system. An elliptical ship domain is employed for ship collision detection as the elliptical ship domain is the most realistic one based on empirical data (Hansen et al., 2013). R represents the dimension of the ship domain, which here include the long and short axis, which are 4 and 1.4 times of ship length respectively. The prohibited areas around this

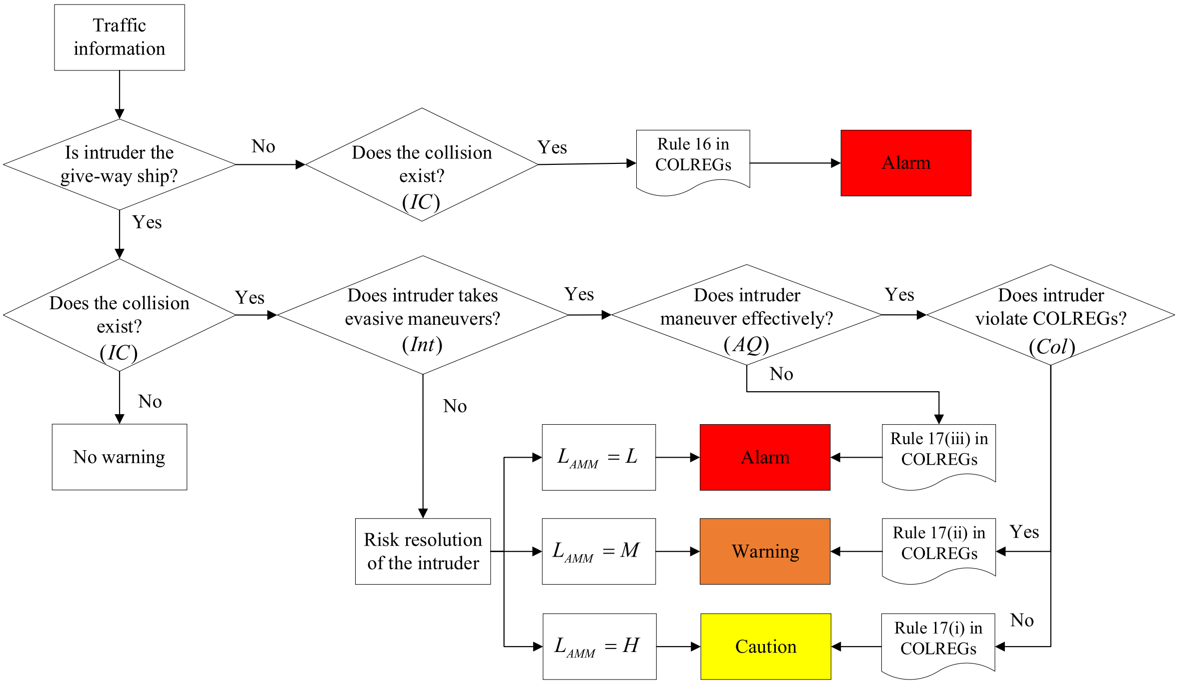

Fig. 3. Flowchart for quantifying the alert levels of external collision.

towing system $P_{OS}\oplus ConfP(O,R)$ include the elliptic ship domain around each ship in this towing system and the area around the towline connecting the tug and the assisted ship.

The collision exists if the velocity of intruder $V_{Intr}(t_0)$ locates in $S_{NL\_VO}(t_0)$.

$$IC(t_0)=\begin{cases}1, if\ V_{Intr}(t_0)\cap S_{NL\_VO}(t_0)\neq\varnothing\\ 0,\text{otherwise}\end{cases}, \tag{14}$$

where IC is index of collision.

4.4.2. Alert level quantification

Ship collision alert is to alert the towing operators of a collision hazard. Specifically, this work aims to alert towing operators whether there is a need to conduct evasive maneuvers for collision avoidance. Rule 16 and 17 in COLREGs provide reference to quantify the collision alert level (CAL) based on the ship maneuvers performance and maneuver obligation for collision avoidance. Fig. 3 illustrates how to quantify the CAL of external collision, adapted from Du et al. (2020b). Basically, there are two main steps. The first step is to determine whether a ship is a give-way ship or a stand-on ship based on their relative position. The second step is to quantify CALs according to Rule 16 and 17. We provide two different strategies for a give-way ship and a stand-on ship respectively.

For a give-way ship, she shall take early and substantial actions to keep safe when the collision risk exists, as specified in Rule 16 in COLREGs. Therefore, we set the alert as alarm when the collision risk exists to remind the give-way ship of the need to take evasive action.

For a stand-on ship, the CAL can be divided into three levels: caution, warning, and alarm, similarly as IMO 2007 recommendations (IMO, 2007). The caution indicates to the towing operators that ship collision will occur so more attention to the current situation is needed, but the towing operators are required to remain ship course and speed. The warning specifies that the towing operators can take evasive maneuvers to avoid ship collision as the intruder's maneuver is evidently improper, including the violation of Rule 15 in COLREGs. The alarm designates that the intruder's less effective/ineffective maneuvers cannot eliminate the risk of collision, so the towing operators are required to take evasive maneuvers.

When the towing ship is in a give-way position, the index of collision IC is measured from formula (12) and (13). When the towing system is in a stand-on position, the alert level quantification is more complicate when the collision exists. If an intruder does not take evasive maneuvers for collision avoidance, the risk resolution of this intruder will be measured to determine the alert level. If an intruder takes evasive maneuvers, the action quality and COLREGs are scrutinized. For instance, if the intruder takes less effective/ineffective maneuvers, the CAL is set as 'alarm'. In contrast, if the intruder's maneuver is effective but violates the COLREGs, CAL is 'caution. Five indicators are measured to further quantify the alert level, see Fig. 3. Apart from index of collision IC, the explanation and the corresponding calculation models of the remaining 4 indicators are briefly introduced next.

The ship intention estimation module examines whether the intruder takes evasive maneuvers for collision avoidance (Du et al., 2020a).

$$Int(t_0)=\begin{cases}1, if\ V_{Intr}(t_0)\cap S_{NL\_VO}(t_0)\neq\varnothing\&\Delta C_{Intr}(t_0)\neq 0\\ 0,\text{otherwise}\end{cases}, \tag{15}$$

where Int is the index of ship intention, and $Int=1$ means an intruder takes evasive maneuver for collision avoidance. ΔC_{Intr} is the course change of the intruder.

The ship action quality assessment module elucidates whether the intruder's maneuver is effective in eliminating the risk of collision (Du et al., 2020b).

$$AQ(t_0)=\begin{cases}1, if\ Dis(\langle P_{TS}(x,y,t_0),P_{Intr}(x,y,t_0)\rangle)\geq \min DisTS\\ 0,\text{otherwise}\end{cases}, \tag{16}$$

where AQ indicate the performance of the intruder's maneuver, and $AQ=1$ if the maneuver of this intruder is effective. $\min DisTS$ is the critical distance that the ship collision can be avoided by this adopted evasive maneuver if the intruder maneuvers before their relative distance drops to this critical distance. The ship maneuverability is measured based on Nomoto model (Nomoto et al., 1956; Hong and Yu, 2000).

COLREGs scrutiny module clarifies whether the intruder violates the COLREGs. The violation of Rule 15 is considered a danger here.

$$Col = \begin{cases} 1, if\ RB_{CPA} \in \left(\dfrac{\pi}{2}, \dfrac{3\pi}{2}\right) \\ 0, \text{otherwise} \end{cases}, \tag{17}$$

where *Col* presents the result of the COLREGs scrutiny, and $Col = 1$ if the intruder is projected to pass the closest point of approach (CPA) later than the towing system, which complies with Rule 15. RB_{CPA} is the relative bearing from towing system perspective when the ships reach CPA.

