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Coordination and Optimization Control Framework for Vessels Platooning in Inland Waterborne Transportation System

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***Abstract*— Vessels sailing in a single platoon could reduce resistance from the perspective of the whole platoon and the individual vessel, and contribute to improving energy benefits. Moreover, transportation energy costs and traffic efficiency are essential indicators for measuring waterborne transportation systems. We attempt to minimize transportation energy costs by coordinating platoon formation using a distributed framework of controllers. A large-scale coordinated vessel platooning program is proposed to minimize transportation energy costs and optimize traffic efficiency while guaranteeing safety. The control framework covers routing, energy consumption-dependent cooperative platooning decision and speed optimization based on graph search algorithm, cluster analysis, optimal control approach and model predictive control. Firstly, a local scheduling strategy combined with the leader vessel selection algorithm is adopted. Furthermore, we used cluster analysis to create a series of mergeable vessel platooning sets. Then, we used the mathematical planning method and a two-step hybrid optimal control approach to calculate the improvement and optimization of each vessel platoon's path and speed. Finally, the scalability of the scheduling strategy is elucidated. In a simulation of large scale inland waterborne network, savings surpassed 3.5% when six hundreds vessels participated in the system. These simulation results reveal that the scheduling strategy coordinating vessels into vessel platooning, which improves transportation efficiency as well as descends cost, comparing to a fixed origin route in the waterway network.**

***Index Terms*— Vessel platooning, scheduling scheme, cooperative control, waterborne transportation system, energy consumption.**

I. INTRODUCTION

INLAND waterway transportation is an important component in the transportation system, and plays a key role in the transportation of goods in the world. In Europe, hundreds of cities and industrial districts are connected by more than 37,000 kilometers of waterways [1]. The potential for raising the modal share of inland waterway transportation is being realized thanks to the development of an integrated canal network. In comparison to other modes of transportation, which are often plagued by congestion and capacity issues, inland waterway transportation is distinguished by its dependability, energy efficiency, and significant potential for increasing use.

Optimizing the performance of waterborne transportation systems requires automation of the individual vessels and cooperation among vessels [2], [3], [4], [5].

Vessels sailing in a platoon could bring resistance reduction than when sailing separately [6]. By sailing in a specific formation configurations, sailing vessels experience reduced water resistance. This minimizes the overall amount of energy used, resulting in considerable energy savings for both the whole convoy and each individual vessel. For example, waterway transportation in world uses approximately 350 million metric tons of petroleum fuels every year; therefore, even modest decreases in energy use can yield dramatic savings. In addition, since waterway transportation are a significant contributor to greenhouse gas emissions (In terms of greenhouse gas emissions, shipping is responsible for roughly 2.2% of total world emissions [7], despite the fact that its energy consumption per km/ton of carried commodities is only about 17% that of road transport and 50% that of rail transport. [8]), platooning vessels can also have benefits for environmental impact [2].

Single platoons or individual vessels within a platoon have major interests in vessels' cooperation. Researches have shown that the cooperation and formation of vessels mainly focus on control, communication, optimal path finding, etc. However, most studies' objects are on a single platoon or a single vessel

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within a platoon. So far, coordination and optimization of vessels and platoons achieved in large waterway networks have mainly been ignored. The coordination and optimization of vessels and platoons of vessels throughout a large-scale real-world waterborne network are lacked in nowadays study.

For the research of vessels' cooperation, the research goal is mainly focused on the optimization path of the time dimension and the space dimension, and few papers focus on the energy consumption problem in the cooperative control of vessels.

Inspired by study on 'Vessel Train' and 'Energy Reduce' [1], [2], [6], [9], this paper studies the optimal scheduling problem of ships from a new perspective. Considering that the changes in the sailing route could make more vessels merge into platoons, for vessels with near positions and near paths in the waterway channel, the velocity and path of some or all of the vessels can be dispatched so that they can form vessel platoons in specific public waterway segments. Thereby saving vessels' energy consumption of waterway transportation system.

Therefore, this paper develops a coordination and optimization control framework for multiple platoons with multiple vessels that exploit the benefits of platooning. We propose a framework for energy-optimal coordination where the vessels adapt their path and speeds in order to form platoons during their journeys while sailing, and vessels are guaranteed to arrive at their destinations by their arrival deadlines. We allow all the vessels to act in order to form the platoon. Path and speed changes of the sailing vessels leads to a higher energy consumption. However, the additional energy cost can be regained from platooning long enough.

The main contribution of this paper is that a cooperative multi-vessel platooning transportation system is developed to save energy consumption by tightly integrating the logistics system with the control and cooperation of many fleets of vessels. To support the implementation of this integrated system, a hierarchical approach is presented that allows for a layering of tasks using a three-layer architecture.

- This work investigates a novel method based on graph search algorithm and cluster analysis for forming platoons from scattered vessels in order to save energy and ensure safety. Jointly organize the new sailing path such that the initial vessels without a public section have part of the common section, and dispatch them to the designated common section combined formation based on energy consumption optimization.
- The global optimization merger strategy based on the mathematical planning method and a two-step hybrid optimal control approach is adopted to dispatch all vessels to merge in formation simultaneously. In the current paper, the proposed algorithm involves all vessels acting to form the platoon as energy efficiently as possible without delaying the transports. Note that the algorithm does not guarantee that every vessel saves energy, but the vessels in the whole transportation system will be guaranteed to save energy.
- A distributed control strategy is general for vessels and can handle both merging and splitting maneuvers while tracking the desired velocity trajectory and ensuring the safe desired gap between any two consecutive vessels for a dynamic platooning.

Fig. 1. Vessel Train in NOVIMAR [9].

The remaining part of the paper is organized as follows. In section III of this paper, the coordination and optimization architecture for transportation system are described and the formulation of platooning problem are modeled. The Section IV is concerned with the methodology used for this study, a framework combined with the leader vessel selection algorithm is adopted and then, the mathematical planning method is used to calculate the improvement and optimization of each vessel platoon's path and speed. The Section V presents the results of the research. Section VI concludes this paper with a brief summary and an outline of future work.

II. RELATED WORKS

The last decades have seen a growing trend towards research into platooning vessels. Inspired by similar work in robotics and vehicle technology, researchers have begun researching the feasibility and effectiveness of moving vessels in formation in order to improve the efficiency of vessel-based transportation. Furthermore, regarding inland waterways and port regions, platooning, in which many vessels follow one another and create a vessel train, has been envisaged as the optimal configuration [10]. For inland waterway, a idea of a platooning line-up we developed to work [11]. In addition, a concept of vessel platooning has be adopted in providing transportation service by [12]. The NOVel Iwt and MARitime transport concepts (NOVIMAR, https://novimar.eu/) project develops a waterborne transportation system called the Vessel Train (VT) that is based on the platooning principle researched in the trucking industry [9]. The European short sea transportation system is now exploring the idea of waterborne platooning as seen in [1], and the Vessel Train transportation system's economic feasibility is discussed in the case study. It has been established that vessel platooning has positive environmental effects due to reduced fuel consumption and use of "sailing space".

The emphasis of platooning research has been the control of already-formed platoon vessels. [13], [14], [15], [16]. For instance, strategies for communication inside platooning ships [5], paradigms for visually recognizing obstacles for platooning vessels [5], and procedures for coordinated maneuvering of platooning vehicles [10] have been investigated.

Compared with vessels, the research in the field of truck platooning started earlier. In [17], a distributed network of controllers is used to coordinate platoon formation in an effort to conserve the most fuel possible. However, platooning applications have a number of significant obstacles in [18], including communication and control, as well as security. The different planning problems in truck platooning were classified [19], and presenting future research directions. Platooning technical issues and their solutions in communication and security based on energy efficiency, safety and cost balancing are present in [20]. The main issues of communication, security and privacy in autonomous vehicles coordination and different approaches to deal them were introduced in [21].

Currently, vessels do not actively coordinate their operations with others [22], thus as traffic density increases, each vessel operating on its own may create inefficiency.

The majority of the literature on vessel platooning has focused on vessels staying in the platoon throughout the trip. In actuality, however, platoons need be established, combined, or divided since vessels have diverse sources and destinations.

The current researches lack research on optimizing energy consumption in the system by dispatching vessels in large-scale inland Waterborne transportation system to form multiple platoons. However, based on researches 'Vessel Train', 'Energy Reduce', [1], [2], [6], [9] etc., we found that this new idea becomes a possibility. Since the current study is unable to deal effectively with such above realistic scenarios and the optimization results are not guaranteed to be viable, it is necessary to investigate cooperative platooning control for these situations at the entire system level in an integrated manner.

III. PROBLEM STATEMENT AND MODELING

In this paper, we focus on vessels' cooperative optimization scheduling of multi platoons with multi vessels in waterway networks. In this section, the assumptions are provided and we present a architecture for the cooperative optimization scheduling of vessels in waterway networks. A large-scale planning, cooperation, and real-time optimization/automation system are addressed in this study that incorporates possible vessels.

A. Problem Statement

According to [23], the waterway ship coordination and optimization problem considers a set of vessels $I = 1, \dots, i$, a set of available waterways $N = 1, \dots, n$, and a set of time steps $T = 1, \dots, t$. For each vessel I in the waterway network, we can assign a arrival location $P_i^a \in \mathrm{N}$ and departure location $P_i^d \in \mathrm{N}$.

There is a set of limited transportation tasks T^t in the target waterway network, and each transportation task is bound to a cargo vessel. The transportation tasks of vessel i are $T_i^t = (P_i^d, P_i^a, T_i^d, T_i^a)$, including the departure position P_i^d, arrival position P_i^a, departure time T_i^d and arrival time T_i^a. The current position of vessel $P_i^c = (n_i(t), x_i(t))$, $n_i(t)$ represents the waterway segments where the vessel is located, and $x_i(t)$ represents the distance that the vessel sails in this waterway segments. The function $M(s_i)$ represents the mapping relationship between the waterway network model and the actual waterway length.

A given waterway network could be modeled as a graph. $W = (S, N)$ to describe the network, S is the set of all nodes(the waterway intersections), and N is the waterway segment connecting the two intersections. Notice that all waterways are considered flat and straight in our waterborne network, and each vessel is represented as a point location.

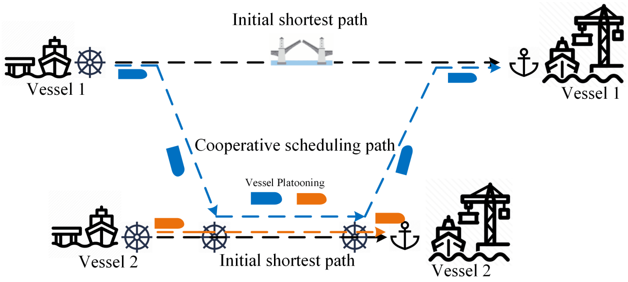


Fig. 2. The schematic diagram of vessel merging.

The energy saved by a platoon of vessels compared to a single-vessel is η in the range of $(0, 1)$. In addition, We note that as a result of less water drag, the vessels in the platoon system will require less energy. For suitable distances between vessels, η can be up to 10%and 7.16% on average [6]. Throughout this study, we choose a more realistic savings of 7 percent based on [6].

Almost all the vessels in the waterway network are sailing alone, there were lacking cooperation among vessels. Based on the fact that vessel train sailing can reduce the energy consumption of the vessels, this paper changes the path and speed of the vessels to make the vessels that used to sail alone have the opportunity to merge into a fleet, which can save energy consumption compared with sailing alone.

The route change and conformation of the vessels are shown in Figure 2. The vessel train merging process includes five stages: departure sailing(t_i^s, t_i^m), merging(t_i^m, t_i^p), vessel train(t_i^p, t_i^{sp}), separate sailing (t_i^{sp}, t_i^d) and arrival sailing(t_i^d, t_i^a). Not all vessels in the system include five transportation stages. For example, some vessels sail in a fleet with other vessels from the place of departure, and there is no separate sailing and merging stage; not all merged vessels need to change the path. Figure 2 is an explanation of the scheduling strategy for two ships of this paper.

Finally, we define vessel transportation plan $P = (n, \upsilon, t)$, including path n, speed series υ, time-series t. Path n consists of the sequence of N_e edges in the waterway network, $n = (n[1], n[2], \dots, n[N_e]), n[k] \in N$, the speed sequence $\upsilon = (\upsilon[1], \upsilon[2], \dots, \upsilon[N_\upsilon])$, N_υ is series number of speed sequence υ, N_e is the number of waterway network's edges. In principle, the vessel speed can change at any time. This article assumes that the speed is only in traffic. There is a change in scheduling or congestion, and other conditions are maintained at a constant speed. We define the time series $t = (t[1], t[2], \dots, t[N_\upsilon + 1])$, and the velocity $\upsilon[k]$ remains unchanged at $(t[k], t[k+1])$.

