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**DOI**
10.1109/MITS.2020.3014107

**Publication date**
2020

**Document Version**
Final published version

**Published in**
IEEE Intelligent Transportation Systems Magazine

**Citation (APA)**
Chen, L., Negenborn, R., Huang, Y., & Hopman, H. (2020). Survey on cooperative control for waterborne transport. *IEEE Intelligent Transportation Systems Magazine*, *13 (2021)*(2), 71-90. https://doi.org/10.1109/MITS.2020.3014107

# A Survey on Cooperative Control for Waterborne Transport


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*Digital Object Identifier 10.1109/MITS.2020.3014107*
*Date of current version: 2 October 2020*

***Abstract*—This article provides a comprehensive overview on cooperative control methods for waterborne transport. We first proposed a hierarchical architecture of cooperation in the waterborne transport systems. Three layers of cooperation are identified according to the range of communication and cooperation, i.e., the individual layer, the local layer, and the network layer. The individual layer is the basis layer where a controller controls the dynamics of an individual vessel. The local layer considers the vessel-to-vessel (V2V) and vessel-to-infrastructure (V2I) interactions. The network layer considers not only V2V and V2I interactions but also the interdependence of the interconnected infrastructures, i.e., infrastructure-to-infrastructure interactions. Existing research for cooperation at each layer is reviewed, and the main research gaps are provided.

Optimizing the performance of waterborne transport systems requires not only automation of the individual vessels but also cooperation among vessels. In current waterborne transport systems, vessels do not actively coordinate their actions with others. This may lead to some problems. First, misunderstanding the intentions of the encountering vessels may lead to oscillation and even collisions [1]–[3]. Second, when the traffic becomes denser, each vessel acting on her own may cause inefficiency, even chaos. According to the ship accidents that occurred in Dutch inland waterways [4], the places that accidents frequently occurred are the areas where vessel-to-vessel (V2V) and vessel-to-infrastructure (V2I) interactions increase, such as ports and intersections. Third, conflicting time schedules could lead to inefficient utilization of infrastructure resources. For example, 40% of the average time a vessel spends in the Port of Rotterdam is waiting time [5].

Cooperation can bring many benefits. First, cooperation can enhance the safety of waterborne transport with communication between vessels. Communication among the vessels can provide additional information, such as data about the objects beyond the reach of sensors, the intentions of others, and so on. The additional information can assist vessel controllers in negotiating and collaborating with others to take effective actions. Second, transport efficiency can be greatly improved with cooperation. For instance, vessels can coordinate their voyage plans to avoid congestion at ports and locks [6], [7]. Moreover, compared to an individual vessel, greater efficiency and operational capability can be realized by a team of vessels working in a cooperative fashion [8].

Seeing the advantages that cooperative vessels may have, an increasing number of pieces of research proposed different methods for cooperation in recent decades, such as cooperative collision avoidance (CA), formation control, and so on. However, existing literature reviews for the control of vessels are usually from the perspective of an individual vessel, such as motion control [8], [9] and CA techniques [10]–[12], among others. Similarly, related reviews on the research for infrastructure planning or scheduling, e.g., for locks [13] or for terminals [14], do not consider the links with other controllers.

As an emerging technology, no systematic overviews have been reported on cooperative control of vessels and infrastructure for waterborne transport. In this article, we carried out a survey on existing research on the cooperative control of vessels and infrastructure in waterborne transport systems, and the main research gaps and trends are identified.

## Scope and Methodology

The scope of this review is cooperative control for waterborne transport. Two main components in waterborne transport systems are vessels and infrastructures. Vessels are the means of transport. Infrastructures are necessary to guarantee navigability. For example, waterways provide navigable waters, and locks create stepped navigational pools with reliable depths. For vessels, six different motion components are used to determine the position and orientation in six degrees of freedom (DOF), defined as surge, sway, heave, roll, pitch, and yaw. Studies for the path/trajectory/heading control of vessels usually focus on the motion in the horizontal plane. Therefore, in this article, we focus on motion control of vessels. The term *motion* means the position and orientation in 3 DOF, i.e., surge, sway, and yaw. For infrastructures, this review focuses on planning and scheduling problems, i.e., the allocation of temporal and spatial resources.