The risk resolution calculation module checks the capability of the intruder to eliminate the collision.

$$L_{AMM} = \begin{cases} H, if\ AMM > AMM_1 \\ M, otherwise \\ L, if\ AMM < AMM_2 \end{cases}, \tag{18}$$

where L_{AMM} reflect the capability of the intruder to eliminate the collision. The high-risk resolution of a ship indicates that this ship can easily eliminate this collision. Available Maneuvering Margins (AMM) is the proportion of maneuvers by which a ship can eliminate potential conflicts to all the available maneuvers (Du et al., 2021b). AMM_1 and AMM_2 are two thresholds to divide L_{AMM} into three classes. For small-size cargo ship, $AMM_1 = 0.9$ and $AMM_2 = 0.4$, which are derived from a large sample of vessel encounters using automatic identification system (AIS) data, see Du et al. (2021)(a).

5. Case study

In this section, a case study is designed to illustrate the feasibility of this proposed method to provide information for enhancing the safety and automation of towing operations. The environmental disturbance is considered during the towing operation. Section 5.1 designs the case studies and Section 5.2 presents the results. The simulation experiments are carried out using Matlab 2018b.

5.1. Scenario design

5.1.1. Description of towing system

The operation of towing an unpowered ship is conducted by two tugs, as shown in Fig. 1. We use the scale models for the ships. The basic information of the tugs and an assisted ship in this tandem towing system are shown in Table 2. The tugs and an assisted ship are modelled based on the 'TitoNeri' (Haseltalab and Negenborn, 2019) and 'CyberShip II' (Skjetne et al., 2004), respectively. 'CyberShip II' is a scaled-down model vessel from a real ship with a scaling factor of 70 (Skjetne et al., 2004). The desired elongation of towline is 1m. The center of gravity of the tug and assisted ship are 0.5m and 0.67m away from their bow, respectively. The maximum value of thruster forces is 10N. The change rate of towing angle does not exceed 5°/s. The maximum towing force is 3N, and the change rate of towing force is less than 1N/s.

5.1.2. Encounter scenarios

Table 3 presents the plan of towing operation. The scale models for the ships are used. The initial state, including the ship starting position and heading, are given (the velocity of each vessel is 0).Two turning points are designed, which contain the position and heading information. The towing system has to follow the waypoint with the reference heading. The wind is assumed to be constant. The wind speed remains 1 m/s, which is a fresh breeze according to Froude's scaling law (Moreira et al., 2007), the scaled velocity is determined by the square root of the scaling factor, so the real wind speed is around 8.5 m/s. The wind direction is 255° coming from the southwest. Furthermore, this towing operation is conducted in good visibility conditions.

Two intruders are designed during the towing operation in this scenario. Both intruders are small cargo ships, and none of them is not under command. The information of the intruders is shown in Table 4, including their ship parameters and initial states. The first intruder appears from the beginning and remains present until 300s, which keeps her course and speed unchanged before 100s. The presence time of the second intruder is from 300s to 600s. The second intruder approaches the towing systems with constant speed and course before 400s.

Table 2
Ship parameters of towing system.

Vessel		Length (m)	Width (m)	Mass (kg)	Thrusters
Tug		0.97	0.3	16.9	One bow thruster Two stern azimuth thrusters
Assisted ship		1.255	0.29	23.8	/

5.1.3. Determination of safe distance limit

Fig. 4 illustrates the stopping inertia stroke of a tug and an assisted ship. The tug's main engine is designed to fail while the towing system is sailing steadily at a speed of about 0.05 m/s. A tug stops around 10s while the assisted ship keeps moving forward with a decreasing speed until about 120s. The stopping inertia stroke of a tug is smaller than that of an assisted ship, thus generating a collision risk between the assisted ship and the fore tug (Tug 1). From Fig. 4, the peak of the decrease in the relative distance between the assisted ship and the fore tug (Tug 1) is 0.867m. Accordingly, the safe distance limit is set as 0.867m.

5.2. Results

5.2.1. Ship trajectory control

Following the planned trajectory is critical for the safety of towing operations. The feasibility of using this proposed ship trajectory control method to follow the planned trajectory with environmental disturbance is demonstrated first. Fig. 5 illustrates the positions of each ship in the towing system during the towing process, including the entire trajectories, and the ship positions when reaching the turning points and ending point. The linear velocity and heading of ships are shown in Fig. 6. Fig. 7 displays the distance that the assisted ship offsets from the planned trajectory. This distance is the Euclidian distance from the towed ship's center of gravity to the planned trajectory. Figs. 8 and 9 show the time-varying control inputs for the assisted ship and two tugboats, where Fig. 8 is the variation of the towing angles and towing forces, and Fig. 9 is the variation of the tugboat thruster forces and moment. It can be observed that all the control inputs satisfy their constraints.

Before reaching the first turning point, two tugs cooperate to make the assisted ship go straight with a desired 90-degree initial heading. Due to environmental interference, the ship heading shifts to the port side (Fig. 6), which in turn causes the ship to offset to the left of its planned trajectory (Fig. 7). Under the control of the proposed MPC strategy, the tugs continuously adjust the towing angles and forces, so that the ship courses are stabilized between 80° and 90° (Fig. 6), and the deviation distance from the planned route is within 1m (Fig. 7).

The towing system reaches the first turning point at around 290s. The positions of three ships at the first turning point are displayed in Fig. 5(b). When approaching the first turning point, the velocities of the towing system decrease slightly to leave time for the tugboats to adjust their motion states, and then the headings of the three ships increase slightly. The heading of the assisted ship reaches 87.2° at the first turning point, see Fig. 6. The distance that the ship deviates from the planned trajectory remains less than 1m (Fig. 7).

After passing the first turning point, the second turning point becomes the next target. Due to the preset of the position and ship heading

Table 3
The plan of towing operation with designed turning points with environmental disturbance.

Initial state (x(m), y(m), ψ (degree))			Turning points (x(m), y(m),ψ (degree))	Ending point (x(m), y(m),ψ (degree))	Wind	
Assisted ship	Tug 1	Tug 2			Speed (m/s)	Direction (degree)
(0,0,90)	(2.08,0,90)	(-2.17,0,90)	(15,0,90) (30,10,60)	(50,20,75)	1	255

Table 4
The information of intruders.

Intruders	Ship parameters		Intrusion time (s)	Initial state (x (m), y(m), ψ (degree), V_{Intr} (m/s))	First maneuvering timing (s)
	Length (m)	Width (m)			
Intruder 1	1.255	0.29	1–300	(20, −10, −30, 0.05)	100
Intruder 2			300–600	(35, 40, 180, 0.05)	380

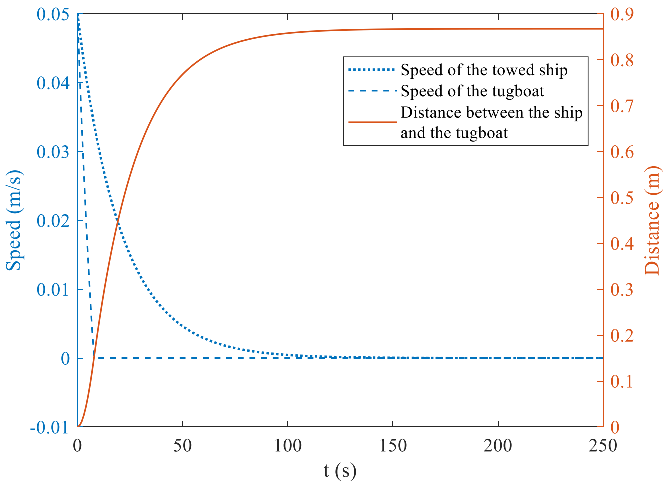

Fig. 4. Safe distance limit between a tug and an assisted ship.

of the second turning point (Table 3), the tugs adjust the magnitude and direction of the towing force. The speed of the three ships slightly increases, while their headings decrease continuously and rapidly (Fig. 6). After about 130s, the ship heading decreases to 65° and gradually stabilize. In the early stage of the ship heading change process, the deviation of the assisted ship from the planned trajectory fluctuates but the fluctuations are still within 1 m (Fig. 7). Due to the environmental disturbance, the ship heading increases slightly and reaches 64.6° at 589s (Fig. 6).