B. Coordination and Optimization Framework for Vessel Platooning

The coordination and optimization system is a complex, large-scale and closely connected multi-agent system based on current and new communication and computation infrastructures. The layered design shown in Fig. 3 is a natural fit

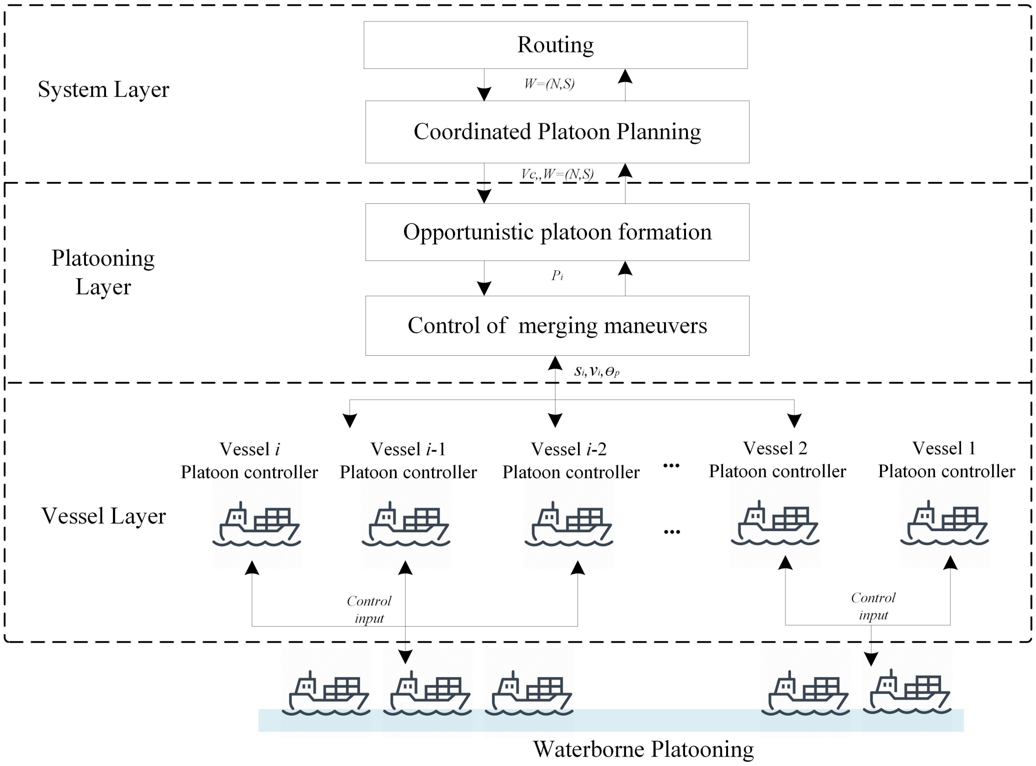


Fig. 3. Layered coordination and optimization architecture.

for this large-scale coordinating challenge. The vessel layer deals with individual vessel management, while the platooning layer focuses on platoon behavior and formation. Finally, the system layer handles the large-scale coordination of vessel platoons.

Specifically, the vessel layer builds upon existing vessel control systems to safely and automatically operate vessels and vessel platoons to achieve the desired speed. Here, utilizing vessel-to-vessel communication and enhanced sensor data, a decentralized controller is designed to maintain the tracking of a defined inter-vessel distance and the rejection of disruptions. The vessel layer has a decentralized implementation embedded into the vessel' onboard systems.

Energy consumption may be reduced by sailing vessels in platooning that are appropriately spaced apart. The platooning layer seeks to accomplish two things. It first calculates energy-optimal velocities for vessel platoons, taking into consideration the waterway terrain and traffic. It also determines whether vessels should form a platoon based on their overlapping waterway route segments, which is done by the platooning layer. In addition, platoon formation's optimum regulation of merging maneuvers is handled in this layer along with other critical decisions.

The system layer is concerned with coordinating a large number of vessels, maybe belonging to various groups, across a vast region. If the individual vessel itineraries and transport plans are kept up to date, platoon formation may be promoted while using less energy overall. Additionally, the system layer is tasked with transport planning in order to make better use of the transportation system's capacity. Therefore, the individual fleet cost should be included in this layer's optimization criteria. As multiple vessels are taken into account in this coordination and optimization issue, a centralized implementation is required.

C. Vessel Train Formation

Navigable waters are often constrained by the banks of rivers in waterway networks, making waterways corridors. Therefore, vessels should also observe specific guidelines while sailing. A good example is a requirement that boats traveling on the starboard side of the canal reference [24]. This means that when boats work together to navigate inland rivers, they will form platoons.

Vessels are mainly used to move goods from one location to another. In order to facilitate this, boats are frequently bound to specific destinations and routes. As a result, vessels are tempted to remain near to one other in order to share information and get the advantages of sailing together.

Thus, in the waterway ship scheduling problem, following rules are applied:

(1) Path Planning: find the best path of vessel i to the arrival port;

(2) Optimization Scheduling: changes the path and speed of the vessels to make the vessels have the opportunity to merge into a fleet, which can save energy consumption;

D. Dynamic Model of Vessel

A dynamic model of the vessel is used to implement the vessel control and collaboration algorithms. The dynamics of a vessel i is modeled as the following discrete-time model:

$$\begin{aligned} p_i(k+1) &= p_i(k) + v_i(k) \\ v_i(k+1) &= v_i(k) + a_i(k) \end{aligned} \tag{1}$$

Here, $p_i(k), v_i(k)$ denote vessel position and velocity, and $a_i(k)$ is the acceleration of vessel. We used the same parameter values for all vessels to make exposition easier. Base on Eq.1, a state space representation for the dynamics is

$$\begin{aligned} x_i(k+1) &= A_i x_i(k) + B_i u_i(k) \\ y_i(k) &= C_i x_i(k) + D_i u_i(k) \end{aligned} \tag{2}$$

where $x_i(k) = \begin{bmatrix} p_i(k) \\ v_i(k) \end{bmatrix}$, $A_i = \begin{bmatrix} I, I \\ I, 0 \end{bmatrix}$, $B_i = \begin{bmatrix} 0 \\ I \end{bmatrix}$, $C_i = \begin{bmatrix} I, 0 \end{bmatrix}$, $D_i = 0$, $x_i(k)$ and $y_i(k)$ denote the vessel i system state and output at time step k, $u_i(k)$ is the system's input, and $A_i \in \mathbb{R}^{n_{i,x} \times n_{i,x}}$, $B_i \in \mathbb{R}^{n_{i,x} \times n_{i,u}}$, $C_i \in \mathbb{R}^{n_{i,y} \times n_{i,x}}$, $D_i \in \mathbb{R}^{n_{i,y} \times n_{i,u}}$ are matrix parameters of system.

In Eq. 2, maximum speed and maximum engine power are physical constraints on the vessel' dynamics., etc. Which is bounded as:

$$\begin{aligned} u_{\min} &\leqslant \|u(k)\|_2 \leqslant u_{\max}, \\ v_{\min} &\leqslant \|v(k)\|_2 \leqslant v_{\max}, \end{aligned} \tag{3}$$

Mathematics symbol $\| \cdot \|_2$ means the Euclidean norm.

For safe navigation, vessel i should keep a safety distance (d_{safe}) with its neighbour vessel j,

$$\|p_i - p_j\| \geq d_{safe} \tag{4}$$

E. Energy Consumption Computational Model

While moving through the network, vessels will accumulate a energy cost depending on the fuel weights of their path and the paths of other vessels. If multiple vessel sail along the same waterway at the same time, we assume they can form a platoon, which reduces their resistance [6] and reduce energy consumption.

In an analysis of reduce energy consumption in formation sailing, He [6] found that the total resistance coefficient of the formation system could decrease by 7.16% on average in tandem formation, and the largest reduction of the system is 10.82% with setting parameters.

When sailing in the vessel train, it is considered that all vessels in the vessel train have the same position and speed, and each vessel train includes a leader vessel and one or more following vessels. Many researchers have utilised polynomial to describe the relationship between velocity and consumption for engine. Knowing the power requirements of the vessels makes it now possible to calculate the fuel consumption using the specific fuel consumption. The fuel consumption of an engine is usually given at its design speed, which is around 80 % - 85 % maximum continuous rating (MCR) [5], [25]. The fuel consumption factor is estimated as follows:

$$\begin{aligned} \mathbf{Fuel_{ship}}(\mathbf{v}) = \beta_0 + \beta_1 \times \ S_f \ + \beta_2 \times \ S_f{}^2 \\ + \beta_3 \times \ L_f \ + \beta_4 \times \ L_f{}^2 \end{aligned} \tag{5}$$

where β are population parameters, S_f and L_f are load factors estimated. For the purpose of energy consumption analysis, first-order polynomial of speed's function is used to model the energy consumption per unit distance [26]. And it is considered that this modelling method is close to the actual engine fuel consumption in the speed range $[v_{min}, v_{max}]$ which meets the research needs of this paper. The fuel consumption model can be described as:

$$\begin{aligned} f(v, \theta(p)) = \theta(p)(F_{1p} \times Fuel_{ship}(v) + F_{0p}) \\ + (1 - \theta(p))(F_1 \times Fuel_{ship}(v) + F_0) \end{aligned} \tag{6}$$

where v represents the vessel's speed, F_1, F, F_{1p} and F_{0p} are constants, $\theta(p)$ is a binary function, $\theta(p) = 0$ represents the vessel sailing alone or as the leader vessel in the fleet, and $\theta(p) = 1$ represents the following vessels in the fleet.

Therefore, the total fuel consumption of vessel i from the starting point to the end point is

$$F_i(v, \theta(p)) = \sum_{n=1}^{N_i^d} \int_0^{M(s[n])} f\left(v_i[m], \theta(p)\right) \mathrm{d}x \tag{7}$$

Among them, $v_i[m]$ represents the speed sequence of vessel i and the M value of each vessel is different, and N drepresents the number of waterway sections of vessel i from the starting point to the end point. The total fuel consumption of all vessels after the merger is

$$F_{\text{total}} = \sum_{i \in N_c} F_i(v, \theta(p)) \tag{8}$$

IV. COLLABORATIVE PLATOONING AND OPERATION OPTIMIZATION SCHEDULING

As mentioned, the collaborative platooning and operation optimization scheduling are, in fact, a resource allocation problem. In this section, vessels share the transportation information of the vessel in real-time through advanced sensing and communication technology and then calculate the transportation plan of each vessel through the central processing unit and send it back to the vessel.

In general, this article aims to ensure that the most energy-efficient transportation plan is planned under the premise all vessels reach their destination on time. The transportation plan of each vessel mainly includes the path and speed of the vessel from the starting point to the end point.

A. Coordination Workflow Description

The control decision can be executed immediately. The planning of vessel transportation scheme on the network plane is divided into the following stages:

(1) Collect the first N_i^A available paths that each vessel can choose;

(2) Analyze the feasibility of merging all target vessels;

(3) Plan out the transportation scheme of vessels preliminarily, and screen out the leader vessels;

(4) Add speed optimization, and plan the transportation scheme of vessels i.

For the sake of easy handling of analysis, we only considers the deterministic case in this paper that there is no time delay in this contribution. The influence of network transmission delay on long-distance vessel scheduling is neglected.

B. System Layer

1) Route Plan: Since the path planning problem reflecting to Fig. 3 has already had a reasonably mature algorithm, this section needs to plan to satisfy the N_i^S shortest paths with condition $\sum_{i=1}^{I_i^d} M(e[n])/u_{i\max} <= t_i^d - t_i^s$ are sufficient.

Branch & Cut(B & C) and Branch & Bound(B & B) [27], [28] are graph search algorithms that specialize in answering NP-hard problems that are impossible to solve using conventional methods. They are used in a variety of optimization applications. The method systematically enumerates every potential solutions, but once it determines that the optimum cannot be found there, it discards significant groups of possibilities at once. While the worst-case complexity of such an approach is typically still exponential, the solution to some issues can be discovered rapidly in the majority of situations.

This method relies on moving ahead in time and considering all feasible choices at each timestep. While the number of branches is excessively enormous for a naive method, the structure of our network enables us to exclude substantial portions of the search space without evaluating every possibility, significantly speeding up the solution process. The number of branches that must be checked at each timestep is proportional to the number of different courses that each vessel may take at that timestep. If we define the set of vessel I's possible options at iteration $\mathcal{X}$ as $\mathcal{X}_{i,I}$, then the number of branches equals:

$$N_i^B = \prod_I |\mathcal{X}_{i,I}| \tag{9}$$

First step of Algorithm 1 illustrates the algorithm in its entirety.