Accordingly, we collect studies with three steps:

1) First, we search in *Web of Knowledge* and *Scopus* to collect journal and conference papers published during 2000–2019, limiting the language to “English” and research domain to “engineering”:
   a) We searched for research on vessels, studies with the following keywords in title: “ship,” “vessel,” “surface vehicle,” “tug,” “boat,” “USV,” “ASV,” “MASS,” and so on, and the following keywords in title, keywords, and abstract: “cooperative/cooperation,” “coordinated/coordination,” “communicate/communication,” “flocking,” “formation,” “platooning,” “manipulation,” “target tracking,” “group,” “multiple/multi-.” Research with keywords that indicate that it is out of our scope is excluded, such as “underwater,” “ROV,”

“UUV,” “AUV,” “aircraft,” “drone,” “car,” and “truck,” among others.

b) We searched for research on infrastructure, studies with the following keywords in title: “lock,” “bridge,” “port,” “waterway network,” and so on, and the following keywords in title, keywords, and abstract: “schedule/scheduling,” “plan/planning,” “route,” “cooperative/cooperation,” “coordinated/coordination,” “communicate/communication.” Research with keywords that indicate that it is out of our scope is excluded, such as “water management,” “design,” “construction,” and “docking,” among others.

2) A further literature filtering is performed to identify the studies that do not completely fit our scopes, e.g., research only related to an individual vessel, communication protocol, supply chain, or operation or management of the infrastructures.

3) After reading the selected papers, we added some papers as a complement to our database. Three types of studies were added: papers that are cited in the selected papers but not included in our database, the studies that were published before 2000 but are classical and are sources of some methods, and the papers that were published in 2019 but have not appeared in the database.

## Categorization of Cooperative Control

Figure 1 provides a hierarchical architecture of cooperation in waterborne transport systems. The physical layer relates to real objects, such as vessels, bridges, and locks. Three control layers are identified according to the range of communication and cooperation.

The individual layer is the basis layer where a controller controls the motion of a vessel or makes schedules for infrastructure. At this layer, a controller does not communicate with other controllers. A vessel controller can obtain information via its own sensors. Based on the obtained information, the controller decides the trajectory and controls actuators to make the vessel move toward the desired position. The research topics related to the control of vessels at this layer are motion planning and control. The main challenges are to describe and deal with the highly nonlinear dynamics of the vessels and handling various control constraints [8]. Various models have been proposed to describe the dynamics of vessels [12]. However, no models can predict the dynamics of the vessels operating in real-life environments without any error, as the dynamics are influenced by many factors, such as the shape and dimension of hulls. Even for a vessel, its dynamics can vary with different loads. Moreover, the motion of vessels is strongly influenced by external disturbances, such as wind, wave, and current [15]. How a controller can be robust against disturbances is also a challenging problem.

The local layer considers the V2V and V2I interactions, including cooperation at links and nodes. Links refer to waterway segments where vessels have similar directions. The cooperation at links usually involves a fleet of vessels. The main task is to design coordination strategies. However, communication and connectivity are often limited. It is also challenging to decide what, when, and with whom the communication takes place [11], [12]. Moreover, the problem becomes more complicated if some vessels are noncooperative or fail to find solutions [16], [17]. Existing