Similar to the process of approaching the first turning point, the ship starts to slow down about 90s before reaching the second turning point. Meanwhile, the tugs' heading, towing force and direction are constantly updated. The assisted ship is on a heading of 65.6° as it passes the second turning point (Fig. 6), where the offset distance is around 0.5m (Fig. 7).

Afterwards, the ships of the towing system aim to reach the ending point on a 75° heading. The ship heading increases gradually from 65.6° at 600s to 75° at 764s (Fig. 6). From 764s to 1000s, the towing force keeps updating to eliminate environmental interference on the motion of the towing system, and therefore there are some slight fluctuations in the course and speed of these three ships. At 1000s, the assisted ship reaches the ending point (Fig. 5), and its heading is 76.1° (Fig. 6). During this period, the assisted ship follows the planned trajectory, and the offset distance of the assisted ships is still less than 1m (Fig. 7).

5.2.2. *Internal collision*

By applying the desired geometric configuration of the towing system, the desired trajectories of the two tugboats are updated online as the ship follows its trajectory to ensure that the distances between the ship and two tugboats are always compliant with the safe distance limit.

Fig. 10 shows the minimum distances between the assisted ship and two tugboats. In the case of small-scale models of the vessel and no big steering of the towing process, these values can be calculated by the distance of assisted ship's bow to Tug 1's stern and assisted ship's stern to Tug 2's bow. It is observed that the distance from the assisted ship to tug 1 and the assisted ship to tug 2 is always larger than the safe distance limit 0.867m. Therefore, no internal collision is observed during the whole towing operation under environmental disturbance.

Fig. 11 shows the trajectory tracking errors of the two tugboats, where the figures in the first row are the position errors and the figures in the second row are the heading errors. It is observed that the position and heading errors of the two tugboats are very small, indicating that the proposed control algorithm has good performance in trajectory tracking. Therefore, the internal collisions between the assisted ship and two tugboats can be prevented.

5.2.3. *External collision*

The encounters of the towing system with intruders 1 and 2 are set to occur in the early and late stages of the towing operation, respectively in this simulation. Figs. 12–14 and Figs. 15–17 show the results of the collision analysis between the towing system and the intruders 1 and 2, respectively. Figs. 12 and 15 present the ship position, heading, and information of alert level at sampled times. Figs. 13 and 16 display the distance between each ship in this towing system and the intruders, which is calculated from the center of gravity of the two scaled ships. Figs. 14 and 17 show the results of collision detection and alert level quantification.

When dealing with intruder 1, the collision is present throughout the encounter process (Fig. 14). As the intruder 1 approaches this towing system from her starboard, this towing system is in the give-way position and needs to keep away from the intruder 1. As this towing system does not take effective evasive maneuvers, a dangerous close-distance encounter ensues. The encounter scenarios at six sampled times (1s, 100s, 120s, 150s, 240s and 300s) are selected to demonstrate how the alert level is quantified, seen Fig. 12. At the beginning, the collision risk occurs, so the alert level is 'alarm' (Fig. 12(a)). As the towing system keeps her course and speed, the collision risk remains and their relative distance drops gradually, so the alert level remains at 'alarm' (Fig. 12(b)(c)(d)). Around 200s, the ship domains of assisted ship is violated by intruder 1. At 250s, the distance between intruder 1 and the assisted ship reduces to a minimum value (Fig. 13). The alert level remains 'alarm' before 280s (Fig. 12(e)). From 280s onwards, intruder 1 starts to move away from the towing system and there is no collision hazard afterwards (Fig. 12(f)).

For the encounter with intruder 2, this is a crossing encounter. The towing system is in stand-on position and has the priority to use the channel. The collision occurs at the beginning but is successfully eliminated by intruder 2's effective maneuvers at 470s (Fig. 17). Fig. 14 presents the ship position and information of alert levels at six sampled times. At 300s, the collision between this towing system and intruder 2 emerges. As intruder 2 does not maneuver for collision avoidance but its risk resolution is high at this moment, the alert level is marked as

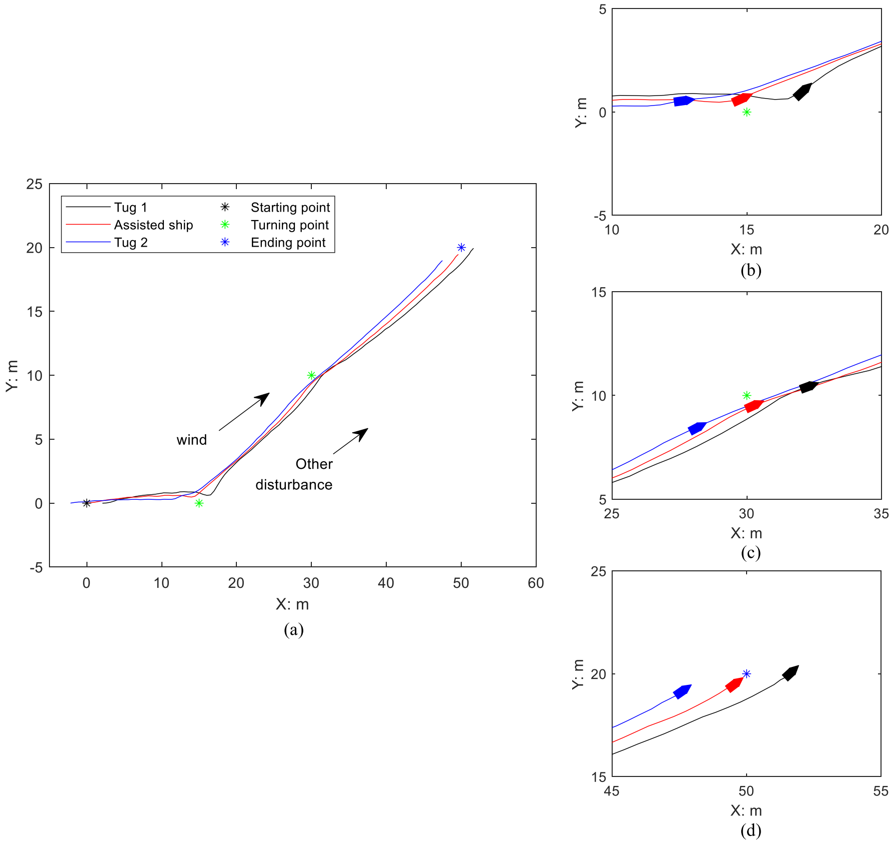

Fig. 5. Ship motion state of the towing system under environmental disturbance: (a) Ship trajectories of the whole towing operation; (b) Ship positions at the first turning point; (c) Ship positions at the second turning point; (d) Ship positions at the ending point.

'caution' (Fig. 15(a)). Before 380s, the intruder 2 keeps approching this towing system with constant speed and course (Fig. 16). At 340s, the collision danger is still present and intruder 2's AMM drops but is still at medium level, and therefore the alert level is 'caution' (Fig. 15(b)). At 370s, the collision danger exists but the AMM of intruder 2 drops to medium level, so the alert level is marked as 'warning' (Fig. 14(c)). From 390s to 520s, intruder 2 keeps turning to the starboard side at the same rate of course change to avoid the collision. Through the action quality assessment and COLREGs scrutiny, the maneuvers adopted by intruder 2 is judged as effective and COLREGs-compliant. At 420s, the distance between intruder 2 and the assisted ship is reduced to around 19m (Fig. 16). Considering that the collision can be eliminated by intruder 2's adopted maneuvering alone, the alert drops to 'caution' (Fig. 15(d)). Due to the effective and COLREGs-complaint maneuvers taken by intruder 2, the collision is eliminated since 470s, see Fig. 17(a). At 470s, the collision alert is inactive (Fig. 15(e)). The towing system and intruder 2 keeps approaching until 590s. At 590s, intruder 2 and the assisted ship reaches the closest point of approach (CPA), and their distance is reduced to a minimum value of 7.38 m (Fig. 16), which is beyond the safe distance limit. There is no collision alert at 590s (Figs. 15(f), Figure 17(b)). From 590s onwards, they pass each other safely and their distance increases. For detailed infortaion on these five indicators and alert level, see Table 1A in Appendix.