2) Cooperative Platooning Method: The formation of platoon is very important for vessel scheduling. How to effectively form platooning with vessels scattered on the waterway is the key problem of this paper. Before scheduling, it is necessary to compare the differences of predicted sail time and energy consumption of each waterway, and the utility value will increase beyond a certain threshold after changing the route. To this end, it is necessary to judge whether the vessels i and j meet the conditions of conversion merger. Whether the vessel scheduling meets the transportation task can be analyzed from the perspective of time, space and energy consumption.

$$\begin{aligned}
t_i^s + \frac{\sum_{n=1}^{N_i^{D_i}} M(s[n])}{v_{i\max}} &< t_i^d t_j^s + \frac{\sum_{n=1}^{N_j^{D_j}} M(s[n])}{v_{j\max}} \\
&< t_j^d \left| \frac{\sum_{n=1}^{N_i^m} M(s[n])}{(1-\gamma)v_{i\max} + \gamma v_{i\min}} \right. \\
&\qquad \left. - \frac{\sum_{n=1}^{N_{j|}^m} M(s[n])}{(1-\gamma)v_{j\min} + \gamma v_{j\max}} \right| \\
&< \left| t_i^s - t_j^s \right|, s\left[N_i^m\right] \in \left(s\left[t_m\right], s\left[t_{sp}\right]\right) \\
J_{\text{platoon}} + f_{pn} &< J_{\text{normal}} \\
J_{\text{save}} &= (J_{\text{normal}} - J_{\text{platoon}} - f_{pn})/J_{\text{normal}}
\end{aligned} \tag{10}$$

where $N_i^{D_i}$ and$N_j^{D_j}$ represent the total number of waterway segments from the departure place to the destination of the vessels i and j, the superscripts D_i and D_j represent the set of alternative paths, N_i^m and N_j^m represent the number of waterway segments from the departure place to the encounter waterway segment of the vessel, $s[tm]$ and $s[tsp]$ respectively represent the start and end of the public waterway section. γ is a binary function, when the distance between the vessel i and the public waterway section is greater than the vessel j, $\gamma = 0$, otherwise, $\gamma = 1$. $J_{platoon}$ and J_{normal} represent respectively the optimal energy consumption of the combined sailing of the vessel sailing alone and changing waterway. f_{pn} is the combined threshold, which means other costs added after changing the path or speed. To simplify the design, this paper considers $f_{pn} = 0$. Therefore, the first equation is the feasibility of the combined route, and it represents the set of alternative ways for vessels to arrive on time, the second equation is time feasibility, which means that vesselss can complete combined sailing on public waterways, the last equation is fuel consumption feasibility, which means that the combined sailing scheme is more independent sailing can save fuel consumption, where $J_{platoon}$ and J_{normal} are expressed as follows:

$$\begin{aligned}
J_{\text{normal}} &= \left(\sum_{n=N_i^{\text{now}}}^{N_i^{d_{\min}}} M(s[n]) - x_i^{\text{now}} \right) \\
&\quad \times \left(F_1 \frac{\sum_{n=N_i^{\text{now}}}^{N_i^{d_{\min}}} M(s[n])}{t_i^d - t_i^s} - \frac{x_i^{\text{now}}}{t_i^d - t_i^s} + F_0 \right) \\
J_{\text{platoon}} &= v_c t_c (F_i Fuel_{ship}(v_c) + F_0) + \left(\sum_{n=N_i^{\text{now}}}^{N_i^{sp}} M(s[n]) \right. \\
&\quad \left. - x_i^{\text{now}} - v_c t_c \right) (F_{1p} Fuel_{ship}(v_p) + F_{0p}) \\
&\quad + \left(\sum_{n=N_i^{sp}+1}^{N_i^d} M(s[n]) \right) (F_1 Fuel_{ship}(v_a) + F_0)
\end{aligned} \tag{11}$$

where, $v_p = \sum_{n=1}^{N_j^{\min}} M(s[n]) / \left(t_j^d - t_j^s\right)$ indicates the speed of the fleet sailing. $t_c = (\sum_{n=N_j^{\text{now}}}^{N_m} M(s[n]) - \sum_{n=N_i^{\text{now}}}^{N_m} M(s[n]) + x_i^{now} - x_j^{now})/(v_c - v_p)$ indicates that the rear vessels catches up with the front vessels after t_c time, N_i^{now}, N_i^{sp}, N_i^{dmin}, N_i^{dc} is the number of sections of the current moment, separation moment, shortest path and scheduling path, respectively, x_i^{now} indicates the distance the vessel i sails on the section N_i at the current moment. The speed v_a after fleet separation depends on the catch-up speed v_c, which function as follows:

$$\begin{aligned}
v_a &= \frac{\sum_{n=N_i^{sp}+1}^{N_i^{dc}} M(s[n]) v_0 v_p}{X - Y - Z} \\
X &= v_p v_0 \left(t_i^d - t_i^s - t_c\right)
\end{aligned}$$

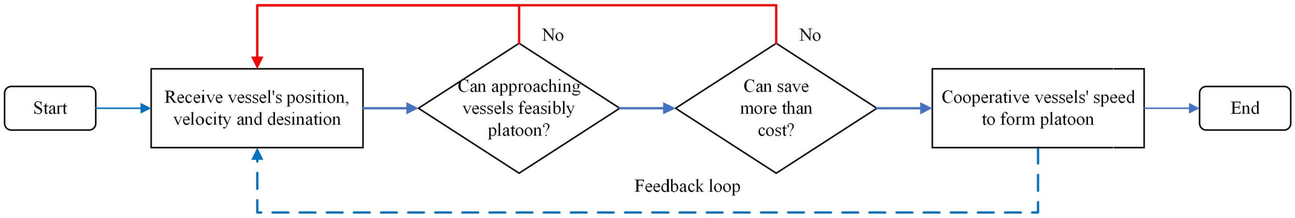


Fig. 4. Controller's logical flow.

$$
\begin{aligned}
Y &= v_0\left(\sum_{n=N_i^{\text{now}}} M(s[n]) - x_i^{\text{now}} - v_c t_c\right)\\
Z &= v_p\left(\sum_{n=1}^{N_i^{\text{now}}-1} M(s[n]) + x_i^{\text{now}}\right)
\end{aligned}
\tag{12}
$$

So the optimal energy consumption catch-up speed vc is indicated as follows:

$$
\begin{aligned}
v_c = \underset{v\in[v_{\min},v_{\max}]}{\arg\min}\ \Bigg[&vt\left(F_1 Fuel_{ship}(v)+F_0\right)\\
&+\left(\sum_{n=N_i^{\text{now}}} M(s[n]) - vt - x_i^{s_i}\right)\\
&\quad\times\left(F_{1p} Fuel_{ship}(v_p)+F_{0p}\right)\\
&+\left(\sum_{n=N_i^{sp}+1}^{N_i^{dc}} M(s[n])\right)\left(F_1 Fuel_{ship}(v_a)+F_0\right)\Bigg]
\end{aligned}
\tag{13}
$$

Among them, time t indicates the time when the vessels catching up with the vessels in front, the same meaning as the t_c above. The logical folw is as shown in Fig. 4.

The pseudocode of the algorithm used in this section is shown below:

C. Coordination Layer

1) Vessel Merger Decision: This section combines the default transport scheme with a scheduling scheme to plan consolidated collections of vessels from a wide range of vessels. Each vessel collection consists of a leader vessel and many optimal following vessels, combining the vessel and its leader vessel in the vessel collection to maximize energy savings. The team leader vessel maintains its default transportation plan and follows the vessel to implement the scheduling plan.

In this section, the default transport scheme means that the vessel follows the selected path and speed at the time of departure, and the path and speed do not change until it reaches the destination. The scheduling scheme means that vessels merge with other vessels by changing the path and speed on a public section.

We defined the vessel coordination graph is the directed weighted graph $G = (Nc, c, Wc)$, Nc is the set of nodes, each node represents a transport vessel, c is the set of edges connecting the two nodes, and $Wc = k_J$ is the non-negative weight for each edge. There is no edge between the two nodes if vessels cannot be combined into fleets or save energy consumption.

Algorithm 1 Branch & Cut Algorithm Based Cooperative Platooning Method

```
Input: Number of Vessel $I$, initial positions $R_1^I$, destinations $d^I$ and arrival times $T_d^I$ of every vessel;
Output: Optimal vessel paths $W_{\text{sol}}$
  Set UpperBound to the amount of energy consumed if every vessel follows its shortest path, set $t = 1$, set $V_1 = 0$;
  Function RecursiveFunction $(t, W_t, V_t)$
  for k=1:K do
    for all vertices $v_i$ adjacent to $R_t^k$ do
      if $v_i \neq R_{t-1}^k \& t + \text{timedist}(v_i, d^k) < T_d^k \& detourisfeasible$ then
        Add $v_i$ to $\mathcal{X}_{t,k}$;
      end if
    end for
    if $\mathcal{X}_{t,k} isempty$ then
      break
    end if
  end for
  Create the set $\mathcal{X}_t$ of all possible combinations of $\mathcal{X}_{t,k=1,\dots,K}$;
  for $all x \in \mathcal{X}_t$ do
    Calculate $c(x)$ the energy cost of executing decision $x$, calculate $W_{t+1}(x)$ the vessel positions after executing decision $x$;
    if $V_t + c(x) >$ UpperBound then
      continue
    else if $W_{t+1}^k = d^k \forall k$ then
      $W_{\text{sol}} \leftarrow W, UpperBound \leftarrow V_t + c(x)$
    else $V_{t+1} \leftarrow V_t + c(x)$ call RecursiveFunction $(t+1, W_{t+1}, V_{t+1})$
    end if
  end for
```

According to the above definition, the leader vessel is first selected through the leader vessel selection algorithm. As a result, part of the edges in the coordination map is simplified. Then, the merged collection of vessels is planned through the clustering algorithm. In the algorithm, j represents the collection of vessels directly connected to i in the coordination diagram, k_{ij} is the energy-saving rate of vessels i and j combined sailing, where i is the leader vessel, j is the following vessel,$k_{(j+1)(j+2)} > k_{j(j+1)}$ indicates the existence of a energy-saving rate of vessel combination $j+1$, $j+2$ is more significant than all vessels j, $j+1$ combination. After the

Algorithm 2 Team Leader Vessel Selection Clustering Algorithm

```
Input: finitely transport assignments $T^t$
Output: Leading vessel set $N_I$
  while $i \le N_c$ do
      if $k_{ij} > k_{ji} \& k_{ij} > k_{j(j+1)} \& k_{ij} > k_{(j+1)j}$ then
          $N_I \leftarrow N_I \cup \{i\}$;
      else if  then$k_{ij} < 0$ and
  $(k_{ij} > k_{j(j+1)} \parallel k_{ij} < k_{(j+1)j})$ and
  $(\exists k_{(j+1)(j+2)} > \forall k_{j(j+1)})$
          $N_I \leftarrow N_I \cup \{i\}$
      end if
       $i \leftarrow i + 1$
  end while
```

leader vessel collection screening is completed, it is necessary to determine the following vessels in each collection. As the determination of the leader vessel simplifies the relationship between the edges of some vessels in the coordination map, the selection of candidate vessels is similar to the cluster analysis problem in mathematics. The number of cluster centres is known, so the k centre point algorithm is used to obtain the following vessels that the vessel i should belong to.

$$k_J = 1 - \frac{J_{\text{platoon}}}{J_{\text{normal}}} \tag{14}$$

$$P^{(i)} := \underset{n_l \in N_l}{\arg\min} k_{i,N_l} \tag{15}$$

where $P^{(i)}$ indicates that vessel i is allocated to the team with the highest energy saving rate among the N_l platoons. By comparing the maximum energy saving rate between the candidate following vessel and the different team leader vessels k value, the following vessel with the most considerable k value is set to determine the merger scheme of the vessel initially.

