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MPC-based COLREGS Compliant Collision Avoidance for a Multi-Vessel Ship-Towing System

Zhe Du, Vasso Reppa, Rudy R. Negenborn

Abstract— **Collision avoidance plays a vital role in autonomous vehicle systems. As the complexity and scale of missions increase, multi-vehicle systems are adopted in practice. However, there is limited research on collision avoidance of a physically interconnected multi-vessel system. This paper proposes a control scheme for tugboats to tow a ship in congested port areas ensuring collision avoidance that is compliant with COLREGS. The Model Predictive Control (MPC) strategy is used to optimize the towing angles, towing forces, and tugboats' thruster forces and moment. The COLREGS rules are integrated into the ship reference system by altering predefined waypoints to guide the towing system in a safe and lawful way. By designing the cost function for the ship and tugboats in the MPC controller system, the proposed control scheme makes the ship-towing system stay away from the obstacles and follow the calculated waypoints, achieving collision avoidance. Simulation experiments indicate that the proposed method can deal with static and dynamic obstacle situations in complex water traffic environments, and the collision avoidance operations comply with the COLREGS rules.**

I. INTRODUCTION

Collision avoidance is essential for ensuring the autonomous operation of vehicle systems, like Unmanned Aerial Vehicles (UAVs), Unmanned Ground Vehicles (UGVs), and Autonomous Surface Vessels (ASVs) in complex missions. In the maritime domain, collision avoidance should also comply with standards of global regulations called "The International Regulations for Preventing Collisions at Sea", shortly COLREGS [1]. Although COLREGS were designed to be followed by humans, they must still be obeyed during the operations of autonomous vessels in order to guarantee their lawfulness at sea [2]. Research works usually combine rules 13-17 (the specific actions that the give-way vessel should take) with classical guidance or control methods to solve collision avoidance of ASVs, such as the Velocity Obstacle (VO) [3], Artificial Potential Fields (APF) [4], Model Predictive Control (MPC) [5], and many more. The above research focuses on the situation where a single vessel avoids obstacles.

However, in recent years the complexity and scale of the missions motivate the deployment of multi-vessel systems. According to the type of connection, such systems are classified into cyber-connected and physical-connected. The cyber-connected system means that all vessels are clustered in a certain range maintaining a safe distance, and the connection is realized through the networks. The physical-connected system implies that there is a physical link (like cable and rope) between vessels. Compared to the cyber-connected system, this type has less freedom of motion and more constraints of dynamics. Collision avoidance research of the multi-ASV systems mainly lies in the first type, and researchers usually propose a formation to coordinate multiple ASVs. Some scholars adopt a triangle formation composed of three vessels to realize collision avoidance in port areas [6]. Some researchers propose a line formation (or a vessel-train formation called in the literature) [7] to deal with collision avoidance in a narrow waterway of port areas.

Since the physical-connected systems have more constraints of motions, the operations of collision avoidance are more challenging. Research works in collision avoidance of the physical-connected system are mainly related to the ground and aerial autonomous vehicles. For ground vehicles, the tractor-trailer system [8] and the wheeled-robot object-manipulation system [9] are often studied, and the collision avoidance strategy is based on the optimal control and the potential field theory. For aerial vehicles, the multi-UAV system is usually applied for payload transportation [10], [11]. In this case, two or three UAVs are used to transport a payload connected by cables. By taking collision avoidance as a part of the control objectives or constraints, the multi-UAV system can achieve collision avoidance during the mission of payload transportation.

For the physically interconnected systems of multiple ASVs, there is limited research focusing on the collision avoidance problem. Thus, the goal and the main contribution of this work is to propose a collision-avoidance method for a physically interconnected multi-ASV system performing a towing process. The towing manipulation from the open sea to the terminals is an important but also hazardous and challenging task for waterborne-land transportation. The increased traffic and complex port environment make collision avoidance critical for ensuring the safety of ship towing. The proposed method in this paper can deal with static and dynamic obstacle situations in complex water traffic environments, and the collision avoidance operations comply with the COLREGS rules. The rest of the paper is organized as follows: Section 2 formulates the problem of the multi-vessel ship-towing system. The design of the proposed approach is given in Section 3. In Section 4, simulation experiments are carried out to illustrate the potential of the proposed method. Conclusions and future research directions are given in Section 5.

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II. PROBLEM STATEMENT

The objective of this work is to propose a cooperative control method for two tugboats to autonomously manipulate a ship safely and lawfully (COLREGS) to the desired position with the desired heading and to ensure collision avoidance.