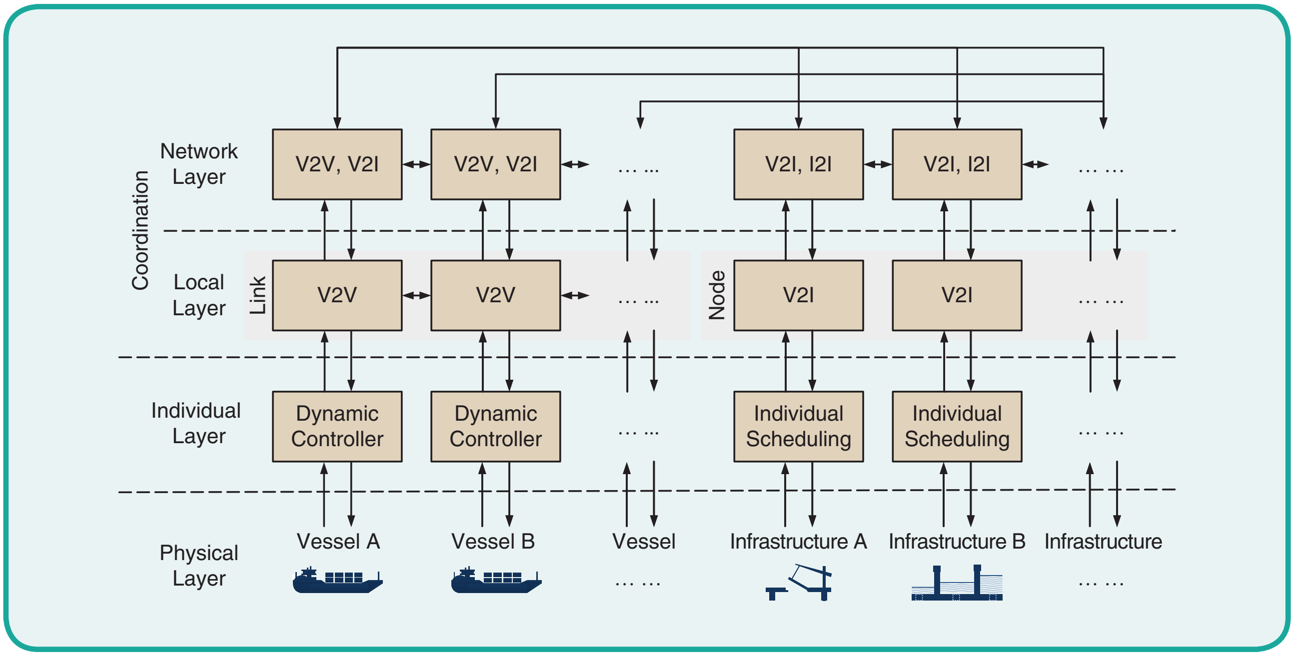

**FIG 1** The hierarchical architecture of cooperation in waterborne transport systems.

Table 1. A comparison of different layers of cooperation.

| Layer | | Range | Comm. | Vessel | Infra. | Challenge | Topic |
|---|---|---|---|---|---|---|---|
| Network | | A waterway network in an area, a port | I2I, V2I | Many | Many | Interdependence of interconnected infrastructures, + *underneath challenges* | Route choice, coordinated scheduling |
| Local | Node | A lock, a movable bridge, an intersection, a terminal | V2I | Many | One | Limit resources; uncertainties in arrivals, fairness, + *underneath challenges* | Infrastructure scheduling |
| | Link | A fleet | V2V | Several | None | Interaction modeling, communication and connectivity, consensus methods, noncooperative participators, fault, + *underneath challenges* | Cooperative CA, formation control, cooperative manipulation |
| Individual | | A vessel | — | One | None | Highly nonlinear dynamics, control constraints, disturbances | Motion planning and control |

Comm., communication, including V2V, V2I, and I2I communications; Infra., infrastructure, such as a lock, a movable bridge, and an intersection ; + *underneath challenges*: challenges at the individual layer are also challenges at the local layer, and the challenges at the local layer are also challenges at the network layer.

studies for V2V cooperation at links can be classified into three categories, i.e., formation control, cooperative CA, and cooperative manipulation.

Nodes refer to the places connecting waterway segments, e.g., a lock, a movable bridge, an intersection, and terminals. The cooperation in links mainly involves a small number of vessels. At nodes, infrastructure controllers make schedules with the predicted time of arrival reported by vessel controllers and also keep an eye on the state of the infrastructure, e.g., availability, waiting time, and length of the line. In return, the operation schedules also have impacts on vessel controllers' decision making on departure time and speed choices. Topics that are related to cooperation at this layer include infrastructure scheduling, i.e., deciding the order and duration of each vessel utilizing available recourses [18]–[20].

When looking into a waterway network, the interdependence of interconnected infrastructures is an important factor that should be considered. Improvement of the traffic situation at one piece of infrastructure may lead to congestion at other places [21], [22]. Moreover, the network structure makes it possible for vessels to choose different routes. If accidents or congestion occurs in a specific area, there may be alternative routes.

Table 1 provides a comparison of the three layers. In this article, we review the cooperation of vessels and infrastructures at the local and network layers. For path planning and motion control of an individual vessel [8]–[11], [23] provided comprehensive reviews of related methods.