6. Discussion

6.1. Features and advantages of the proposed method

A cooperative multi-agent control strategy is employed to specify the direction and magnitude of the towing forces by the two tugs in real-time so that the towing operations can be carried out strictly according to the plan, even under environmental disturbance. This could increase the safety of towing operations and their adaptability to the external dynamic environments. Towing operations are largely subject to weather conditions (Berg, 2017). Although towing operations are usually planned to implement under good weather conditions, in reality, the tugs and the assisted ships are always disturbed by winds from different directions (Fitriadhy et al., 2013), especially for emergency towing tasks (Bruzzone et al., 2017). Uncertainties in weather forecasts, such as sudden changes in wind and waves during towing operations, may threaten the safety of towing operations (MAIB, 2008; Sinibaldi and Bulian, 2014). Figs. 5 and 6 indicate that the proposed framework and methods help the assisted ship to navigate to the desired position with a desired heading and velocity under environmental disturbances. This proposed collaborative multi-agent control strategy may lead to significant cost savings and accident reduction during the towing operation.

The internal collision can be prevented. An acceptable safe distance can be guaranteed, which is ensured by using the MPC-based ship trajectory control method to determine the position and heading of the tugs. Compared to a single tug towing configuration (Tao et al., 2019), this tandem towing configuration, containing two tugs in front and behind, enhances the controllability of the towing operations. In particular, the rear tug helps to decelerate the assisted ship and assist to alter the heading of the assisted ship, to achieve a more rapid response in the control of the ship towing operations. The cooperation of two tugs helps to regulate the distances between the tugs and the assisted vessel more effectively. Fig. 6 attests that the safe distance between every two ships have been kept even under environmental disturbance.

The external collision can be reduced by the design of an alert system. The dynamic nature of ship maneuver is considered to improve the accuracy of collision risk detection (Chen et al., 2018). Then the alert level is quantified based on the maneuver adopted by intruders and the

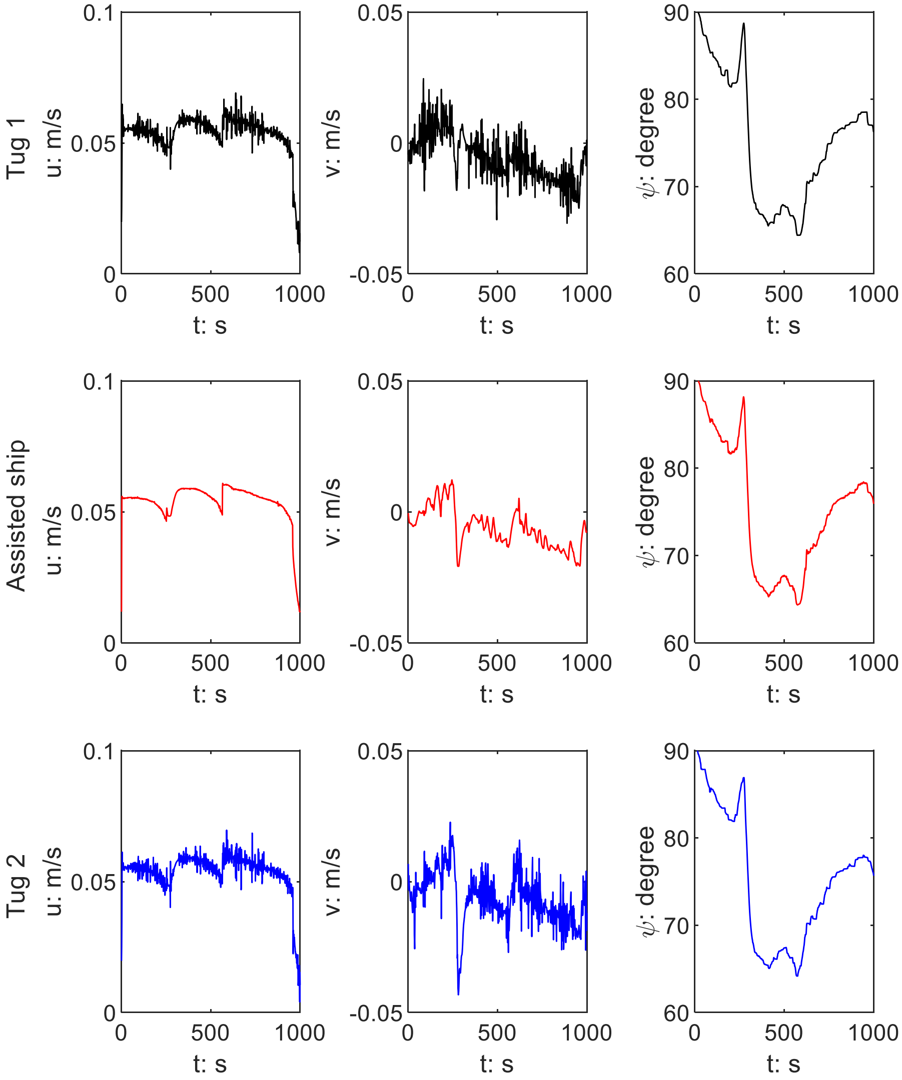

Fig. 6. Velocity and heading of ships under the environmental disturbance.

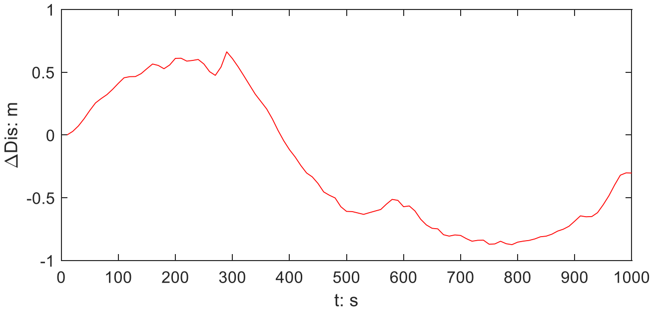

Fig. 7. The variation of distance that the ship of towing system deviates from the planned trajectory under environmental disturbance.

explanation of rules as specified in COLREGs. The violation of COLREGs is also regarded as a potential danger. The alert with a specific level indicates to the towing operators the potential danger and their action obligation. Some precautions can be developed by the towing operators to achieve safe passage. In addition, it can enhance the efficiency of ship transportation, especially in busy waters, such as the fairways leading to the ports. Being equipped with a good control system and an external collision alert system, ships conducting towing operations can be regarded as normal ships. The previous measures to restrict the passage of other ships in nearby waters can be gradually and prudently relieved. In this way, on the premise of ensuring the safety of the towing operation, navigation efficiency in busy waters can be improved to the greatest extent.

The framework and methods of collision prevention of ship towing operations under environmental disturbance contributes to automating the towing operations. The work pressure of the towing operators can be significantly alleviated. During the towing process, the main task of the towing operators will shift to updating the safety parameters (such as the safe speed of the towing system and safe distance between ships under different environmental disturbances) and formulating maneuvering strategies to respond to alerts. Compared to the traditional towing operation under human supervision based on the experience of the towing operators (Altosole et al., 2013; Goerlandt et al., 2017; Wu et al., 2021), this proposed method could also reduce the occurrence of accidents that caused by human error. Considering that the towing operation has also been applied for assisting ships to berth automatically, this proposed strategy can further contribute to the development of smart port.