2) Speed Optimization of the Vessel Platooning: This section considers the speed optimization of vessels in fleet collection P in Equ. 15 planned through Section IV-C.1. When vessels are combined into a fleet, simultaneously adjusting the speed of both vessels can save more energy consumption relative to a single ship sailing strategy. Moreover, the dispatching scheme above is determined based on the default transport scheme for the team leader vessel and the dispatching scheme for following the vessel. This paper makes further speed optimization on the premise that all vessels in the vessel collection can complete the merger, changing the speed and path of all vessels in the fleet collection. All vessels in the fleet collection can execute each fleet scheduling scheme. Among them, the public section collection of all vessels in the fleet collection is represented by $W = N_1, N_2, \ldots, N_n$, and n is the number of public waterway sections. Considering that each vessel collection contains leader n_l and multiple following vessels $N_{f_{\upsilon,i},N_l} = f_{\upsilon,1}, f_{\upsilon,2}, \ldots$, you need to plan the speed series $V_i = \upsilon_i^s, \upsilon_i^m, \upsilon_i^p, \upsilon_i^{sp}$ and time series $T_i^t = t_i^s, t_i^m, t_i^p, t_i^{sp}$. The vessel's speed optimization problem in vessel train is described as follows:

$$\begin{aligned} &\min_{e:e_i \in R} \sum_{i \in \upsilon} d_i f_{\upsilon,i}\left(\upsilon_i, \theta_p\right) \\ &\text{s.t.} \quad \sum_{N=N_i^{\text{now}}}^{N_i^m} M(s[n]) \le \upsilon_i^c \left(t_i^p - t_i^c\right) \\ &\qquad + x_i^{\text{now}} \le \sum_{n=n_i^{\text{now}}}^{n_i^{sp}} M(s[n]) \\ &\qquad + \upsilon_{\min} \le \forall \upsilon \le \upsilon_{\max} \end{aligned} \tag{16}$$

$$d_i = \begin{cases} \dfrac{\sum_{N=N_f^{\text{now}}}^{N^m} M(s[n]) - \sum_{N=N_l^{\text{now}}}^{N^m} M(s[n])}{\upsilon_f^c - \upsilon_l^c} \upsilon_i^c \\ \quad + \dfrac{x_l^{\text{now}} - x_f^{\text{now}}}{\upsilon_f^c - \upsilon_l^c} \upsilon_i^c, & t \in \left[t_i^m, t_i^p\right] \\ \dfrac{\displaystyle\sum_{N=N_l^{\text{now}}}^{N_l^{sp}} -x_l^{\text{now}} - \upsilon_l^c \left(t_l^p - t_l^c\right) \upsilon_l^p}{\sum_{i=N_i^{sp}}^{N_i^d} M(s[n])}, & t \in \left(t_i^p, t_i^{sp}\right) \\ \dfrac{\upsilon_i^{sp}}{\upsilon_i^{sp}}, & t \in \left[t_i^{sp}, t_i^d\right] \end{cases} \tag{17}$$

where the objective function (16) has the same meaning as formula (8), indicating the energy consumption of all vessels from departure to destination in each vessel collection. Two limitations respectively indicate limits on the merger position and speed. The merger of all vessels must occur at public sections, and the vessel speed always remains within the speed range allowed by waterway traffic. Where υ_i represents the speed sequence of the vessel i and d_i indicate the distance of each stage.

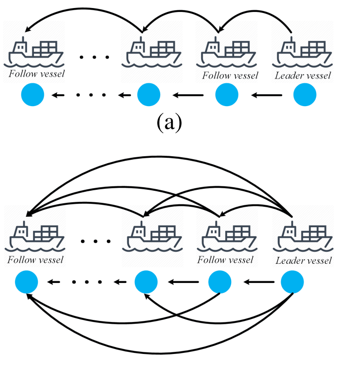
The above optimization problem can obtain the optimal sailing speed of each stage and each vessel with the help of a computer using a two-step hybrid optimal control approach [29] and bring the results to obtain the corresponding merger points, and separation points moments and positions.

When the velocity of the vessel is much lower than the transportation required velocity for the scheduling, it indicates that a congestion may have occurred in this channel segment. In this case, we introduce a variable m to further solve the congestion problem.

$$m = \frac{x_f(t) - x_i(t)}{x_f(t+1) - x_i(t+1)} \tag{18}$$

where m denotes the rate of change of the vessel's distance from the vessel in front. If the factor m decrease continuously to a certin value, the waterway is considered to be congested and the transportation plan of vessels needs to be re-planned.

Since congestion caused by unexpected conditions cannot be predicted in advance, it is necessary to predict the congestion time of vessels when re-planning, and to implement the planned transportation plan when vessels resume free sailing.



(a)

(b)

Fig. 5. Topology network.

The velocity of vessels during congestion depends on the congestion situation of the waterway and the velocity is difficult to determine.

Therefore, a linear function is used to approximate the relation between vessel congestion situation and vessel's velocity when $w_i \in [1, w_i(max)]$.

$$v\left(\omega_i\right) = -\frac{v_0}{c_{\max} - c_i}\left(c_i \omega_i - c_{\max}\right)$$
$$\omega_i = \frac{N_i^{\omega}}{c_i} \omega_i \in \left[1, \frac{c_{\max}}{c_i}\right] \tag{19}$$

where ω_i means the saturation of the waterway, N_i^{ω} is the number of vessels on waterway i, c_i is the congestion tolerance of the waterway. When $\omega_i >= 1$, it means that the waterway is congested, but the vessel can still sailing at a speed. When the number of N_i^{ω} reaches the maximum congestion tolerance $w_i(max) * c_i$ of the waterway section, the vessel speed is 0.

According to the position of the congested waterway section $P_c = (e_c, x_c)$, the current position of the vessel $P_i = (e_i(t), x_i(t))$ and the average number of vessels N_i^{ω} in the congested waterway section, the congestion time t_{ct} of the vessel is estimated, and it is taken as the merging stage t_i^m, t_i^p are added to the above optimization process to recalculate the transportation plans of the vessels.

D. Vessel Layer

1) Vessel Modeling and Control Objective: As seen in Fig. 5, this section considers a heterogeneous vessels platoon with a diverse set of communication topologies operating on waterway with N vessels (or nodes), one leading vessel and the others following vessels. The communication between nodes is expected to be unidirectional from front vessels to behind vessels. Fig. 5a means predecessor-following topology and Fig. 5b means two-predecessor-leader following topology.

Although the platoon is dynamically decoupled, it is restricted spatially by the formation. Each node has a nonlinear dynamical system with input restrictions, the DMPC's control purpose is to accomplish global coordination in terms of movement and geometry of the platooning.

To simplify the problem based the vessel model in section III-D, this paper considers the vessel longitudinal dynamics, the vessel control and cooperation algorithms can be simplified based on a dynamic model of the powertrain [30].

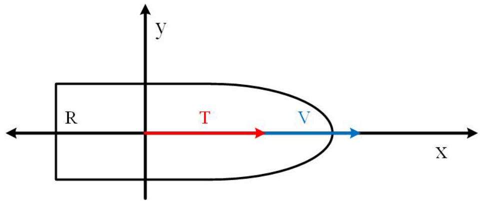


Fig. 6. Model for manoeuvres on straight.

Specifically, the longitudinal dynamics of a vessel indexed i is modelled as:

$$\begin{cases} \dot{s}_i = v_i \\ (m + m_x) \cdot \ \frac{dv}{dt} = u_i(1 - t) + R \end{cases} \tag{20}$$

where m is ship mass, m_x is added mass, R is the resistance for constant speed, u_i is the thrust of the propulsion system, t is thrust deduction coefficient due to the suction t of the propellers at the ships stern, s_i and v_i denote its longitudinal position and velocity.

$$u_i \in \mathcal{U}_i = \left\{u_{\min,i} \leq u_i \leq u_{\max,i}\right\} \tag{21}$$

where $u_i \in \mathbb{R}$ R represents the intended sailing/braking torque. The box $[u_{\min,i}, u_{\max,i}]$ restriction applies to the control input.

The platoon control aims to follow the leader vessel's pace while maintaining a desirable separation between any subsequent vessels, as indicated by the desired spacing policy:

$$\begin{cases} \lim_{t \to \infty} \left\|v_i(t) - v_0(t)\right\| = 0 \\ \lim_{t \to \infty} \left\|s_{i-1}(t) - s_i(t) - d_{i-1,i}\right\| = 0 \end{cases}, \ i \in \mathcal{N} \tag{22}$$

where $d_{i-1,i}$ is the required interval distance between two vessels, the choice of d controls the platoon's geometrical formation. The constant spacing strategy is followed here, which means

$$d_{i-1,i} = d_0 \tag{23}$$

2) Vessel Control for Platooning: We describe a distributed MPC synthesis approach for a heterogeneous platoon in which each vessel is allocated a local optimum control issue solely depending on the knowledge of its nearby vessels.

Based on the velocity optimization results v_{ref}^i, the platoon controller's goal is to achieve minimal inter-vessel distances while monitoring a variable reference velocity. Therefore, a velocity following error v_e^i may be specified for each vessel, signifying the divergence from the intended reference velocity profile.

$s_0(t)$ and $v_0(t)$ represent the location and velocity of the leader, respectively. Node i's ideal state and input settings are as follows:

$$\begin{cases} x_{\mathrm{des},i}(t) = \left[s_{\mathrm{des},i}(t), v_{\mathrm{des},i}(t), T_{\mathrm{des},i}(t)\right]^T \\ u_{\mathrm{des},i}(t) = T_{\mathrm{des},i}(t) \end{cases} \tag{24}$$

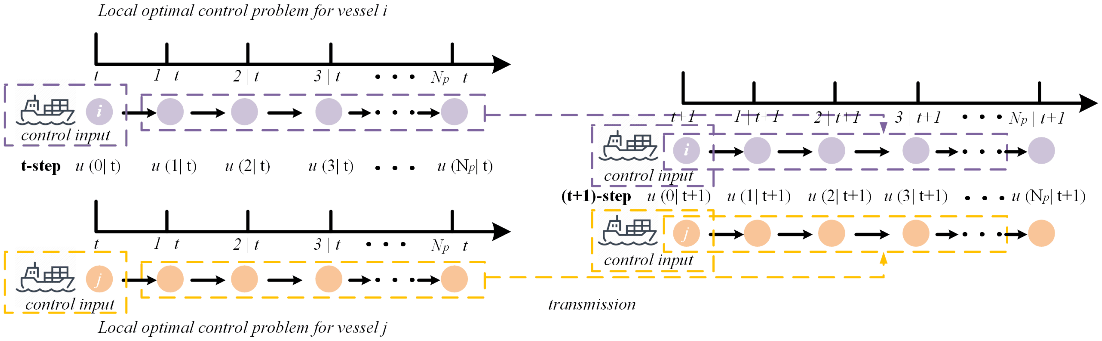


Fig. 7. The schematic technique for constructing.

Then, for each vessel i, we formulate the local optimum control problem J for $i \in \{1, 2, \ldots, N\}$ at time t:

$$\begin{aligned} \min_{u_i^p(0|t),\ldots,u_i^p(N_p-1|t)} & J_i\left(y_i^p, u_i^p, y_i^a, y_{-i}^a\right) \\ &= \left\| y_i^p(k \mid t) - y_{\mathrm{des},i}(k \mid t) \right\|_{Q_i} \\ &\quad + \left\| u_i^p(k \mid t) - h_i\left(v_i^p(k \mid t)\right) \right\|_{R_i} \\ &\quad + \left\| y_i^p(k \mid t) - y_i^a(k \mid t) \right\|_{F_i} \\ &\quad + \sum_{j \in \mathbb{N}_i} \left\| y_i^p(k \mid t) - y_j^a(k \mid t) - \tilde{d}_{i,j} \right\|_{G_i} \end{aligned} \tag{25}$$

subject to

$$\begin{aligned} y_i^p(k \mid t) &= \gamma \cdot x_i^p(k \mid t) \\ x_i^p(0 \mid t) &= x_i(t) \\ u_i^p(k \mid t) &\in \mathcal{U}_i \\ y_i^p\left(N_p \mid t\right) &= \frac{1}{|\mathbb{I}_i|} \sum_{j \in \mathbb{I}_i} \left(y_j^a\left(N_p \mid t\right) + \tilde{d}_{i,j} \right) \\ T_i^p\left(N_p \mid t\right) &= h_i\left(v_i^p\left(N_p \mid t\right)\right) \end{aligned} \tag{26}$$

where $Q_i \in \mathbb{S}^2$, $R_i \in \mathbb{R}^2$, $F_i \in \mathbb{S}^2$ and $G_i \in \mathbb{S}^2$are the weighting matrices. Subject to equation.20 and dynamic constraint in section.III-D.

All followers are expected to be synchronized in this DMPC framework throughout the phase of control execution, i.e., updating the system state concurrently inside a shared global clock. The schematic technique for constructing assumed inputs is shown in Figure. 7.

Then, it is next to create a distributed controller on the basis of the optimal object 25 and vessel dynamics 6 based on mpc-based method [22], [31], hereby satisfying two objectives, the DMPC methods is shown as follow Algorithm. 3.