A 3-DoF (degree of freedom) hydrodynamic model [12] is selected for modelling the motion of the ship and tugs, the kinematics and kinetics formulations are expressed as

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

where $\boldsymbol{\eta}(t)=[x(t)\ \ y(t)\ \ \psi(t)]^{\mathrm{T}}\in\mathbb{R}^3$ is the position vector in the world frame (North-East-Down) including ship position coordinates $(x(t),\ y(t))$ and heading $\psi(t)$; $\boldsymbol{\nu}(t)=[u(t)\ \ v(t)\ \ r(t)]^{\mathrm{T}}\in\mathbb{R}^3$ is the velocity vector in the Body-fixed frame containing the velocity of surge $u(t)$, sway $v(t)$ and yaw $r(t)$; $\boldsymbol{R}\in\mathbb{R}^{3\times3}$ is the rotation matrix from the body frame to the world frame, which is a function of heading; $\boldsymbol{M}\in\mathbb{R}^{3\times3}$, $\boldsymbol{C}\in\mathbb{R}^{3\times3}$ and $\boldsymbol{D}\in\mathbb{R}^{3\times3}$ are the Mass (inertia), Coriolis-Centripetal and Damping matrix, respectively; $\boldsymbol{\tau}(t)=[\tau_u(t)\ \ \tau_v(t)\ \ \tau_r(t)]^{\mathrm{T}}\in\mathbb{R}^3$ is the controllable input referring to the forces $\tau_u(t)$, $\tau_v(t)$ and moment $\tau_r(t)$ offered by actuators in the Body-fixed frame.

The controllable inputs of the ship denoted by $\boldsymbol{\tau_S}$ ($\boldsymbol{\tau}=\boldsymbol{\tau_S}$ in (1)) are the forces from the towing lines applied by the two tugs (see [13] for details on modelling of the ship towing system), which can be expressed as:

$$\begin{aligned}\boldsymbol{\tau_S}(t)&=-\boldsymbol{B}(\alpha_1(t))F_1(t)+\boldsymbol{B}(\alpha_2(t))F_2(t)\\ \boldsymbol{B}&=\begin{bmatrix}\cos(\alpha_i(t))\\ \sin(\alpha_i(t))\\ l_i\sin(\alpha_i(t))\end{bmatrix}\qquad(i=1,2),\end{aligned}\tag{2}$$

where $F_1(t)$ and $F_2(t)$ are the towing forces of the aft (Tug 1) and forward (Tug 2), respectively. We assume no force loss on the towing line. The term $\boldsymbol{B}$ is the configuration matrix which is a function of the towing angle ($\alpha_i(t)$), l_i is the distance from the center of gravity of the ship (G) to the ship stern (l_1) or the ship bow (l_2).

To increase the flexibility of the manipulation process, the actuator system of the tug generally contains two stern azimuth thrusters and one bow tunnel thruster, known as the *ASD tug*, that can obtain omnidirectional forces and moments [14]. The inputs of the i-th tug denoted by $\boldsymbol{\tau_i}$ ($\boldsymbol{\tau}=\boldsymbol{\tau_i}$ in (1)) consist of the reaction towing force and the thruster forces expressed as:

$$\begin{aligned}\boldsymbol{\tau_i}(t)&=\boldsymbol{B}_i(\beta_i(t))F_i(t)+\boldsymbol{\tau}_{T_i}(t)\\ \boldsymbol{B}_i&=\begin{bmatrix}\cos(\beta_i(t))\\ \sin(\beta_i(t))\\ l_{\mathrm{T}_i}\sin(\beta_i(t))\end{bmatrix}\qquad(i=1,2),\end{aligned}\tag{3}$$

where $\boldsymbol{B}_i$ is the configuration matrix of the tugs; $\beta_i(t)$ is the tug angle; l_{T_i} is the distance from the center of gravity of the tug (G_i) to the tug stern (l_{T_2}) or the tug bow (l_{T_1}); $\boldsymbol{\tau}_{T_i}(t)\in\mathbb{R}^3$ is the forces and moment offered by the tug thrusters.

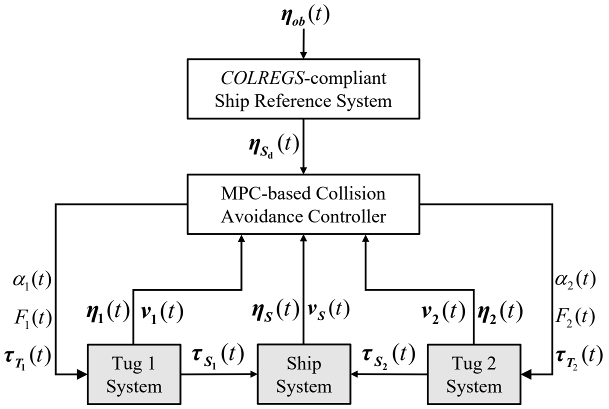


Fig. 1. System control diagram.