6.2. Future improvement

This work focuses on the safety and automation of towing operations,

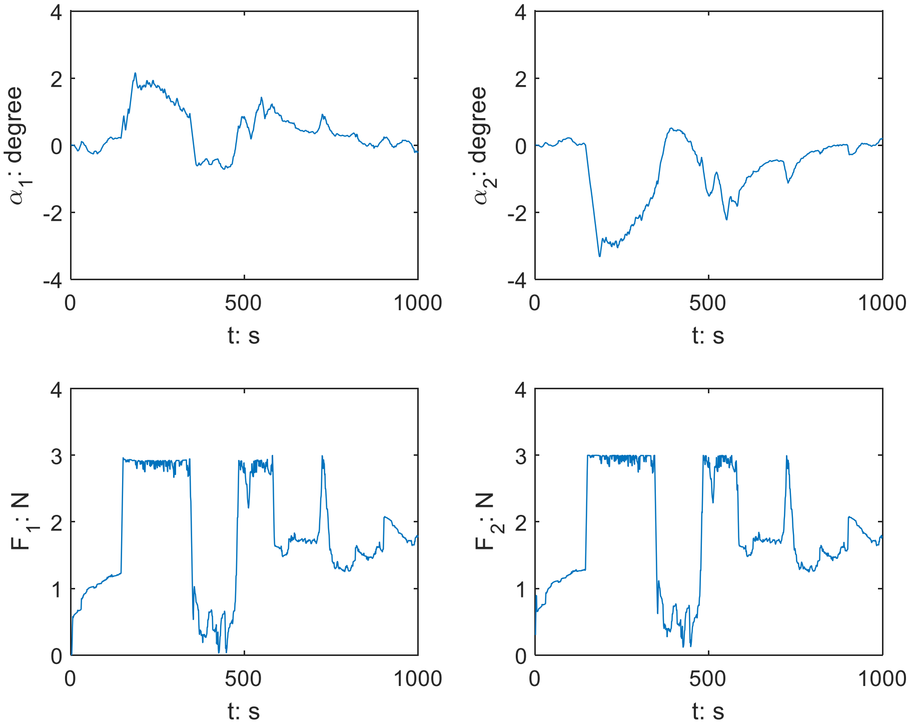

Fig. 8. The variation of two towing angles (the first row) and two towing forces (the second row).

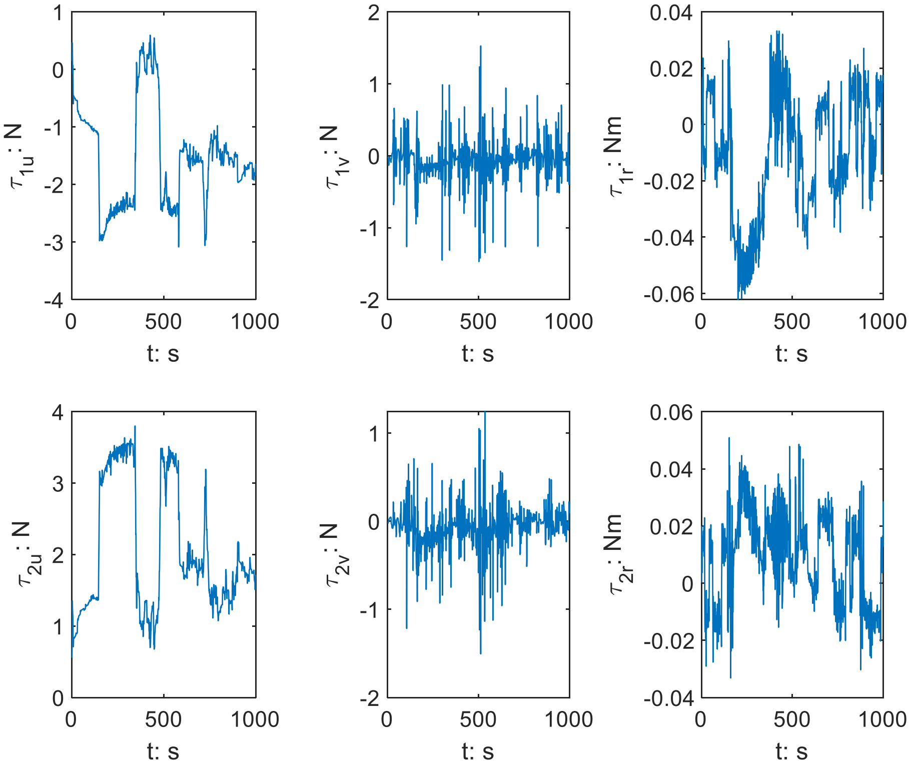

Fig. 9. The variation of thruster forces and moment for two tugboats (the first row stands for Tug 1, the second row stands for Tug 2).

while the time cost of towing operations is not considered. Fig. 18 demonstrates the ship motion states, including linear velocities and heading, without the environmental disturbance based on this proposed cooperative multi-agent control strategy. The results shown in Figs. 6 and 18, indicate that this control method is applicable for the towing operations under/without environmental disturbance. Under conditions of environmental disturbance, it takes more time to perform the same task of towing operations. The speed of the two tugs and the assisted vessel during the towing process is stable at around 0.09 m/s in the absence of wind (Fig. 18). The towing system reaches the ending point in nearly 600s. However, under environmental disturbance, the speed of the assisted vessel is about 0.06 m/s, and the towing task is completed in

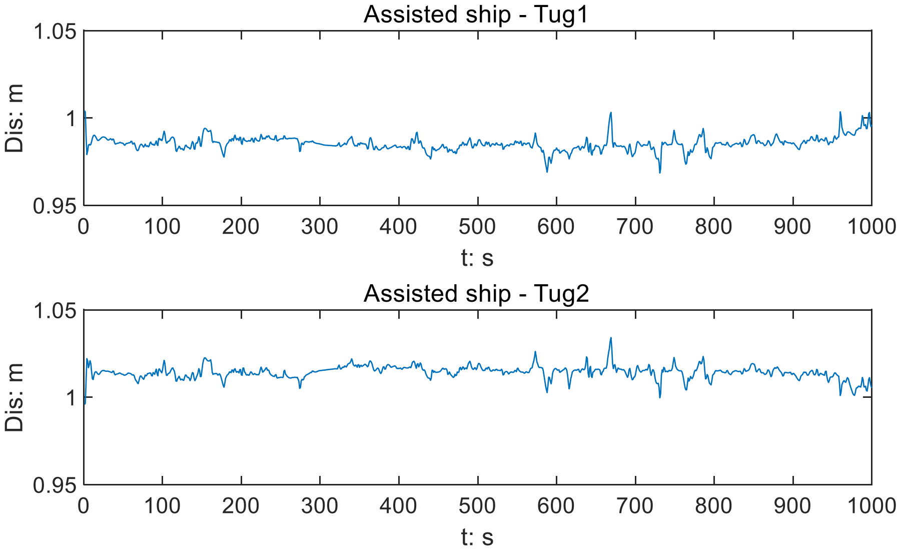

Fig. 10. The relative distance between each ship of the towing system under environmental disturbance.

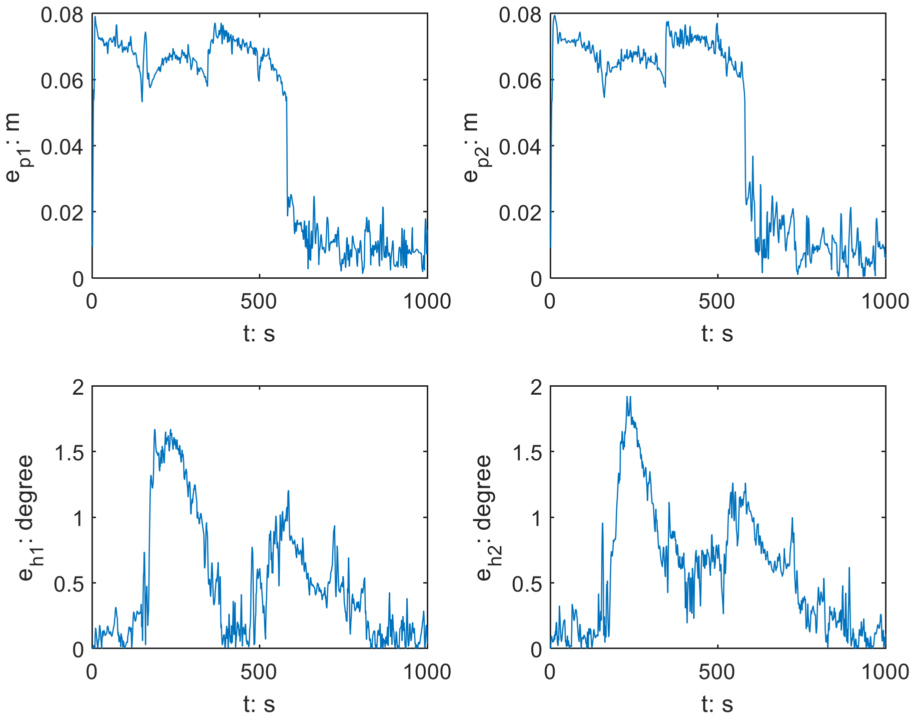

Fig. 11. Trajectory tracking errors of the two tugboats: the two figures in the first row are the position errors (e_{p1} and e_{p2}), the two figures in the second row are the heading errors (e_{h1} and e_{h2}).

about 1000s (Fig. 6). The proposal of a ship motion control strategy that can ensure both the safety and efficiency of towing operations is one improvement of our future work.