Algorithm 3 Control Algorithm

```
Input: current state $x_i(t)$, assumed output $y_i^a(k \mid t)$, assumed
  outputs from its neighbors $y_i^a(k \mid t)$
Output: optimal control sequence $u_i(k \mid t), k = 0, 1, \ldots, N_p - 1$
  Initialize $u_i^a(k \mid 0) = h_i(v_i(0)), \quad y_i^a(k \mid 0) = y_i^p(k \mid 0), \quad k = 0, 1, \ldots, N_p - 1$
  (1) Optimize problem according to its current state $x_i(t)$, assumed output $y_i^a(k \mid t)$, assumed outputs from its neighbors $y_i^a(k \mid t)$, yielding optimal control sequence $u_i(k \mid t), k = 0, 1, \ldots, N_p - 1$;
  (1) Using optimum control, calculate the optimal state in the prediction horizon: $u_i(k \mid t)$, $x_i^*(k+1 \mid t) = \phi_i(x_i^*(k \mid t)) + \psi_i \cdot u_i^*(k \mid t), k = 0, 1, \ldots, N_p - 1, x_i^*(0 \mid t) = x_i(t)$;
  (2) By discarding the first term and adding one more term, compute the presumed control input for the following phase:
  $u_i^a(k \mid t+1) = \begin{cases} u_i^*(k+1 \mid t), k = 0, 1, \ldots, N_p - 2 \\ h_i(v_i^*(N_p \mid t)), k = N_p - 1 \end{cases}$;
  (3) Assumed output is calculated using this formula: $x_i^a(k+1 \mid t+1) = \phi_i\left(x_i^a(k \mid t+1)\right) + \psi_i u_i^a(k \mid t+1), x_i^a(0 \mid t+1) = x_i^*(1 \mid t), y_i^a(k \mid t+1) = \gamma x_i^a(k \mid t+1), k = 0, 1, \ldots, N_p - 1$;
  (4) Transmit $y_i^a(k \mid t+1)$ to the nodes in set $\mathbb{O}_i$, receive $y_{-i}^a(k \mid t+1)$ from the nodes in set Ni, and then compute $y_{des,i}(k \mid t+1)$ using the leader vessel's information;
  (5) Utilize the first element of optimum control sequence to implement the control effort, $u_i(t) = u_i^*(0 \mid t)$;
  (6) Increment t and go to step (1).
```

In the platooning sailing scenario, there is a merging and splitting maneuver between vessel and platooning, so it is necessary to consider the control under the communication topology changes under merging and splitting maneuver.

Considering different topology conditions and vessel behaviors, we add three sets of simulations for three scenarios. Three kinds of topological transformations are considered respectively: one vessel leaves the platoon, one vessel merges the platoon and one vessel leaves and another vessel joins the platoon.

In order to build a coupled cost function in the DMPC, a precise topological structure model is essential. In a platoon, the communication topology may be characterized as a directed graph. Three matrices, namely the adjacency matrix $\mathcal{A}^{TN}$, the Laplacian matrix $\mathcal{L}^{TN}$, and the pinning matrix $\mathcal{P}^{TN}$, are formed from the characteristics of graph $\mathcal{G}^{TN}$.

Let $\mathcal{A}^{TN} = a_{ij}$ represent the adjacency matrix, where $a_{ij} = 1(or0)$ indicates whether or not the vessel i may transfer data to the vessel j.

Each following vessels' relationship to the leader vessel is modeled using the pinning matrix $\mathcal{P}^{TN} \in \mathbb{R}^{N \times N}$, which is described as

$$\mathcal{P}^{TN} = \operatorname{diag}\{p_1, p_2, \ldots, p_N\} \tag{27}$$

The vessel i is (is not) pinned to the leader vessel in platoon and receives (does not get) information

TABLE I

SIMULATION SETUP FOR EXP

Options	β_0	β_1	β_2	β_3	β_4	f_{1p}	f_{0p}	f_1	f_0
Value	179.0568	882.0727	-550.886	-1602.37	1954.498	$4.573*10^{-6}$	$9.4371*10^{-5}$	$8.9431*10^{-6}$	$4.8021*10^{-5}$

from it if $p_i = 1 (= 0)$.

$$\mathbb{P}_i^{TN} = \begin{cases} \{0\}, & \text{if } p_i = 1 \\ \emptyset, & \text{if } p_i = 0 \end{cases} \tag{28}$$

The sets of following vessels that the vessels i may receive information from and transmit information to are denoted as $\mathbb{N}_i := \{ j \mid a_{ij} = 1, j \in \mathcal{N} \}$ and $\mathbb{O}_i := \{ j \mid a_{ji} = 1, j \in \mathcal{N} \}$, respectively. The set $\mathbb{I}_i := \mathbb{N}_i \cup \mathbb{P}_i$ is made up of all the vessels that are sending data to the following vessel i. The definition of the Laplacian matrix $\mathcal{L}^{TN}$ is $\mathcal{L}^{TN} = \mathcal{D}^{TN} - \mathcal{A}^{TN}$, where $\mathcal{D}^{TN}$ is called the in-degree matrix, defined as $\mathcal{D}^{TN} = \operatorname{diag}\{\deg_1, \deg_2, \ldots, \deg_N\}$. And $\deg_i = \sum_{j=1}^{N} a_{ij}$ represents the in-degree of node i in $\mathcal{G}^{TN}$.

Here, we propose the extending the DNMPC to include actions of dynamic merging and splitting from platoon. Assume that the total number of initial following vessels in the platoon is N_υ, and there are N_υ^j joining and N_υ^l leaving movements. We use $t_i^{\upsilon,j}$, and $t_j^{\upsilon,l}$ to indicate the times of the vessel i joining and vessel j leaving procedures, respectively. The time of convergence of a dynamic platoon, including potential joining and following operations, is determined by the following theorem.

When having merging and splitting maneuvers, problem 25 guarantees convergence of the output to the desired output in at most $t_{\text{conv}} = \max_{i,j} \left[t_{ci,i}, t_{co,j} \mid \forall i \in \mathcal{N}_{ci}, \forall j \in \mathcal{N}_{cj} \right] + N + N_{ci} - N_{co}$ time steps. We modify the constraint to be $\boldsymbol{y}_i^p \left(N_p \mid t \right) = \boldsymbol{y}_{\text{des},i} \left(N_p \mid t \right), \forall t \geq t_{\text{conv}}$. For the static platoon, is a special case which is for a dynamic platoon.

V. SIMULATION EXPERIMENTS

This section studies the vessel platooning method proposed in this paper. Then, a simulation of cooperative optimization in transportation is presented to illustrate how it helps to save the energy consumption of waterborne transport. The effectiveness of the proposed switching merger strategy and the shortest path scheduling strategy is verified.

A. Simulation Setup

The platoon coordination and optimization control algorithms provided in this article are shown using a simulation scenario simulating a part of the Netherlands and Belgium's waterways network. For our purposes, we assume a set number of vessels on a fixed network, and the speed of the vessel isn't affected by the flow of other traffic. The area of simulation is shown in Fig. 8a. We utilize a simplified graph of the European waterway network with 582 nodes and 621 edges to test the performance of our approach on a large scale as shown in Fig. 8b. Hundreds of vessels originate from random sites and sail to five destinations through this network. Each vessel's origin-destination pair is picked at random within these places. There are four sets of experiments in the following sections. The first set of experiment in Section V-B aimed to evaluate coordinated platoon planning in this scenario for two vessels. Table II contains the parameter values for each vessel in Section V-B. The second set of experiment in Section V-C aimed to test the coordinated platoon planning methodology described in Section IV from five vessels' coordinated platoon planning evaluation. The third and last sets of experiment in Section V-E.1 and V-E.2 aimed to analyze the impacts of vessel numbers and energy consumption factors parameters by control variates. The parameter settings of the relevant experiments are shown in the following tables.

TABLE II

SIMULATION SETUP FOR EXP. IN V-B

Options in Sect. V-B	case 1	case 2
Vessel numbers	2	2
Platoon fuel-savings rate	7%	7%
Starting position of ship1 and ship2	(10,69)	(15,63)
Destination position of ship1	(45,59)	(45,69)
Destination position of ship2	(65,37)	(65,37)

TABLE III

SIMULATION SETUP FOR EXP. IN V-C

Options in Sect. V-C	ship 1	ship 2	ship 3	ship 4	ship 5
Platoon fuel-savings rate	7.55%	7.55%	7.55%	7.55%	7.55%
Destination position	(26,45)	(27,47)	(29,46)	(20,55)	(13,53)
Destination position	(63,7)	(59,15)	(52,24)	(51,37)	(61,38)

TABLE IV

SIMULATION SETUP FOR EXP. IN V-E.1

Options in Sect. V-E1	case 1	case 2	case 3	case 4	case 5
Vessel numbers	100	200	300	400	500
Platoon fuel-savings rate	7%	7%	7%	7%	7%
Repeated times	100	100	100	100	100
Starting position of ships	random	random	random	random	random
Destination position of ships	random	random	random	random	random

Our platooning approach is shown by the following findings.

B. Shortest Paths Versus Energy-Optimal Routes

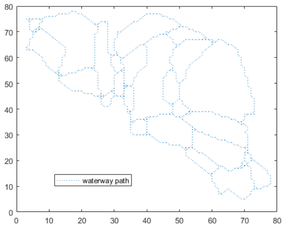
Now, we will demonstrate a single instance of a controller that enables vessel platooning. Consider the map of the European waterway map in Fig. 8a from [32], in which two vessels have a distinct destination (denoted by the stars). We postulate that if the vessels were autonomous, they would follow their own shortest pathways, as seen in Fig. 9a. However, if one vessel slightly alters its pace to coincide with the other, they may form a platoon. First, the controller must determine whether the extra fuel necessary to establish the platoon will be offset by the cost savings associated with platooning. Assuming the controller has access to the $D(i, j)$ matrix of all-pairs shortest paths, it may rapidly calculate the most fuel-efficient route for the vessels by comparing at $J_{platoon}^*$ and J_{normal} in Section. IV-B.2. Please take note that in this case, we evaluate only alternative pathways with a length equal to the shortest path for each vessel. Neither vessel must extend its trip time in response to the controller's instructions.

TABLE V

SIMULATION SETUP FOR EXP. IN V-E.2

Options in Sect. V-E1	case 1	case 2	case 3	case 4
Vessel numbers	200	300	400	500
Platoon fuel-savings rate	7% to 10% (each step add 0.05%)	7% to 10% (each step add 0.05%)	7% to 10% (each step add 0.05%)	7% to 10% (each step add 0.05%)
Repeated times	100^2	100^2	100^2	100^2
Starting position of ships	random	random	random	random
Destination position of ships	random	random	random	random

(a) Simulation Area Part of the European Inland Waterway Network.



(b) Network Topology of the waterway Network System

Fig. 8. Simulation waterway map.

In Fig. 9b, we calculate the shortest path from the origin to the destination for each vessel separately. As seen in Fig. 9a, the fuel-efficient routes provided by Algorithm 1 may result in significant platooning savings. If the benefits of platooning outweigh the cost of formation, the controller may recommend the formation of a platoon.

The process of the ship traveling from the initial path to forming a formation will consume more energy. Therefore, the controller would propose the formation of a platoon if the energy savings from platooning outweigh the expense of the above energy consumption. In this experiment, we set the $\eta = 0.07$.

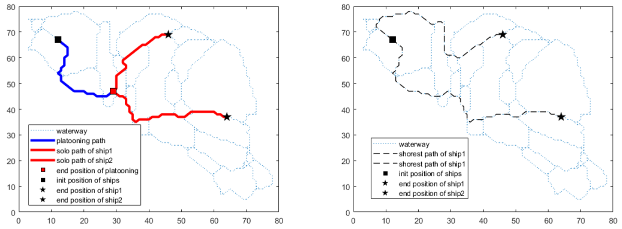
A single instance of a local controller aiding vessel platooning is now shown. Take a look at the major canal map of the Netherlands and Belgium in 9a, where two vessels are approaching a junction (depicted by the red square), each with a different destination (denoted by the black stars).

In the first experiment in Section V-B, the average of 100 observations of energy savings is 1.83%. In the second experiment in Section V-B, the average of 100 observations of energy savings is 1.75%.

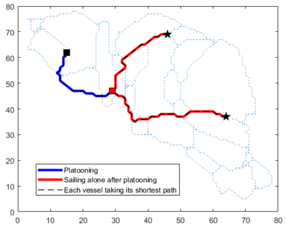
Consider a special case where the shortest path and the optimal path are the same, and the experimental planning results are shown in the Fig. 9c

C. Coordinated Platoon Planning Evaluation

The coordinated platoon planning methodology described in Section IV is utilized to choose appropriate coordination leader vessels and their respective follower vessels. In addition, pairwise plans are studied in this Section, in which coordination followers catch up with their leaders and platoon until one or both of their routes ends or splits.