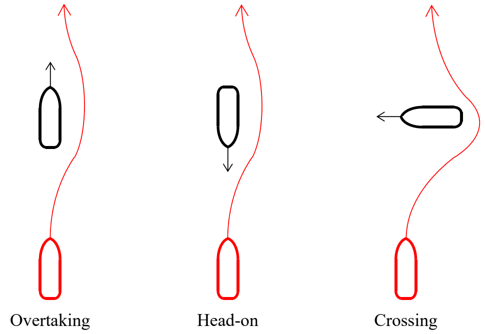


Fig. 2. Collision avoidance actions vessel should take according to the COLREGS rules in three situations: the red one is the own-vessel (give-way vessel), the black one is the target vessel (stand-on vessel).

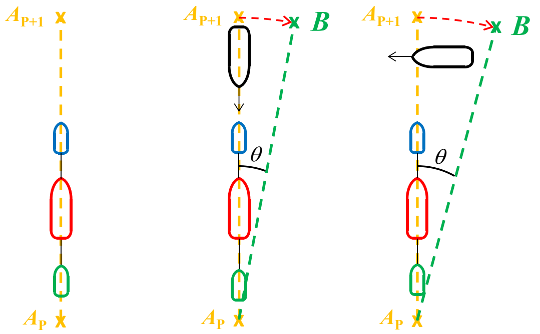
III. MPC-BASED AND COLREGS COMPLIANCE COLLISION AVOIDANCE SCHEME

In this work, an MPC-based and COLREGS compliant collision avoidance scheme is proposed for towing the ship in a safe manner shown in Fig. 1.

The COLREGS-complied ship reference system provides waypoints that the ship needs to follow ($\boldsymbol{\eta}_{S_{\mathrm{d}}}(t)$) without colliding with obstacles whose positions are assumed to be known ($\boldsymbol{\eta}_{ob}(t)$). This operation can be seen as the pre-stage of collision avoidance that focuses on complying with COLREGS rules. The MPC-based controller, which can be implemented in a computer located at the onshore control center, uses the above information and the current states of the ship ($\boldsymbol{\eta}_S(t)$, $\boldsymbol{\nu}_S(t)$) and tugs ($\boldsymbol{\eta}_i(t)$, $\boldsymbol{\nu}_i(t)$) to compute the towing angles $\alpha_i(t)$, towing forces $F_i(t)$, and the thruster forces and moment $\boldsymbol{\tau}_{T_i}(t)$, and sends them to the tugs.

A. COLREGS-Complied Ship Reference System

As shown in Fig. 2, the rules 13-17 in the COLREGS explicitly prescribe operations that an own-ship (the ship under control) should follow in three different situations. Since a ship-towing system usually navigates at a low speed, the collision avoidance problem will focus on the head-on and crossing situations. The prescribed actions indicate that



(a) (b) (c)

Fig. 3. Ship reference scheme: (a) under normal condition; (b) under the head-on situation; (c) under the crossing situation.

the give-way vessel should steer to starboard (right) so that each vessel passes on the port side (left) of each other. However, the movement of the ship in the towing system can only be made by controlling the motion of the connected tugs. Thus, the prescribed operations should be formulated in a different way.

In maritime practice, there are often some fixed waypoints to guide a ship towing system following the predefined path (as shown in Fig. 3 (a)). These waypoints can be used for the first stage of collision avoidance. Fig. 3 (b) and (c) are the alternative way for achieving the prescribed operations of the COLREGS under the head-on and crossing situation. In this way, it is essential to replace the operation of starboard steering with a clockwise waypoint altering. As observed in Fig. 3 (b) and (c), when encountering the head-on or crossing situation, the current goal waypoint (A_{p+1}) is altered by a new waypoint (B). The new waypoint is determined by an arc of the circle with center the last predefined waypoint (A_p) and radius the distance between A_p and A_{p+1}. The direction is clockwise for the operations of starboard steering. The planar coordinates (x_B, y_B) of the new waypoint can be computed as:

$$\begin{gathered}\begin{bmatrix} x_B \\ y_B \end{bmatrix} = \begin{bmatrix} x_A(p) \\ y_A(p) \end{bmatrix} + r \cdot \begin{bmatrix} \sin(\theta) \\ \cos(\theta) \end{bmatrix} \\ r = \left\| \begin{bmatrix} x_A(p) \\ y_A(p) \end{bmatrix} - \begin{bmatrix} x_A(p+1) \\ y_A(p+1) \end{bmatrix} \right\|_2 , \end{gathered} \tag{4}$$

where $(x_A(p+1), y_A(p+1))$ is the current predefined waypoint; $(x_A(p), y_A(p))$ is the coordinates of the last predefined waypoint; r is the distance between the above two waypoints; θ is the altering angle and satisfies $\theta > 0^\circ$ (for clockwise rotation), its value should be small such that ensures the collision avoidance of the ship towing system with the bank of the waterway during maneuvering.

B. MPC-based Collision Avoidance Controller

The COLREGS-complied ship reference scheme can not guarantee the collision avoidance of the towing system especially for the front tug, because the physical connection restrains the movement of the three vessels and reduces the effectiveness of the steering operation. Moreover, the low speed of the system increases the response time of the action. Thus, a further operation for collision avoidance is necessary to ensure safety for the ship-towing system.

Considering the multiple control inputs (towing forces, towing angles, and thrust forces and moment of the two tugs), the multiple constraints of the towing system, and the online collision avoidance operations, the model predictive control strategy is formulated as:

$$\begin{aligned} J^* = \min_{\alpha_1,\alpha_2,F_1,F_2,\boldsymbol{\tau}_{T_1},\boldsymbol{\tau}_{T_2}} \quad & \sum_{h=1}^{H_\mathrm{P}} \{ w_S J_S(k+h|k) + \\ & \sum_{i=1}^{2} w_T J_i(k+h|k) \}, \end{aligned} \tag{5}$$

where H_P is the length of the prediction horizon; h is the hth time prediction step; k is the current sample time; $J_S(k+h|k)$ and $J_i(k+h|k)$ are the prediction made at k about the cost of the ship and tug i at $k+h$, respectively; w_S and w_T are the weight coefficients for the ship and tugs.

The cost function of the ship J_S is designed as:

$$\begin{aligned} J_S(k+1) &= w_1 \boldsymbol{e}_{\eta_S}^\mathrm{T}(k+1) \boldsymbol{e}_{\eta_S}(k+1) + w_2 \boldsymbol{\nu}_{S_\mathrm{P}}^\mathrm{T}(k+1) \boldsymbol{\nu}_{S_\mathrm{P}}(k+1) \\ &\quad + w_3 \sum_{j=1}^{n} (d_{S_j}(k+1) - d_{S\mathrm{d}_j})^{-2} \\ \boldsymbol{e}_{\eta_S}(k+1) &= \boldsymbol{\eta}_{S_\mathrm{P}}(k+1) - \boldsymbol{\eta}_{S_\mathrm{d}}(k+1), \end{aligned} \tag{6}$$

where $\boldsymbol{e}_{\eta_S} \in \mathbb{R}^3$ is the position error of the ship; n is the number of obstacles; d_{S_j} is the distance between the ship and obstacle j; $d_{S\mathrm{d}_j}$ is the safety distance between the ship and the obstacle j; w_1, w_2 and w_3 are the weight coefficients (positive scalar); $\boldsymbol{\eta}_{S_\mathrm{P}} \in \mathbb{R}^3$ and $\boldsymbol{\nu}_{S_\mathrm{P}} \in \mathbb{R}^3$ are the predicted position and velocity of the ship; $\boldsymbol{\eta}_{S_\mathrm{d}} \in \mathbb{R}^3$ is the desired position of the ship.

The cost function of tug i is designed as:

$$\begin{aligned} J_i(k+1) &= w_{i1} \boldsymbol{e}_{\eta_i}^\mathrm{T}(k+1) \boldsymbol{e}_{\eta_i}(k+1) + w_{i2} \boldsymbol{\nu}_{i\mathrm{P}}^\mathrm{T}(k+1) \boldsymbol{\nu}_{i\mathrm{P}}(k+1) \\ &\quad + w_{i3} \sum_{j=1}^{n} (d_{i_j}(k+1) - d_{i\mathrm{d}_j})^{-2} \\ \boldsymbol{e}_{\eta_i}(k+1) &= \boldsymbol{\eta}_{i\mathrm{P}}(k+1) - \boldsymbol{\eta}_{i_\mathrm{d}}(k+1), \end{aligned} \tag{7}$$

where $\boldsymbol{e}_{\eta_i} \in \mathbb{R}^3$ is the position error of the tug i; d_{i_j} is the distance between the tug i and obstacle j; $d_{i\mathrm{d}_j}$ is the safety distance between the tug i and the obstacle j; w_{i1}, w_{i2} and w_{i3} are the weight coefficients (positive scalar); $\boldsymbol{\eta}_{i\mathrm{P}} \in \mathbb{R}^3$ and $\boldsymbol{\nu}_{i\mathrm{P}} \in \mathbb{R}^3$ are the predicted position and velocity of the tug i; $\boldsymbol{\eta}_{i_\mathrm{d}} \in \mathbb{R}^3$ is the desired on-line position of the tug i.