## V2V Cooperation at the Local Layer

V2V cooperation at the local layer involves vessels within a certain range that coordinate their behavior for improving safety and efficiency or performing specific tasks. According to the objectives, V2V cooperation at the local layer can be divided into three types. Cooperative CA aims at finding collision-free trajectories for vessels through communication or predefined protocols. Vessels only cooperate when there are high collision risks. Formation control aims at steering a fleet of vessels to form a specific geometric configuration. Cooperative manipulation aims at coordinating a fleet of vessels to perform certain tasks.

### *Cooperative CA*

The determination of CA actions can be generally divided into three basic processes, namely, motion prediction, conflict detection, and conflict resolution [12], as depicted in Figure 2. Motion prediction estimates the future actions and trajectories of the own ship (OS) and the target ships (TSs), which is the basis for conflict detection and resolution. Conflict detection checks collision risk and launches collision warnings if necessary; conflict resolution determines the evasive solutions. The future actions and trajectories of TSs can be predicted by the OS with certain assumptions (e.g., TSs keep a constant speed) or through communication with the TSs. Communication means the process of information broadcasting and receiving among the controllers.

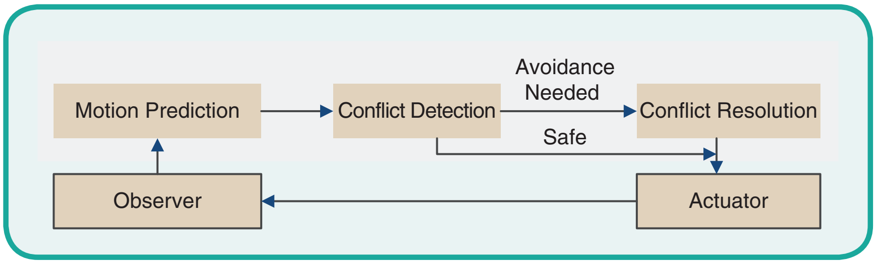

**FIG 2** The CA decision-making process (adapted from [12]).

#### Classification

According to the existence of communication and the cooperation level, existing CA methods can be classified into five groups, as seen in Table 2. Conventional collision avoidance methods usually do not consider the communication between controllers. Assumption-based methods, e.g., potential field [24] and velocity obstacles [25], predict the actions that other vessels may take, either by assuming that others sail with constant speed and heading [26], [27] or according to holonomic or kinematic models [28].

Rule-based methods use predefined rules as the protocol to realize cooperation among controllers.

Rule-based methods use predefined rules as the protocol to realize cooperation among controllers. Those approaches draw up rules on the actions that vessels should take under possible encounter situations. Vessels can coordinate their behavior through rule-compliant decision making.

Communication between vessels can provide additional information that is helpful for collision avoidance decision making. In the intention-aware methods, controllers decide their collision avoidance actions according to the intentions broadcast by other controllers, such as turning directions, predictive trajectory, and so on.

Different from the intention-aware methods, negotiation methods emphasize closed-loop information exchanges. After a controller broadcasts its decision, the actions that other controllers make based on this decision are sent to the controller as feedback. The controller will adjust its decision accordingly. In this way, agreements among the vessel controllers can be achieved through iterative negotiations.

Competition between vessels is seldom mentioned in existing research. In [29], the problem of collision avoidance between two vessels is modeled as a pursuit-evasion game between a faster elliptical pursuer and a more maneuverable circular evader. In [30], the authors present a method to model the decision-making process of the human operators according to the expected behavior of the TS. This method takes the worst case into account, i.e., in which the TS is actively aiming to hit the OS (e.g., when the other vessel has a malfunction in its rudder or propulsion). In [31], [32], the authors apply the differential game model for collision avoidance considering the uncertainty of information and incomplete knowledge about other objects. In these papers, the collision avoidance problem is formulated as a differential game. However, it is challenging for this method to handle the encounter situations, which involve more than two players [33].

In this article, we focus on communication and cooperation among controllers. Rule-based methods and communication-based methods are reviewed in the next paragraphs. Readers who are interested in CA techniques from other perspectives are referred to the reviews [10]–[12].

### Rule-Based Method

The core of the rule-based method is to draw up rules that state the actions that vessels should take under different situations. When vessels encounter each other, the controllers reorganize the encounter pattern and execute actions to comply with the corresponding rule accordingly.