(a) energy consumption path (b) shortest path

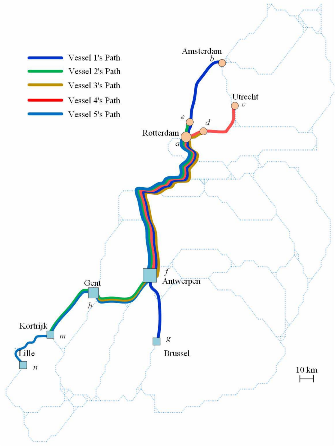


(c) Same paths

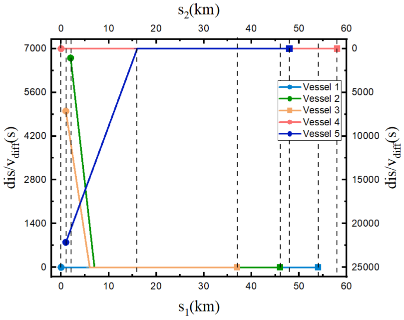
Fig. 9. Simulation results for two vessels.

Platoon plans include two coordination leaders (vessels 1 and 4) and three coordination followers (vessels 2, 3 and 5) who will eventually catch up to the coordination leader and form two vessel platoons. The graph show the time difference between the platoon commander and the location on the waterway, as determined by the individual vessels' paths. The dashed lines in Fig. 10a depict the locations of the nodes representing waterway junctions. For example, consider how the coordination leader departs from Rotterdam and travels to Lille. When the time gap between vessels is zero, and their paths overlap, the vessels form a platoon.

Fig. 10 presentation and analysis of the routes taken by five vessels for (but not 'and') two platooning coordinations (vessel 1-vessel2/vessel3 & vessel4-vessel5). The related trajectories are given in Fig. 10, together with the time gaps for the coordination leader as a function of the route location. Note that the first coordination follower (vessel 3, orange) in the first platooning shares the first portion of its journey with the coordination leader (vessel 1, light blue), but since it begins 1.39 h later, it catches up at maximum speed, as demonstrated by the leader's decreasing distance in Fig. 10b. It then joins the platoon until it reaches its goal. In the first vessel platooning, the second coordination follower's (vessel 2, green) path connects with the coordination leader's, and the coordination follower's start time is such that it catches up to the coordination leader



(a) The routes for a coordination platooning



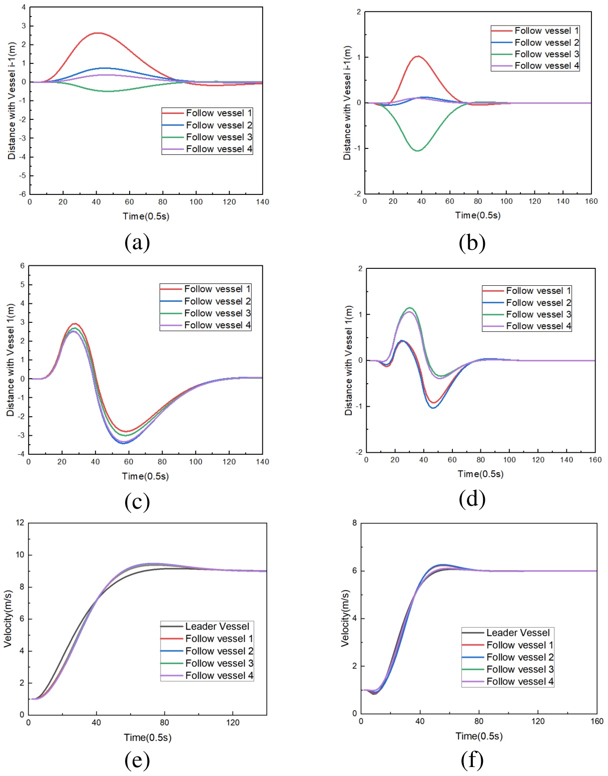
(b) Platoon plans for a coordination platooning

Fig. 10. Platoon plans for a coordination platooning.

at a velocity less than the coordination leader's maximum speed. The coordination follower and coordination leader form a platoon and continue to do so until their pathways divide. For the second vessel platooning, coordination leader(Vessel 4, red) and coordination follower (vessel 5, deep blue) plan to obtain a sailing path with optimal energy consumption. Therefore, the two vessels form a formation at the Rotterdam node about 6.2 hours after departure until Vessel 5 reaches the endpoint.

In order to respond to the fuel-optimality criterion platooning, vessels need to maintain a specific distance and speed in the platooning. This section sets up two sets of simulation, each of five vessels, one leader vessel and four follower vessels. The first simulation set the vessels' expected speed of 9m/s, vessels' spacing of 40m. In the second set of simulations, the desired vessels' speed was 6m/s, and the vessels' spacing was 20m. The platoon's starting state is set to the intended state, which means that the initial spacing and velocity errors are both equal to zero.

The control effect of the controller under two-predecessor-leader following topologies proposed in Section IV-D.2 of this paper is shown in the follow figure. The results for first simulation are shown as Fig. 11a, 11c and 11e in Fig. 11. Fig. 11a shows the vessel's distance error with vessel i-1, Fig. 11c shows the vessel's distance error with leader vessel, Fig. 11e shows the speed control results for five vessels in the platoon.



(a) (b)

(c) (d)

(e) (f)

Fig. 11. Platoon control results for coordination platooning.

It can be seen from the experimental results that the four following ships and the leading ship formed a stable formation at 120 seconds, maintaining a stable ship spacing of 40 meters and a speed of 9 meters per second.

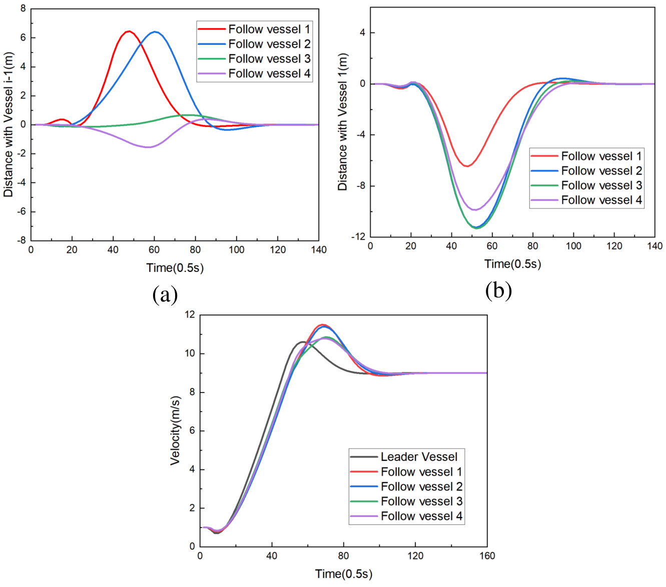
The results for second simulation are shown as Fig. 11b, 11d and 11f in Fig. 11. Fig. 11b shows the vessel's distance error with vessel i-1, Fig. 11d shows the vessel's distance error with leader vessel, Fig. 11f shows the speed control results for five vessels in the platoon.

It can be seen from the experimental results that the four following ships and the leading ship formed a stable formation at 100 seconds, maintaining a stable 20-meter ship spacing and 6 meters per second speed. In details, the target spacing is set at 20 m in the simulations. The platoon's starting state is set to the intended state, which means that the initial spacing and velocity errors are both equal to zero. The result illustrates the platoon's spacing errors under the designed topology. Therefore, it is straightforward to determine if the platoon using the DMPC is stable. For this simulation scenario, the platoons with communication topology had spacing errors of less than $1m$. Additionally, this study demonstrates that no collision occurs throughout the control procedure.

To illustrate, the proposed platoon control laws are compared with the proportional-integral (PI) control laws. The PI control laws are given as follows:

$$u(t) = k_p e(t) + k_i \int_0^t e(t)dt + k_d \frac{d}{dt} e(t) \tag{29}$$

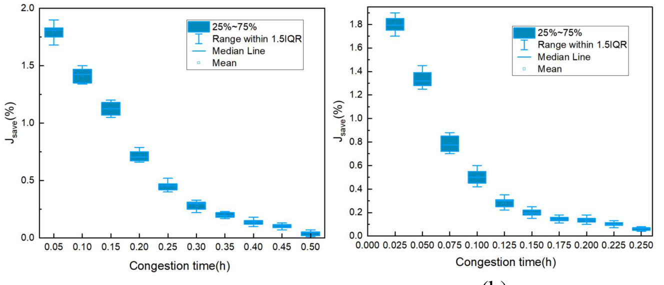
where k_p,k_i and k_d represents the proportional, integral and derivative gain of the system respectively. For this control problem, the difference between positions of the leader and the follower has been taken as an error signal for the controller.



(a) (b)

(c)

Fig. 12. PID platoon control results for coordination platooning.



(a) (b)

Fig. 13. Congestion impact on vessel merging.

This is a very pragmatic approach for longitudinal control of vehicle platooning.

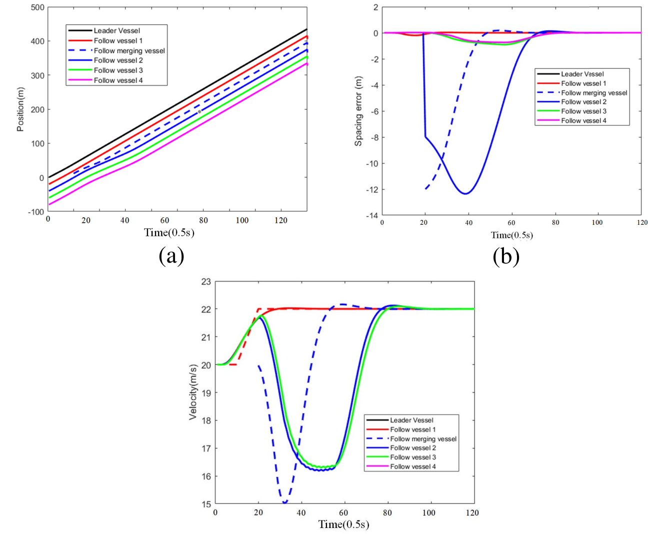
The distance error with vessel i and $i-1$ using the proposed DMPC and the PI control laws are provided in Fig. 12a and 12b. Fig. 12c shows the velocity of vessels in platoon using PID-based methods.

It can be seen from the experimental results that the four following ships and the leading ship formed a stable formation, maintaining a stable ship spacing of 40 meters and a speed of 9 meters per second. It shows that the control accuracy of the proposed DMPC-based method is higher than the another method in the experiment. We can intuitively observe that the convergence and overshoot of the pid control algorithm are significantly larger than our proposed DMPC-based algorithm.

We simulate congestion in different locations by setting different delay times. When traffic congestion occurs in different locations, the maximum fuel saving rate of the two vehicles is shown in Fig. 13. It can be seen that short-term congestion will influence vessels' scheduleing.

D. Coordinated Platoon Control With Merging and Splitting Behaviors

We developed a heterogeneous platoon with some following vessels to test the validity of the proposed method. When having merging and splitting maneuvers, Problem 25 guarantees convergence of the output to the desired output in at most $t_{\text{conv}} = \max_{i,j}\left[t_{ci,i}, t_{co,j} \mid \forall i \in \mathcal{N}_{ci}, \forall j \in \mathcal{N}_{cj}\right] + N + N_{ci} - N_{co}$ time steps. We modify the constraint to be $\boldsymbol{y}_i^p\left(N_p \mid t\right) = \boldsymbol{y}_{\text{des},i}\left(N_p \mid t\right), \forall t \geq t_{\text{conv}}$. For the static platoon, is a special case which is for a dynamic platoon.



(a) (b)

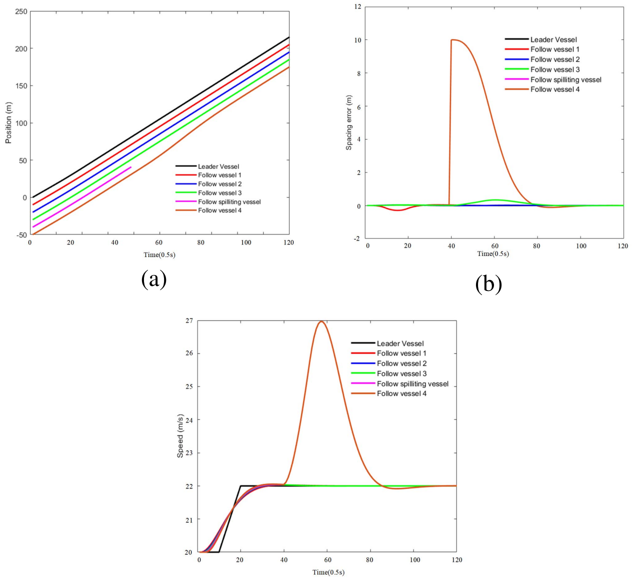
(c)

Fig. 14. Platoon control results considering merging maneuvers for coordination platooning.