This work only focuses on the internal and external ship collision prevention during the towing operation. For internal vessel collisions, the desired safe distance is critical. An initial safe distance value is usually set when settling the towing plan, and will be updated during the towing process based on the actual towing operating environment, including the weather condition and channel width. However, the set of safe distance is not our focus. To be clarified, we aim to improve the automation of towing operation to relief towing operators' workload, rather than replace towing operators' work. Therefore, the set and update the safe distance conducted by these experts could be more accurate and reliable. For external collision, this work does not provide solutions for instructing a towing system to make a maneuvering strategy to avoid external collision. Ship collision alert is designed to alert the towing operators of a collision hazard timely rather than directly proposing collision avoidance maneuvers in the current circumstance. However, in practice, even when the alarm is activated to alert the officers on watch of a collision danger, the officers on watch may adopt inappropriate avoidance strategies (Chauvin and Lardjane, 2008). The strategy of maneuvering for collision avoidance, including the timing of maneuvering and the magnitude of adopted maneuvers, will directly affect the success of collision avoidance (Zhuo and Tang., 2008;

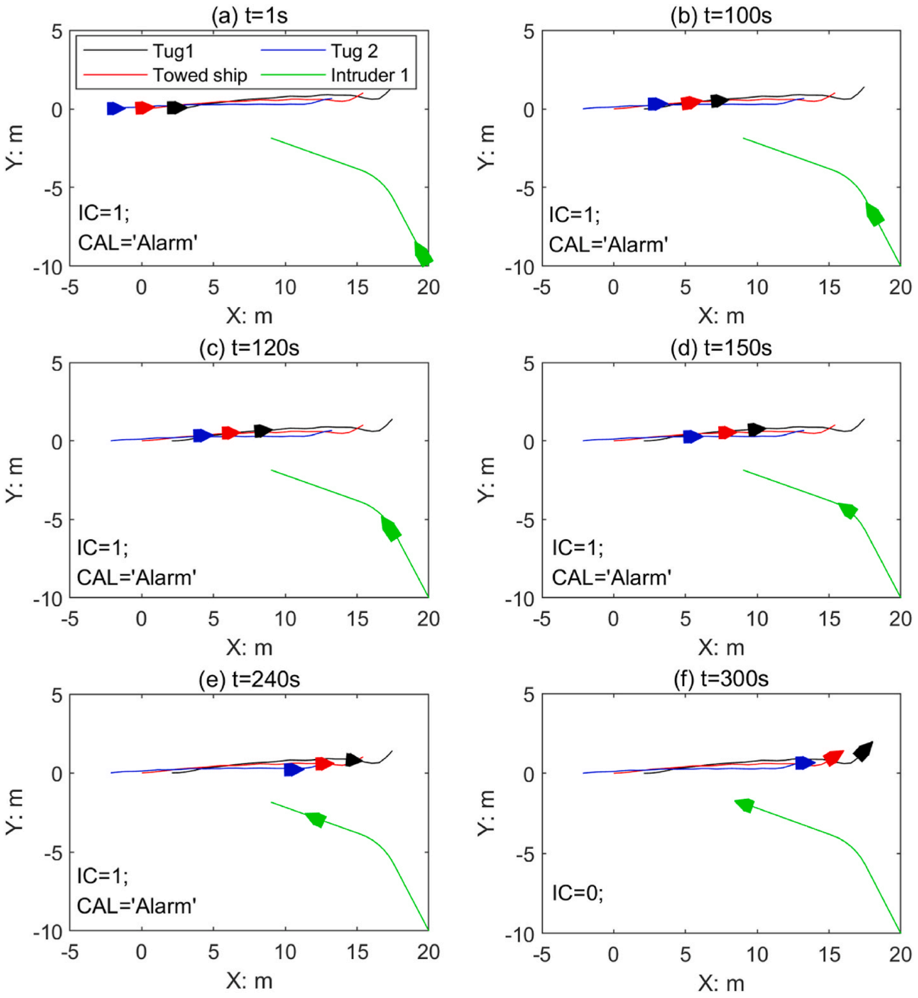

Fig. 12. The ship position, heading, and alert level at several sampled times when encountering the intruder 1.

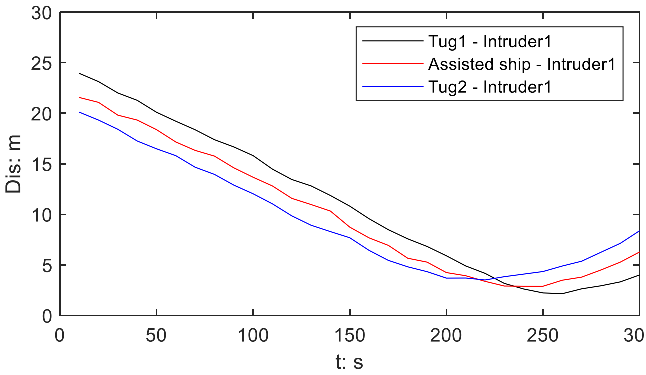

Fig. 13. The relative distance between each ship of this towing system and intruder 1.

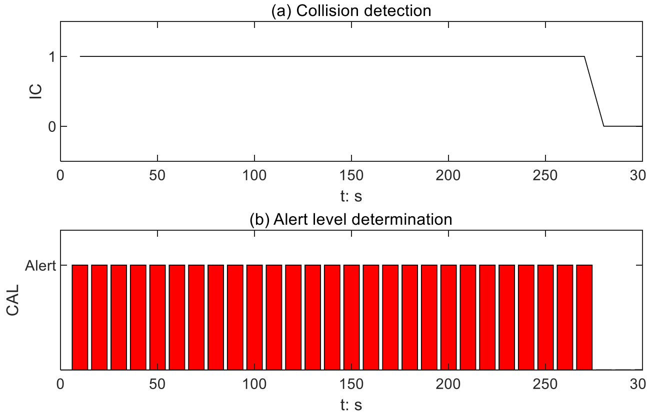

Fig. 14. The variation of alert level during the encountering process with intruder 1.

Montewka et al., 2010), which are not considered in this work. This two-tug tandem towing configuration enables this towing system to be well controlled and has reasonable maneuverability, so it can practically take her responsibilities during the collision avoidance. Such towing systems with reasonable maneuverability can be considered as ordinary vessels and therefore traffic management authorities do not need to restrict other vessels entering towing operation waters. The action obligation of this towing system is determined by the relative bearing and relative heading, as specified in COLREGs, so they will not always be stand-on ships. Therefore, developing appropriate maneuvering strategies for towing systems in the give-way position and stand-on position respectively can increase the safety and automation of towing operations. The ship trajectory planning (Szlapczynski and Szlapczynska, 2012; Lazarowska, 2015; Lisowski, 2016) with traffic complexity (Zhang et al., 2022; Sui et al., 2022) considered for a towing system can be a solution.