The safety distance between the vessel (viz the ship or tugs) and obstacle is calculated in different ways according to the attributes of the obstacle: the static obstacle is treated as the circle and the dynamic obstacle is treated as the ellipse, as shown in Fig. 4:

$$d_{*\mathrm{d}_j} = \begin{cases} L + R + d_{S0} & \text{for circle obstacle} \\ L + 2(a + d_{S0}) & \text{for ellipse obstacle} \end{cases} , \tag{8}$$

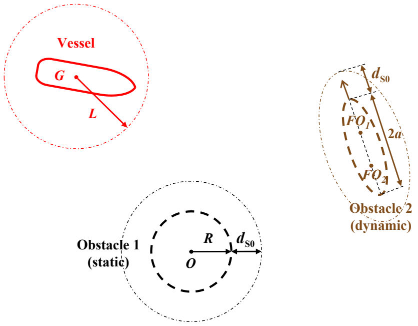


Fig. 4. Distance of different obstacles

where $*$ stands for S or i; L is the length of the own-vessel; R is the radius of the circle obstacle; a is the length of the long axis of the ellipse obstacle; d_{S0} is the surplus distance (buffer) of the obstacles.

As it can be seen from (6) and (7), the cost function contains three parts. The first part is the position error, which is minimized to achieve path following. The second part is the velocity, whose role is to constrain the speed of the three vessels so that it makes the motion of the system smooth. The third part is the distance error between the ship and the obstacles. It is a reciprocal quadratic term meaning that the further the ship is from the safety distance of the obstacle, the less value of this term. This ensures that the ship keeps away from the obstacles.

The predicted position and velocity of the ship and tug i are calculated by discretizing the dynamic model in Section II with a sample time T_s:

$$\begin{aligned}\boldsymbol{\eta}_{S_\mathrm{P}}(k+1) &= \boldsymbol{\eta}_{S_\mathrm{P}}(k) + \int_{(k)T_s}^{(k+1)T_s} \boldsymbol{R}(\psi_S(t))\boldsymbol{\nu}_{\boldsymbol{S}}(t)dt \\ \boldsymbol{\nu}_{S_\mathrm{P}}(k+1) &= \boldsymbol{\nu}_{S_\mathrm{P}}(k) + \int_{(k)T_s}^{(k+1)T_s} \boldsymbol{M}_{\boldsymbol{S}}^{-1}[-\boldsymbol{C}_{\boldsymbol{S}}(\boldsymbol{\nu}_{\boldsymbol{S}}(t))\boldsymbol{\nu}_{\boldsymbol{S}}(t) \\ &\quad -\boldsymbol{D}_{\boldsymbol{S}}\boldsymbol{\nu}_{\boldsymbol{S}}(t) - \boldsymbol{B}(\alpha_1(t))F_1(t) + \boldsymbol{B}(\alpha_2(t))F_2(t)]dt,\end{aligned} \tag{9}$$

$$\begin{aligned}\boldsymbol{\eta}_{i_\mathrm{P}}(k+1) &= \boldsymbol{\eta}_{i_\mathrm{P}}(k) + \int_{(k)T_s}^{(k+1)T_s} \boldsymbol{R}(\psi_i(t))\boldsymbol{\nu}_{\boldsymbol{i}}(t)dt \\ \boldsymbol{\nu}_{i_\mathrm{P}}(k+1) &= \boldsymbol{\nu}_{i_\mathrm{P}}(k) + \int_{(k)T_s}^{(k+1)T_s} \boldsymbol{M}_{\boldsymbol{i}}^{-1}[-\boldsymbol{C}_{\boldsymbol{i}}(\boldsymbol{\nu}_{\boldsymbol{i}}(t))\boldsymbol{\nu}_{\boldsymbol{i}}(t) \\ &\quad -\boldsymbol{D}_{\boldsymbol{i}}\boldsymbol{\nu}_{\boldsymbol{i}}(t) + \boldsymbol{B}_{\boldsymbol{i}}(\beta_i(t))F_i(t) + \boldsymbol{\tau}_{T_i}(t)]dt.\end{aligned} \tag{10}$$