In order to handle possible merging and splitting manoeuvres and ensure safety by tracking the desired velocity and keeping the safe desired distance between the vessels, we presented a DNMPC-based solution based on the objective function Equ. 25. To validate the proposed method, we made a vessel platoon, including five or six vessels at the initial time. Following the dataset in Exp. V-C, we set the initial position and velocity of the leader as $s_0(0) = 0$, $v_0(0) = 10\ m/s$. The velocity of leader vessel is considered as black line in Fig. 14c. The sampling time is $0.5s$, the horizon length is $Np = 25$, and the desired gap is $d = 10m$.

For the first case of dynamic platooning, we introduced a merging behavior between the first and second follow vessels at time $t = 10$. The results of the simulations are shown in Fig. 14 where velocity, relative spacing error with the preceding vessel, and position are illustrated for the platoon. By reducing its speed, the follow merging vessel has increased its gap with the follow vessel 1 to make the desired distance of $10m$ from the follow merging vessel. Consequently, the following vessels have lessened their velocity to keep the desired distance. The plots of velocity verify this fact. Moreover, the relative spacing error shows the jump in the distance error because of the merging maneuver.

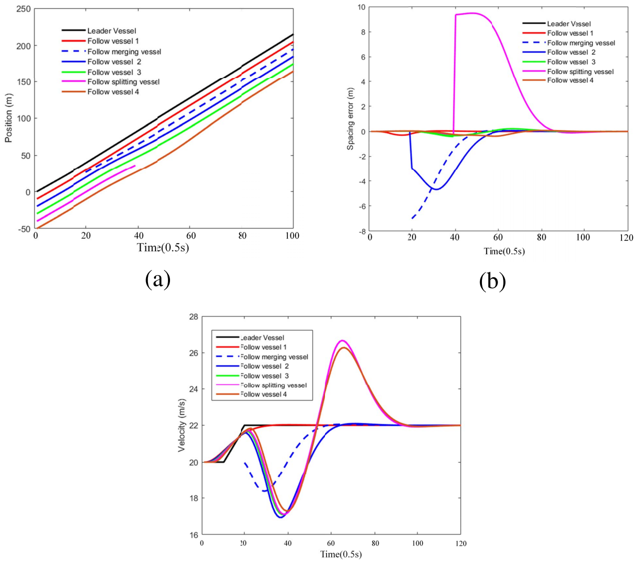
For the second case of dynamic platooning, we introduced a splitting behavior between the follow vessel 3 and follow vessel 4 at time $t = 50$. The results of the simulations are shown in Fig. 15 where velocity, relative spacing error with the preceding vessel, and position are illustrated for the platoon. By rising its speed, the follow vessel 4 has increased its gap after the follow splitting vessel leaving to make the desired distance of $10m$ from the follow vessel 3. Consequently, the



(a) (b)

(c)

Fig. 15. Platoon control results considering splitting maneuvers for coordination platooning.



(a) (b)

(c)

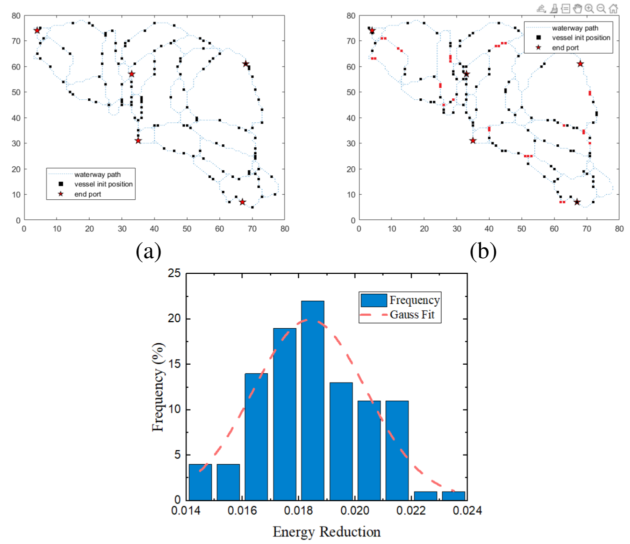
Fig. 16. Platoon control results considering merging and splitting maneuvers for coordination platooning.

following vessel has rising their velocity to keep the desired distance. The plots of velocity verify this fact.

For the third case of dynamic platooning, we introduced merging and splitting behaviors between the follow vessels at time $t_{merge} = 20$ and $t_{split} = 40s$. The results of the simulations are shown in Fig. 16 where velocity, relative spacing error with the preceding vessel, and position are illustrated for the platoon. Moreover, the relative spacing error shows the jump in the distance error because of merging and splitting behaviors.

E. Influencing Factors in the Optimization Algorithm

In general, changes in the number of vessels and energy consumption factors can have a significant impact on the optimization results, thus this section uses control variates to analyze their implications on the energy saving effect.



(a) (b)

(c)

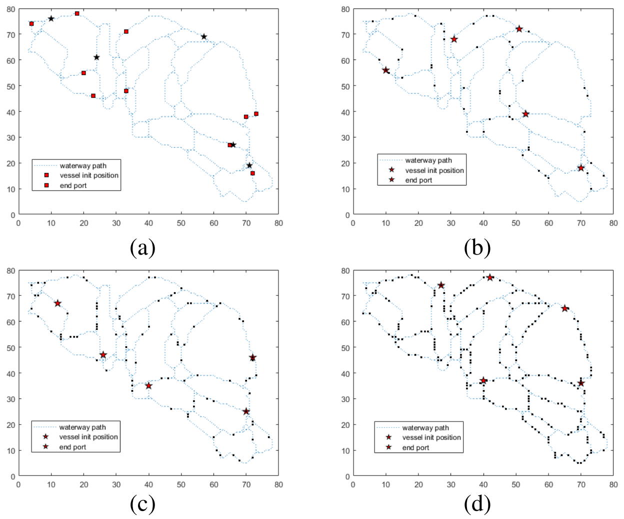
Fig. 17. Large-scale simulation results. (a) A state of our system in its initial condition, with squares indicating vessels, (b) State of the same system as in Fig. 17a after 20 time steps, (c) Results of Energy consumption for 200 vessels, repeated 100 times with random starting positions and destination.

In Section V-E.1 and Section V-E.2, a transportation scenario of multi vessels is simulated to analyze the impacts of vessel numbers and energy consumption factors parameters.

1) Impacts of Vessel Numbers: We study at how overall energy consumption varies as the number of vessels in the network grows. Intuitively, if the density of vessels in the network is low, platooning chances are limited; few vessels will choose a route different than their shortest path. Conversely, as the network's vessel density rises, more boats will take use of platooning possibilities, resulting in more significant savings. The energy consumption value of transportation system is J_{save} for all vessels in the system.

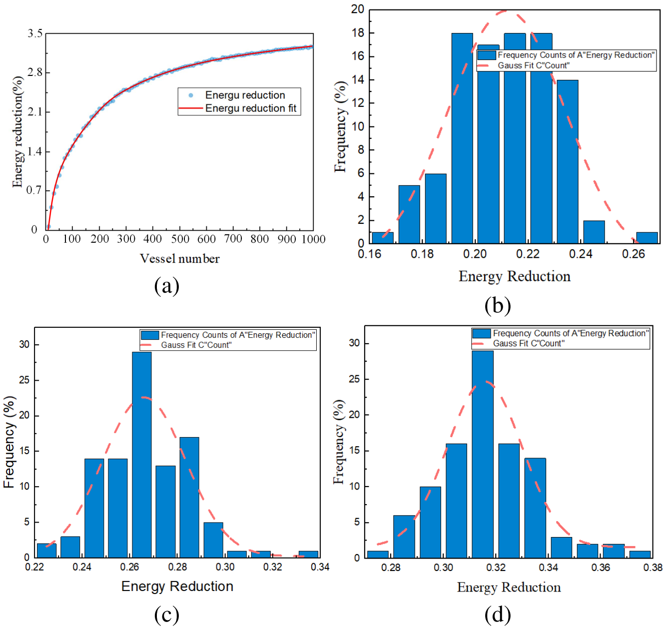
Fig. 17a illustrates one possible beginning state for 200 vessels, with vessels represented by squares. After initiating the simulation with the initial state shown in Fig. 17a, we halt the simulation after fifteen steps to view the network depicted in Fig. 17b, the platooning vessels are shown in red squares, while the alone vessels are highlighted in black. At this time, around 25% of vessels have formed platoons. The simulation is repeated 100 times for 200 boats with random beginning and destination coordinates. As one would assume, certain random configurations facilitate platooning more than others. In Fig. 17c we observe a histogram representing the percentage of total fuel saved by our technique in each simulation when compared to the shortest course sailing by each vessel. The average overall fuel usage has fallen by about 1.9%.

When compared to each vessel following the shortest course and not platooning, our strategy saves a significant amount of energy. Each data point represents the average of savings from five random instances different scenarios as shown in Fig. 19a. Average energy savings regularly increase when the vessels number from 0 and 1000 vessels.



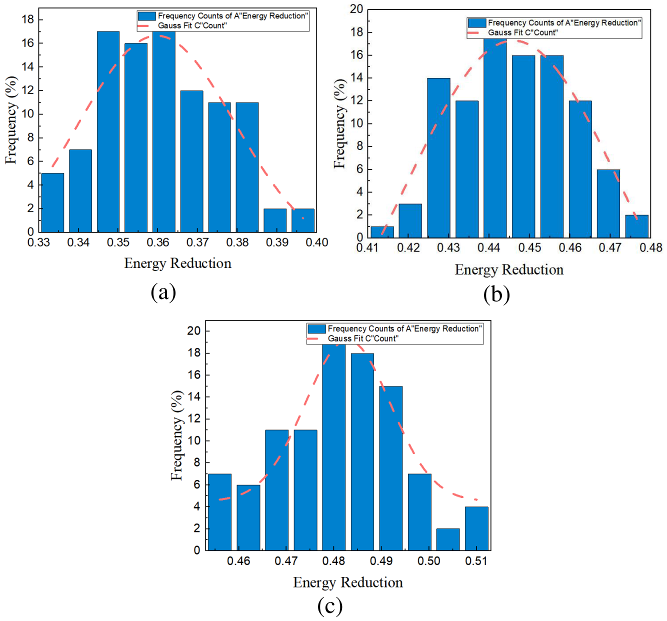
(a) (b) (c) (d)

Fig. 18. Simulation setuo for different vessel numbers (a) 10 vessels, (b) 50 vessels, (c) 100 vessels, (d) 300 vessels.



(a) (b) (c) (d)

Fig. 19. Large-scale simulation results.(a) Results of Energy consumption with different vessel numbers. (b) Results of Energy consumption for 300 vessels, repeated 100 times with random starting points and destination. (c) Results of Energy consumption for 400 vessels, repeated 100 times with random starting points and destination.(d) Results of Energy consumption for 500 vessels, repeated 100 times with random starting points and destination.



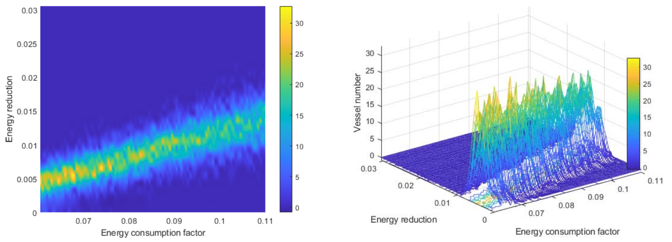
(a) (b) (c)

Fig. 20. Large-scale simulation results.(a) Results of Energy consumption for 600 vessels, repeated 100 times with random starting points and destination. (b) Results of Energy consumption for 800 vessels, repeated 100 times with random starting points and destination.(c) Results of Energy consumption for 900 vessels, repeated 100 times with random starting points and destination.

We performed the simulation a total of 100 times using a randomized set of 200, 300, and 400 vessels with random starting positions and destinations. In each simulation, we observe a histogram showing the proportion of total energy saved by our strategy (compared with every vessel taking its shortest path) in Fig. 19b, 19c and 19d. We can observe that increasing the number of vessels has affected the average overall energy use. For 400 vessels in the transportation system, the evidence shows that energy consumption in the range of 1.9% to 2.8%, and the energy consumption value for average of transportation system is almost 2.4%. For 300 vessels in the transportation system, the evidence shows that energy consumption in the range of 1.4% to 2.3%, and the energy consumption value for average of transportation system is almost 1.9%.For 200 vessels in the transportation system, the evidence shows that energy consumption in the range of 0.7% to 1.7%, and the energy consumption value for average of transportation system is almost 1.3%.