*International Regulations for Preventing Collisions at Sea, 1972* (COLREGs), is the most widely used rule [34]. It sets out the navigation rules to be followed by vessels at sea to prevent collisions between two vessels. An overview of methods that consider COLREGs is provided in [35].

However, COLREGs are written to train and guide safe human operations and are heavily dependent on human common sense in determining rule applicability as well as rule execution, especially when multiple rules apply simultaneously. In [36], the authors proposed a method using multiobjective optimization to capture the flexibility in COLREGs, including the flexibility of when a rule is applied and how it is applied. In [37], the authors carried out a quantitative analysis of COLREGs and seamanship to discriminate encounter situations, stages, and actions. In [38], the authors present a means to quantify and subsequently evaluate the otherwise subjective nature of COLREGS, thereby providing a path toward standardized evaluation and certification of protocol-constrained collision avoidance systems based on admiralty case law and on-water experience.

Moreover, the rule-based method rests on the assumption that all of the vessels follow the rules. However, it is possible that vessels in the same situation have different recognitions of the encounter pattern or the actions that other vessels take in breach of the rules. The probability of a violation of rules is considered in [39]. A probabilistic approach for CA decision making is proposed based on a

Table 2. The categorization of CA methods.

| | Cooperation Level | | |
|---|---|---|---|
| | Cooperative | Noncooperative | Competitive |
| Communication | Negotiation methods | Intention-aware methods | |
| Noncommunication | Rule-based methods | Assumption-based methods | Game theoretical methods |

graphical model consisting of the maneuvering intent and evolution of system states.

Besides COLREGs, other rules can also be used, as long as all of the involved vessels agree to follow the rules. For instance, in [40], a reciprocal velocity obstacles (RVO) method is introduced for sharing the CA responsibility between two encountering vessels. The RVO method suggests that one vessel takes only half of the responsibility, and the other controller takes the remaining half. However, those specific rules are usually only suitable for specific circumstances.

### Communication-Based Method

The communication-based method is characterized by information exchange among the controllers during decision making. The information can be any information that can help the controllers make decisions, such as dynamic models, turning intentions (port-side or starboard-side turnings), predictive trajectories, and so on.

In intention-aware methods, each controller can only access its own sensors and actuators. All the vessels make decisions in a distributed way: Each controller first broadcasts its intentions, such as turning and trajectories to controllers within the communication range, and decisions are made based on the broadcast information. Controllers perform computation and broadcast their intentions in a predetermined sequence, as depicted in Figure 3. Since information is exchanged only once after a controller solved its problem, the amount of communication between controllers as well as the computation time is less. In [41], the authors proposed an intention exchange support system to exchange navigational intentions (e.g., port-to-port passing) between encountered ships. In [42], a single-layer sequential structure is applied for the cooperative control of a fleet of vehicles. The fleet objective can be improved by having some vehicles sacrifice their individual objectives. In [43], each controller makes decisions according to its own observations and the intentions of the other vessels. In [25], vessel controllers find out the set of velocities that lead to collision according to the actions that TSs broadcast and decide the CA actions using generalized velocity obstacle.

In intention-aware methods, the control decision is noncooperative. The controllers can only receive and accept the decisions made by other controllers. Fully cooperative behavior requires all of the involved controllers to negotiate with each other and coordinate their behavior under a common goal. In negotiation methods, the cooperative actions are determined through iterative negotiation. A controller can broadcast its own intentions and its expectations about other controllers, such as the actions that it wishes other controllers would take and the trajectory it prefers rather than the trajectory it computes. When a controller makes decisions, it takes other controllers' expectations into consideration and adjusts the decisions it had made. Thus, such an iterative negotiation framework has a greater potential to achieve overall optimal performance [44].

Two types of control structures are used in negotiation methods, i.e., single-layer structure and multilayer structure. In the single-layer negotiation structure, every controller considers only its own part of the system. Controllers exchange their intentions through communication, as portrayed in Figure 4. According to the order of communication, a single-layer negotiation structure can use two different schemes, i.e., parallel and serial [44], [45]. In parallel schemes, all of the controllers perform computations at the same time. In the algorithm with the single-layer control structure proposed by [46], each subsystem computes optimal inputs for itself and its neighbors. At each time step, the actions are the weighted average of the solutions calculated by the vessel itself and its neighbors. However, the single-layer parallel iterative scheme may lead to nonconvergence. Thus, in [44], a serial iterative scheme is proposed. In the serial schemes, only one controller is performing computations at a time. Serial schemes have the advantage over the parallel schemes in that controllers make use of the most up-to-date information from their neighbors. It shows that the serial scheme has preferable properties in terms of solution speed, by requiring fewer iterations, and solution quality. In [16], [47], a single-layer serial iterative scheme is used for distributed coordination of vessels.