The desired on-line position of the tug i ($\boldsymbol{\eta}_{i_\mathrm{d}}$) is calculated by the desired geometrical relationship between the ship and tugs (shown in Fig. 5) [13]; i.e. for $i = 1,2$:

$$\begin{aligned}\boldsymbol{\eta}_{i\mathrm{d}}(k+1) &= \boldsymbol{\eta}_{S_\mathrm{P}}(k+1) + (l_{\mathrm{tow}_i} + l_{\mathrm{T_i}})\boldsymbol{E}_i(\psi_{S_\mathrm{P}}(k+1), \alpha_i(k+1)) \\ &\quad + l_i\boldsymbol{F}_i(\psi_{S_\mathrm{P}}(k+1)) + \alpha_i(k+1)[0\ 0\ 1]^\mathrm{T},\end{aligned} \tag{11}$$

where l_{tow_i} is the length of the towing line; $\boldsymbol{E}_i \in \mathbb{R}^3$ and $\boldsymbol{F}_i \in \mathbb{R}^3$ are the vectors related to the predicted heading of the ship and the towing angles, formulated as:

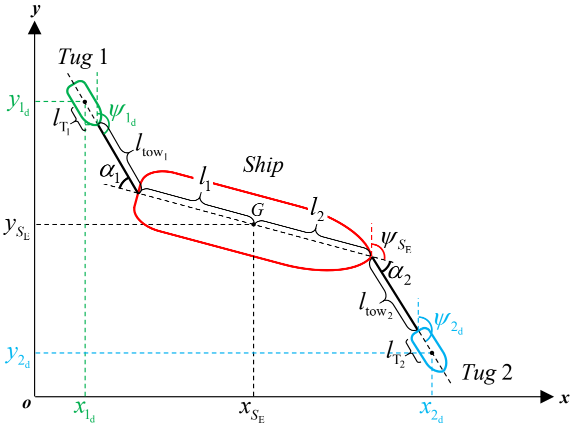


Fig. 5. Kinematic model of the ship towing system.

$$\boldsymbol{E}_i = (-1)^i \begin{bmatrix} \sin(\psi_{S_\mathrm{P}}(k+1) + \alpha_i(k+1)) \\ \cos(\psi_{S_\mathrm{P}}(k+1) + \alpha_i(k+1)) \\ 0 \end{bmatrix}, \tag{12}$$

$$\boldsymbol{F}_i = (-1)^i \begin{bmatrix} \sin(\psi_{S_\mathrm{P}}(k+1)) \\ \cos(\psi_{S_\mathrm{P}}(k+1)) \\ 0 \end{bmatrix}, \tag{13}$$

Besides the kinematics and kinetics constraints (9), (10) and (11), there are operational constraints; i.e. for all k and $i = 1,2$:

$$-\pi/2 \le \alpha_i(k+1) < \pi/2 \tag{14}$$

$$0 \le F_i(k+1) \le F_{i\max} \tag{15}$$

$$-\boldsymbol{\tau}_{i\max} \le \boldsymbol{\tau}_{\boldsymbol{i}}(k+1) \le \boldsymbol{\tau}_{i\max} \tag{16}$$

$$|\dot{\alpha}_i(k+1)| \le \bar{\alpha}_i \tag{17}$$

$$|\dot{F}_i(k+1)| \le \bar{F}_i, \tag{18}$$

where $F_{i\max}$ 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; $\bar{\alpha}_i$ and $\bar{F}_i$ are the maximum change rate value of towing angle and force, respectively.

Constraints (14), (15) and (16) model the saturation of the towing forces, towing angles and thruster forces, stemming from the physical laws and maritime practice [14]; (17) and (18) limit the change rate of the towing angles and forces, in order to make the tug reference trajectory smooth so that improving the performance of the trajectory tracking.

It is noted that the method presented in Sections III. A & B concerns collision resolution. Collision detection is out of the scope of this work.

IV. SIMULATION EXPERIMENT

Results are presented in this section to show the simulation performance of the proposed method applied to a ship-towing system of small scale vessels.

TABLE I

PARAMETERS OF THE CONTROL SYSTEM.