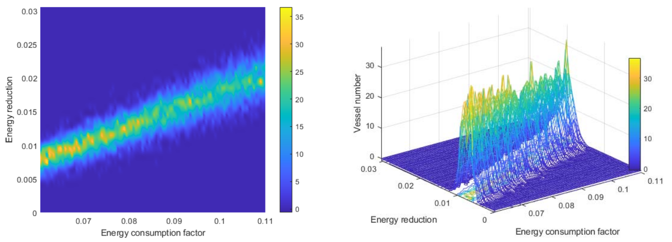
When the number of ships involved in transportation in the waterway network area increases, the opportunity for vessel merging also increases. The simulation results based on the collaboration and scheduling method is shown in the figure. The figure shows that the dispatching effect of the strategy proposed in this paper is significantly improved when there are few vessels and the energy consumption that can be saved increases rapidly with the number of ships. However, with the continuous increase of vessels, average energy savings is increasing, but the growth rate of the dispatching effect of this strategy gradually decreases.

In addition, we performed the simulation a total of 100 times using a randomized set of 600, 800, and 900 vessels with random starting positions and destinations. In each simulation, we observe a histogram showing the proportion of total energy saved by our strategy (compared with every vessel taking its shortest path) in Fig. 20a, 20b and 20c. We can observe that increasing the number of vessels has affected the average overall energy use. For 600 vessels in the transportation system, the evidence shows that energy consumption in the range of 3.3% to 4.0%, and the energy consumption value for average of transportation system is almost 0.36%. For 800 vessels in the transportation system, the evidence shows that energy consumption in the range of 4.1% to 4.8%, and the energy consumption value for average of transportation system is almost 4.5%.For 900 vessels in the transportation system, the evidence shows that energy consumption in the



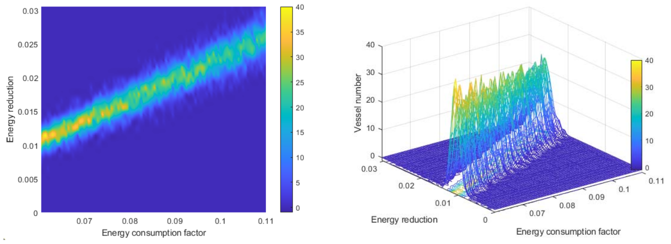
(a) (b)

Fig. 21. Large-scale simulation results of different energy consumption value with 200 vessel numbers.



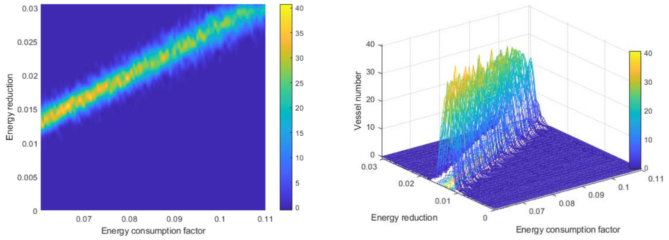
(a) (b)

Fig. 22. Large-scale simulation results of different energy consumption value with 300 vessel numbers.



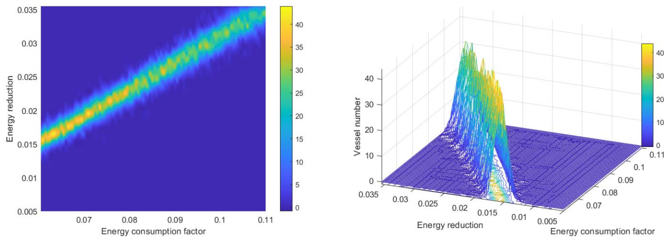
(a) (b)

Fig. 23. Large-scale simulation results of different energy consumption value with 400 vessel numbers.



(a) (b)

Fig. 24. Large-scale simulation results of different energy consumption value with 500 vessel numbers.



(a) (b)

Fig. 25. Large-scale simulation results of different energy consumption value with 600 vessel numbers.

range of 0.44% to 0.51%, and the energy consumption value for average of transportation system is almost 0.48%.

In Fig. 19a, average energy savings rapidly increase between 0 and 300 vessels. As the vessels in the network become more and more, average energy savings increase slowly than before. When the number of vessels is near 1000, adding more vessels will result in only marginal savings.

2) Impacts of Energy Saving Factor: Here, we analyze how the total energy use changes as the increase of energy consumption value in the network increases. "Energy saving factor" is a value in the network means energy-saving ratio of vessels sailing alone and in platoon. It means that the total energy consumption of the platoon system could decrease by value of "Energy saving factor" on average in tandem formation.

We performed the simulation a total of 100 times using a randomized set of 200, 300, 400 and 500 vessels with random starting positions and destinations. Then We repeat the simulation 100 times for number set of energy consumption values from 6% to 11%(each step add 0.02%) with random starting points and end points for 200, 300, 400, 500 vessels.

The relationship between the number of vessels, the value of the energy saved impacts value, and the system's overall energy-saving efficiency is addressed empirically in this section. As expected, the experimental results indicate that when the energy-saving function's value remains constant, the system's overall energy saving rate increases as the number of vessels increases. In addition, when the number of vessels remains constant, increasing the value of the energy-saving function increases the system's overall energy-saving rate.

As the energy saved impacts value and vessels number in the platoon increases, more savings will be exploited. We see that for 200 number of vessels, the average total fuel consumption has been decreased by almost 1%. For 300 number of vessels, the average total fuel consumption has been decreased by almost 1.4%. For 400 number of vessels, the average total fuel consumption has been decreased by almost 1.9%. For 500 number of vessels, the average total fuel consumption has been decreased by almost 2.5%.

We performed the simulation a total of 100 times using a randomized set of 600 vessels with random starting positions and destinations. Then We repeat the simulation 100 times for number set of energy consumption values from 6% to 11%(each step add 0.02%) with random starting points and end points for 600 vessels. For 600 number of vessels, the average total fuel consumption has been decreased by almost 3.0%.

Intuitively, if the network's vessel density is low, platooning chances are limited; few vessels will deviate from their shortest path. As the density of vessels in the network increases, more vessels will utilize platooning options, resulting in increased savings. Similarly, the trend of system energy-saving caused by changes in energy saved impacts value is the same as that caused by changes in vessels number.

VI. Conclusion and Future Research

A. Conclusion

This project was undertaken to design a coordinated framework for vessels platooning in waterborne transportation system,reduce the transportation energy costs and improve the efficiency. The most obvious finding to emerge from this study

TABLE VI
NOMENCLATURE

Symbol	Description
I	Number of vessel
N	Number of waterway segment
T	Time step
P_i^a	Arrival location of vessel i
P_i^d	Departure location of vessel i
T_i^t	Transportation tasks of vessel i
T_i^d	Departure time of vessel i
T_i^a	Arrival time of vessel i
P_i^c	Current position of vessel i
$n_i(t)$	Number of current waterway segments where the vessel i is located at time step t
$x_i(t)$	Distance that the vessel i sails in current waterway segment N at time step t
$M(s_i)$	Mapping relationship value between the waterway network model and the actual waterway length
W	Graph of waterway network
S	Set of all nodes in W(the waterway intersections)
η	Energy saved value by a platoon of vessels compared to a single-vessel
t_i^s	Starting time of vessel i's departure sailing process
t_i^m	End Time of vessel i's departure sailing process and Starting time of vessel i's merging process
t_i^p	End Time of vessel i's merging process and Starting time of vessel i's vessel train process
t_i^{sp}	End Time of vessel i's vessel train process and Starting time of vessel i's separate sailing process
t_i^d	End Time of vessel i's separate sailing process and Starting time of vessel i's arrival sailing process
t_i^a	End Time of vessel i's arrival sailing process
P	Vessel transportation plan
N_v	Number of time series in P
N_e	Number of waterway edges in P
k	Time step
$p_i(k)$	Position of vessel i at time step k
$v_i(k)$	Velocity of vessel i at time step k
$a_i(k)$	Acceleration of vessel i at time step k
$x_i(k)$	System state of vessel i at time step k
$y_i(k)$	System output of vessel i at time step k
$u_i(k)$	System's input of vessel i at time step k
d_{safe}	Safety distance among vessels
$Fuel_{ship}$	Fuel consumption factor
F_i	Total fuel consumption of vessel i from the starting point to the end point
F_{total}	Total fuel consumption of all vessels after the merger
$v_i[m]$	Speed sequence of vessel i and the M value of each vessel
$\theta(p)$	A binary function of fuel consumption equation
$M(e[n])$	Length of waterway segment
N_i^A	Available paths that each vessel can choose
N_i^S	Shortest paths that each vessel can choose
N_i^B	Number of branches equals
$\mathcal{X}_{i,I}$	The set of vessel I's possible options at iteration $\mathcal{X}$
$N_{(i,j)}^{D_{(i,j)}}$	Total number of waterway segments from the departure place to the destination of the vessels i and j
$N_{(i,j)}^m$	Number of waterway segments from the departure place to the encounter waterway segment of the vessel
$s[t_m]$	Start of the public waterway section
$s[t_{sp}]$	End of the public waterway section
$J_{platoon}$	Energy consumption of the combined sailing of vessels via coordination
J_{normal}	Energy consumption the vessel sailing normal
f_{pn}	Costs added after changing the path or speed
v_p	Velocity of the platoon sailing
v_c	Optimal energy consumption catch-up speed
N_i^{now}	Number of sections of vessel i at the current moment
N_i^{sp}	Number of sections of vessel i at the separation moment
N_i^{dmin}	Number of sections of vessel i in the shortest path
N_i^{dc}	Number of sections of vessel i in the scheduling path
x_i^{now}	Distance the vessel i sails on the section N_i at the current moment
v_a	Velocity after platoon separation
G	Vessel coordination graph
k_J	Non-negative weight for each edge in G
k_{ij}	Energy-saving rate of vessels i and j combined sailing
$P^{(i)}$	Vessel i is allocated to the team with the highest energy saving rate among the N_l teams
v_i	Speed sequence of the vessel i
d_i	Distance of each stage
u	Thrust of the propulsion system
t	Thrust deduction coefficient due to the suction t of the propellers at the ships stern
s_i	Longitudinal position of vessel i
$d_{i,i+1}$	Required interval distance between two vessels
v_{ref}^i	Velocity optimization results of vessel i
$s_0(t)$	Location of the leader vessel
$v_0(t)$	Velocity of the leader vessel
m	Rate of change of the vessel's distance from the vessel in front
ω_i	Saturation function of the waterway
N_i^ω	Number of vessels on waterway i
c_i	Congestion tolerance of the waterway
J_i	Local optimum control problem for $i \in \{1, 2, \ldots, N\}$
$\mathcal{A}^{TN}$	Adjacency matrix
$\mathcal{L}^{TN}$	Laplacian matrix
$\mathcal{P}^{TN}$	Pinning matrix

is that the scheduling strategy combines vessels into vessel platooning based on methods in this paper, which transportation costs and efficiency are better than a fixed origin route in the waterway network. We proved how a coordination and optimization approaches could reduce the energy consumption of vessels on a large-scale waterway network. By controlling platoon formation and guiding vessels along fuel-efficient pathways, it is possible to reduce energy costs compared to an origin pathway. According to a large-scale simulation of the European waterway network, energy consumption could be reduced by up to 2% for 300 vessels and 3.6% for 600 vessels.A limitation of this study is that aspects of fleet energy consumption are reasonable assumptions based on existing research. Notwithstanding these limitations, this work offers valuable insights into how vessels can cooperate to form platoons to save energy consumption.

B. Future Research Directions

Much substantial effort has been expended on developing effective coordination and optimization approaches, although several assumptions and simplifications were used to keep the fundamental formulation simple. But a proof of concept has been established, many expansions are possible. The following aspects show a no means exhaustive future research list:

- Conduct simulations and validate conclusions using increasingly precise, sophisticated real-world waterway networks. Randomize vessel behaviour to mimic breakdowns and unexpected driver conduct.
- Deal with disturbances and unpredictability in the dynamics as well as packet losses and communication delays between vessels are additional important challenges.

APPENDIX A
NOMENCLATURE

The mathematical symbols used in paper are listed in the Table VI.

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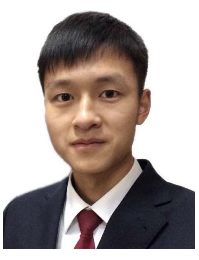

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