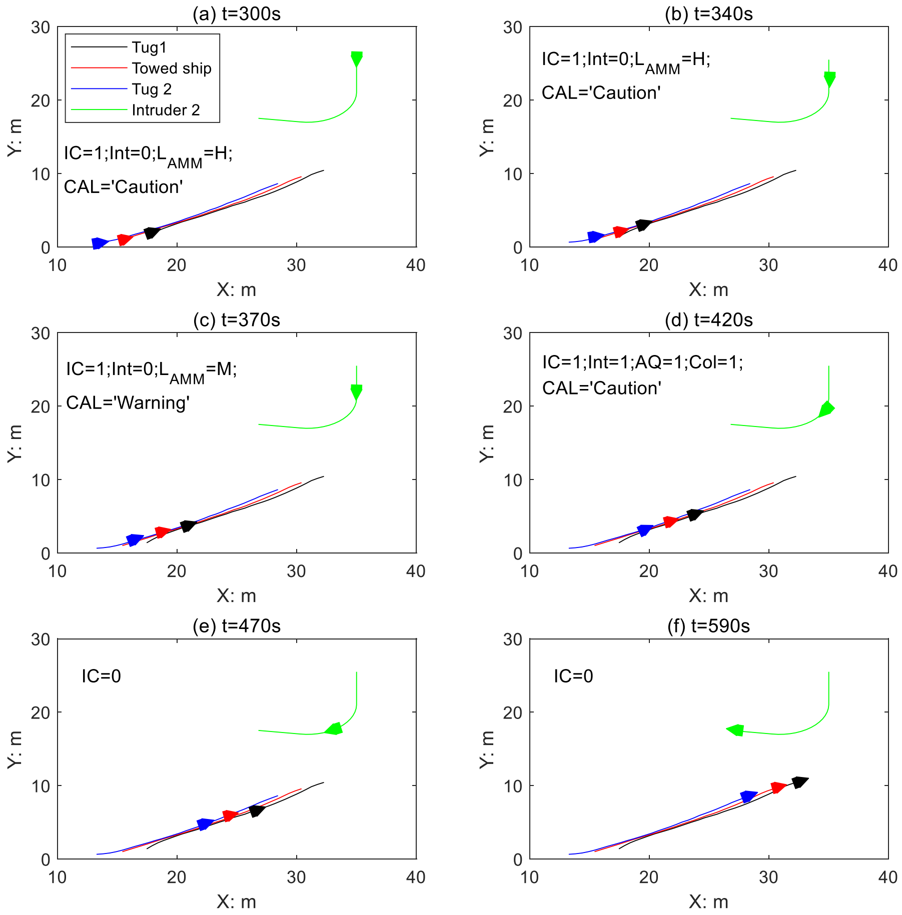

Fig. 15. The ship position, heading, and information of alert level at several sampled times when encountering the intruder 2.

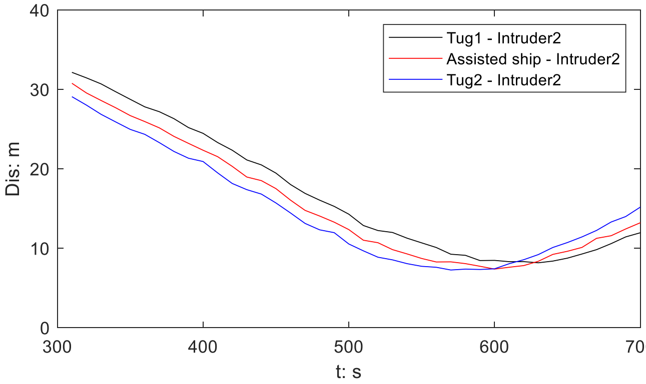

Fig. 16. The relative distance between each ship of this towing system and intruder 2.

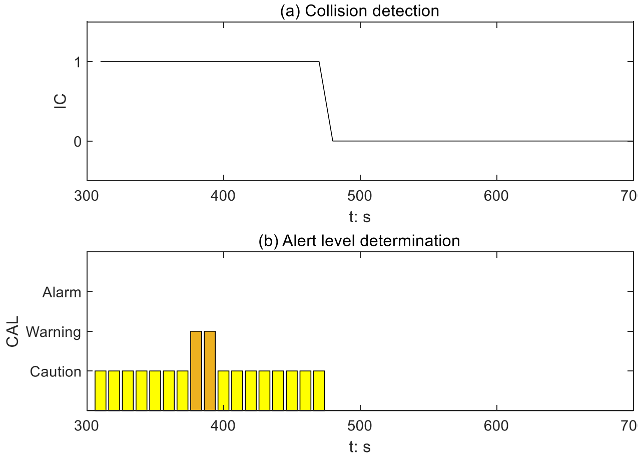

Fig. 17. The variation of alert level during the encountering process with intruder 2.

Communication between ships is not considered. A dangerous close-distance encounter occurs in the simulated encounter with intruder 1. In practice, this close-distance encounter happens frequently, especially in dense traffic waters. A variety of reasons can lead to the occurrence of such close encounters, such as limited channel width or a controlled operation under crew communication. The communication between ships helps to keep these close-range encounters safe (Lee and Park, 2020; Zhang et al., 2020). Nevertheless, the alert method presented in this article can still be useful. This is because the alert aims to help the officers on watch specify collision avoidance strategies, rather than completely replace their work. After the officers on watch receive the alert, they need to formulate a more appropriate collision avoidance strategy based on the actual situation, such as considering the communication situation.

This proposed framework and developed methods are designed for a towing system that consists of an assisted ship and several tugs in near port waters. The towing operation conducted in different waters may influence our risk assessment results. To extend the applicability of this proposed method, we need to update the environment disturbance as the

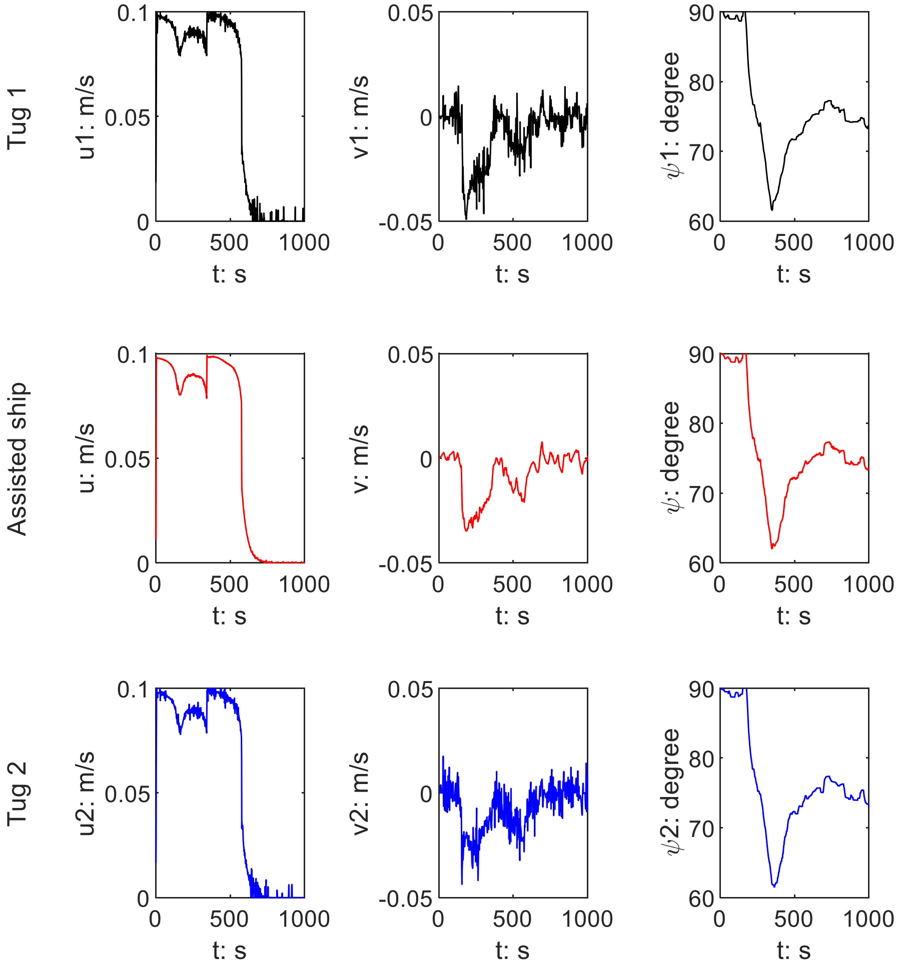

Fig. 18. Velocity and heading of ships without the environmental disturbance based on the model predictive control strategy.

wave disturbance cannot be overlooked in open waters. Further, a more appropriate ship domain needs to be employed for specific waters. The elliptic ship domain is the most frequently used for open waters, while in shallow water or narrow water, a ship domain designed for ships with restricted maneuverability in busy waters could be more suitable (Pan et al., 2021). Besides, regarding the determination of whether a towing system is a give-way vessel, the practical operation under the VTS recommendations may violate the regulation as specified in COLREGs, but the towing operations are recommended to strictly comply with the COLREGs to avoid accident caused by uncoordinated maneuvers.