Altering angle	$\theta = -15^{\circ}$
Prediction horizon	$H_P = 4$
Weight in ship cost	$w_1 = 1,\ w_2 = 60,\ w_3 = 10$
Weight in tug cost	$w_{i1} = 30,\ w_{i2} = 10,\ w_{i3} = 0.1\ (i = 1,2)$
Weight for three vessels	$w_S = 1,\ w_T = 1$

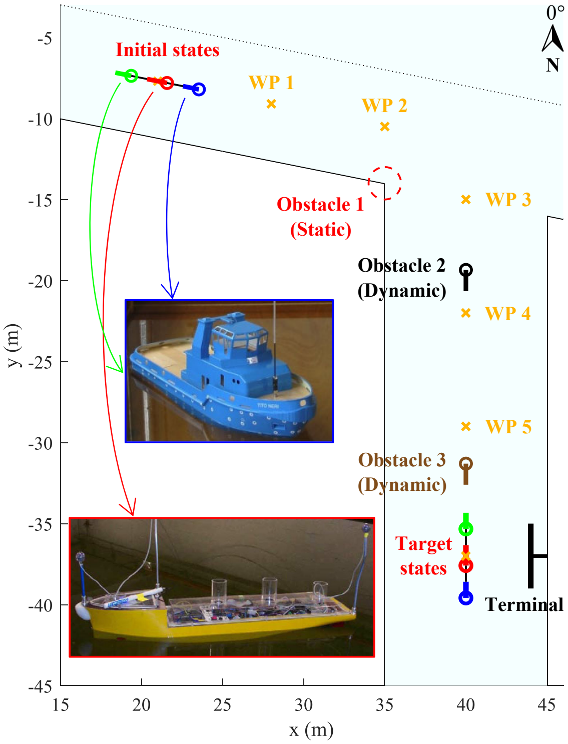


Fig. 6. Simulation initial setting.

A. Simulation Setup

The model of the two tugs are represented by the "*TitoNeri*" developed by TU Delft [15], while the ship is represented by the "*CyberShip II*" [16]. The parameters of the vessel model and the towing system can be found in [13], the parameters of the control system are shown in Table I.

The initial setting is shown in Fig. 6. The objective is to manipulate the ship from initial states ($\boldsymbol{\eta}_{S_0} = [21\ \ -7.7\ \ 101.3]^{\mathrm{T}}$, $\boldsymbol{\nu}_{S_0} = [0\ \ 0\ \ 0]^{\mathrm{T}}$) to the target states ($\boldsymbol{\eta}_{S_t} = [40\ \ -37\ \ 180]^{\mathrm{T}}$, $\boldsymbol{\nu}_{S_t} = [0\ 0\ 0]^{\mathrm{T}}$). Five predefined waypoints (yellow cross) are set between the origin and the destination, which should be followed when there are no obstacles. There are three obstacles on the waterway: one static obstacle lays in the turning corner, two dynamic obstacles are right on the way of the predefined path.

B. Results and Discussion

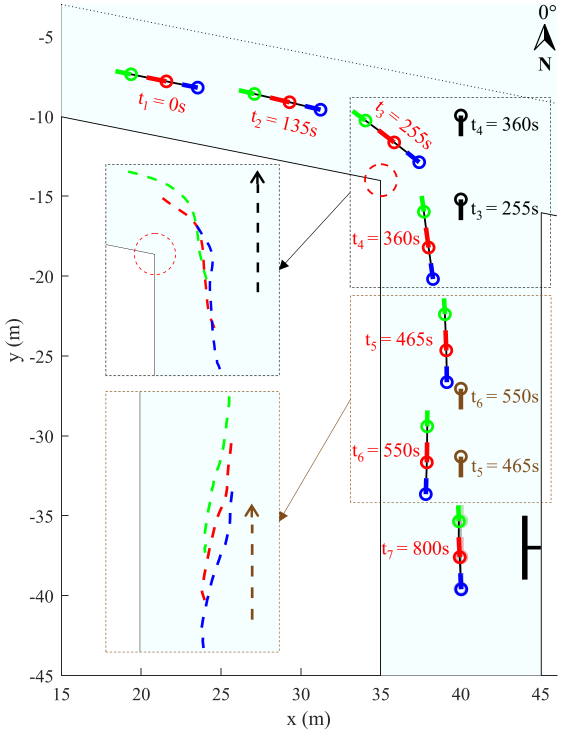


Fig. 7. Towing process with collision avoidance: the dashed lines represent the trajectories, the colored time instants show which vessel is there.