Finally, we only apply these methods to a tandem towing system consisting of two tugs and one assisted ship to illustrate its feasibility in this work. More testing is needed, both in simulated test cases, in bridge simulators with humans in the loop, and in real-world environments, before recommending their use in practical contexts. Further, the feasibility of applying this proposed method in more complicated multi-vessel encounters requires further testing.

7. Conclusions

This work proposes a framework of collision prevention of ship towing operations in the presence of environmental disturbance, with the aim to enhance the safety and automation of towing operations. We first employ a 3-DoF kinematics and kinetics model to simulate the surge, sway and yaw motions of the towing system under environmental disturbance. Then a model predictive control (MPC)-based multi-agent control strategy is employed to optimally control the magnitude and direction of the towing forces by two tugs. The heading, velocity and position of each ship are effectively controlled. The assisted ship can strictly follow the planned trajectory, while ensuring a safe distance between the assisted ship and tugs to avoid internal ship collision. A COLREGs-compliant alert system is designed based on the ship maneuvers performance and maneuver obligation for collision avoidance. The risk alert is divided into caution, warning and alert to quantify the severity of collision with surrounding ships and clarify the obligations for the towing system maneuvering for collision avoidance. The promising results of the designed case study illustrate the feasibility of the proposed methods to prevent internal and external collision.

Nevertheless, we have identified some research limitations that need to be further considered. Ship motion control algorithms that simultaneously ensure the safety and efficiency of towing operations are more appropriate, considering the practical need for its cost-effectiveness. Providing risk elimination measures can help to improve the safety of towing operations. Finally, considering other contextual factors in the encounter process, such as ship communication during close-range encounters, could define more precise and context-aware risk alerts.

CRediT authorship contribution statement

Lei Zhang: Conceptualization, Methodology, Data curation, Writing – original draft, Writing – review & editing, Visualization, Formal analysis. **Zhe Du:** Conceptualization, Writing – original draft, Writing – review & editing, Visualization. **Osiris A. Valdez Banda:** Supervision, Writing – review & editing, Investigation. **Floris Goerlandt:**

Supervision, Writing – review & editing, Investigation. **Lei Du:** Conceptualization, Data curation, Writing – review & editing. **Xiaobin Li:** Supervision, Funding acquisition, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix

Table A1
The detailed information of alert level when encountering the intruder 2

Time: s	*IC*	*Int*	*AQ*	*Col*	*AMM*	*CAL*
310	1	0	/	/	0.9143	Caution
320	1	0	/	/	0.9143	Caution
330	1	0	/	/	0.9143	Caution
340	1	0	/	/	0.9	Caution
350	1	0	/	/	0.9	Caution
360	1	0	/	/	0.9	Caution
370	1	0	/	/	0.8857	Warning
380	1	0	/	/	0.8714	Warning
390	1	1	1	1	/	Caution
400	1	1	1	1	/	Caution
410	1	1	1	1	/	Caution
420	1	1	1	1	/	Caution
430	1	1	1	1	/	Caution
440	1	1	1	1	/	Caution
450	1	1	1	1	/	Caution
460	1	1	1	1	/	Caution
470	0	/	/	/	/	/
480	0	/	/	/	/	/
490	0	/	/	/	/	/
500	0	/	/	/	/	/
510	0	/	/	/	/	/
520	0	/	/	/	/	/
530	0	/	/	/	/	/
540	0	/	/	/	/	/
550	0	/	/	/	/	/
560	0				/	/
570	0	/	/	/	/	/
580	0	/	/	/	/	/
590	0	/	/	/	/	/
600	0	/	/	/	/	/

Table A2
List of abbreviations and notations

AIS	automatic identification system	AMM	Available Maneuvering Margins
CAL	collision alert level	COLREGs	Convention on the International Regulations for Preventing Collisions at Sea
CPA	closest point of approach	DoF	degree of freedom
MPC	model predictive control	NLVO	non-linear velocity obstacle
SD	ship domains	VLCC	Very Large Crude oil Carrier

(*continued on next page*)

Table A2 (*continued*)

AIS	automatic identification system	AMM	Available Maneuvering Margins
AQ	the performance of the intruder's maneuver	AMM	the value of AMM
Col	the index of the COLREGs scrutiny	CAL	index of collision alert level
IC	index of collision	Int	index of ship intention
AMM_1, AMM_2	the upper and lower limit of AMM to divide L_{AMM} into three classes, respectively	A_{Lw}	the side projection area of the ship structure above the ship's waterline
A_{Fw}	the orthographic area of the ship structure above the ship's waterline	$\overline{\alpha}_i$	the maximum change rate value of towing angle
α	the towing angles;	B	the configuration matrix
$\boldsymbol{C}$	Coriolis Centripetal	ΔC_{Intr}	the course change of the intruder
c_x, c_y and c_n	wind coefficients for horizontal plane motions	$\boldsymbol{D}$	Damping matrix
$\overline{F}_i$	the maximum change rate value of towing force	$F_{i\max}$	maximum value of towing force that the two towing lines withstand
F	the towing forces	H_P	the length of the prediction horizon;
j	the jth time step in the prediction horizon	J	the cost of different ships
L_{AMM}	the capability of the intruder to eliminate the collision	L_{oa}	the ship overall length
l_1	the distance from the center of gravity of the ship to its bow	l_2	the distance from the center of gravity of the ship to its stern
l_{tow}	the length of the towing line	l_{T1}	the distance from the center of gravity of the Tug 1 to its stern and bow
l_{T2}	the distance from the center of gravity of the Tug 2 to its stern and bow	$\boldsymbol{M}$	the Mass (inertia)
min $DisTS$	the critical distance that the ship collision can be avoided by this adopted evasive maneuver if the intruder maneuvers before this critical distance	$P_{OS} \oplus ConfP(O, R)$	the prohibited region around this towing system
$P_{TS}(x, y, t)$	the predicted ship trajectory of the towing system	$P_{Intr}(x, y, t_0)$	the current position of the intruder
R	the sum of two SDs' radius	$\boldsymbol{R}$	the rotation matrix
RB_{CPA}	the relative bearing from towing system perspective when the ships reach CPA	r	the velocity of yaw in ship-fixed coordinate system
$S_{NL\_VO}(t_0)$	the conflicting velocity set of a ship leading to a ship collision with this towing system	u	the velocity of surge in ship-fixed coordinate system
v	the velocity of sway in ship-fixed coordinate system	V_{rw}	relative wind speed
$V_{Intr}(t_0)$	the velocity of intruder	$\boldsymbol{v}(t)$	velocity vector
(x, y)	ship position	ψ	ship heading
ρ_a	the air density	w_1, w_2	the weight coefficients
$\boldsymbol{\tau}_S$	the controllable inputs for the assisted ship	$\boldsymbol{\tau}_i$	the controllable inputs for the tugs
$\boldsymbol{\tau}_{Ti}$	the forces and moment to move the tugs.	$\boldsymbol{\tau}_w(t)$	the wind disturbance forces and moment
$\boldsymbol{\tau}_{i\max}$	the maximum value of the thruster forces and moment	$\boldsymbol{\tau}_S$	the controllable inputs for the assisted ship
$\boldsymbol{\tau}_i$	the controllable inputs for the tugs	$\gamma_{rw}(t)$	the wind angle of attack relative to ship bow
$\boldsymbol{\eta}(t)$	position vector	$\boldsymbol{\eta}_d$	the desired position

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