The towing process is shown in Fig. 7. Seven time-sampled states of the ship-towing system illustrate the whole collision avoidance process. From $t_1 = 0$s to $t_2 = 135$s, the control objective is path following. From $t_2 = 135$s to $t_3 = 225$s, the system executes starboard (right) side steering operation. At this moment (t_3), the system encounters two obstacles: one static obstacle on the starboard side, and one dynamic obstacle on the front port (left) side. From $t_3 = 225$s to $t_4 = 360$s, there is a collision avoidance situation. As shown in the left top block diagram, the system passes through two obstacles without collision although the passage is narrow. From $t_4 = 360$s to $t_5 = 465$s, the system returns to the original path to follow the predefined waypoint again. At time t_5, it encounters the second dynamic obstacle. So from $t_5 = 465$s to $t_6 = 550$s, there is the second time of collision avoidance. This time it is a head-on situation and to satisfy the COLREGS, the system steers to the starboard side so that the obstacle and the towing system pass on the port side of each other. The trajectory from the left bottom block diagram shows the collision avoidance process. The last time interval from $t_6 = 550$s to $t_7 = 800$s is the process that the system slowly approaches the destination and adjusts to the desired heading, spending more time than at the earlier towing process stages.

The time-varying states of the ship and two tugs are shown in Fig. 8. It can be seen that the ship states reach their desired value. For the first collision avoidance situation, as the navigable water areas are narrow and the steering process is performed, the system decreases its surge and sway speed and increases the yaw speed. After passing the two obstacles, the system returns to the original path and speeds up. The speed changes are observed from the period 200 to 400

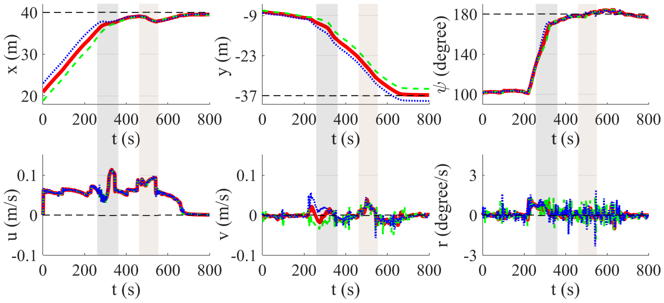


Fig. 8. Six states (position (x,y), heading ψ and velocities (u,v,r)) of the ship (red bold line, black dotted line stands for their desired value) and two tugs (green dashed line stands for Tug 1 and blue dotted line for Tug 2), light black and light brown shadows are the first and second collision avoidance situations, respectively.

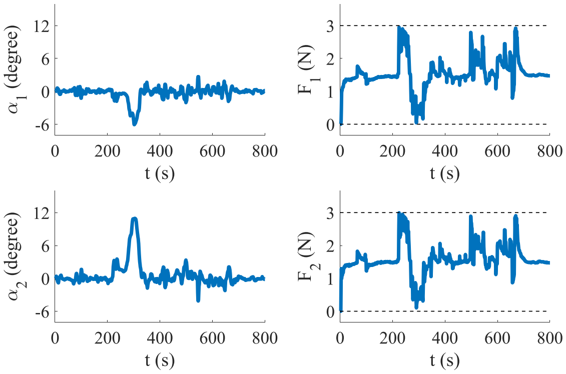


Fig. 9. Towing forces and angles.

seconds in the bottom row of Fig. 8. In the second avoidance situation, the system accelerates for fast starboard-steering to cope with the head-on collision situation (the period 400 $\sim$ 600 seconds of Fig. 8).

The towing forces and angles are shown in Fig. 9. The magnitude of forces is within 3 N, which satisfies the saturation constraints. The changes of frequency and amplitude of the towing angle of Tug 2 (front, α_2) is larger than that of Tug 1 (behind, α_1), because the goal of Tug 2 is to alter the ship's heading while Tug 1 is used to stabilize the heading.

V. CONCLUSIONS AND FUTURE RESEARCH

This paper focuses on the collision avoidance of a physically connected multi-vessel system. We propose an MPC-based COLREGS compliant method for a ship towing system to achieve collision avoidance in restricted waters. Considering the multiple control inputs and constraints and the online collision avoidance operations, the MPC strategy is used to calculate the optimal control inputs. The COLREGS rules 13-17 are integrated into the ship reference system by altering predefined waypoints to guide the towing system moving in a compliance way. This operation is the pre-stage of collision avoidance, while the main stage is implemented by the MPC controller. By designing the cost function containing position error, velocity error, and distance error for the ship and tugs, the controller makes the ship-towing system stay away from the obstacles while following the calculated waypoint.

Simulation experiments indicate that the proposed method can deal with static and dynamic obstacle situation in narrow waterways for the ship towing system, and make the collision avoidance operation compliant COLREGS. Future research will focus on designing a distributed control architecture for the ship towing system, before implementing the actual model tests.

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