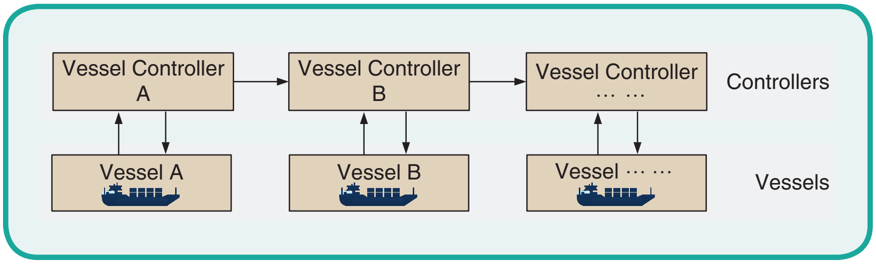

**FIG 3** The structure of intention-aware methods.

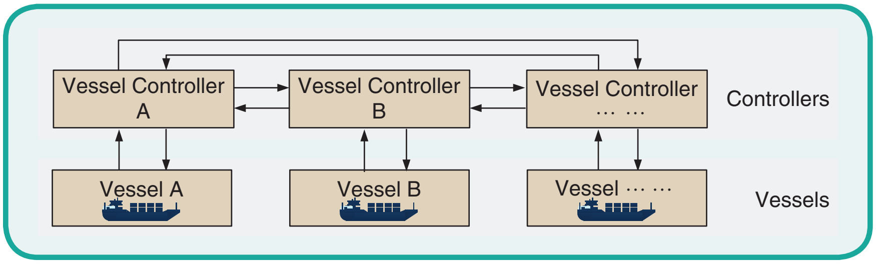

**FIG 4** The structure of single-layer negotiation methods.

In the multilayer negotiation structure, a coordinator at the higher level coordinates the action of local controllers at a lower level, as can be seen in Figure 5. In [48], [49], a coordinator was responsible for the coupling CA constraints. Agreements among vessels were reached through iterations alternating between the coordinator and local path-following controllers. Communication among controllers at the lower level may also exist. As the central coordinator has complete information about the whole system, a multilayer negotiation structure can help the distributed methods find solutions that are closer to a centralized controller. At the same time, a multilayer structure avoids the nonconvergence problem that a single-layer structure may experience.

### Remarks

The rule-based method uses a simple and direct way to coordinate the behavior of encountered vessels. Using the rule-based method to decide CA actions for an autonomous surface vessel (ASV) will make it act like a human-operated vessel, which makes the ASV easier to integrate into current transport systems and to coordinate with human-operated vessels in future mixed-traffic situations. However, some disadvantages exist when applying the rule-based method. First, it is difficult to figure out all of the possible scenarios. Second, the rule-based method is usually suitable for scenarios involving two vessels only. Encountering multiple vessels incorporates multiple rules, and finding the best solution is difficult [11], [12]. Third, as the rules limit actions that a controller can choose, the decisions are usually not optimal. In some cases, the controller cannot even find out rule-compliant actions, especially when a vessel is sailing in restricted waters. Finally, as the rules are made ahead of time, vessel controllers cannot adjust the rules to get better performance or handle emergencies. Thus, controllers using the rule-based method are partially cooperative.

In general, communication can provide the controllers with more information, including information beyond the range of sensors and intentions of other controllers. Through negotiation, the communication-based method can improve both local and overall performance. However, connectivity between the controllers is difficult to guarantee. How to deal with communication delays and packet losses is still a problem that needs to be solved. Moreover, the information being exchanged is provided by each controller. It is challenging to distinguish whether the information is reliable or not. A comparison of the rule-based methods and communication-based methods is presented in Table 3.

### *Formation control*

Formation control aims at steering a group of vessels to form a specific geometric configuration and control their coordinated collective motion. There are a large number of publications in the fields of cooperative and formation control multiagent systems [17], [50]–[52], multiple unmanned

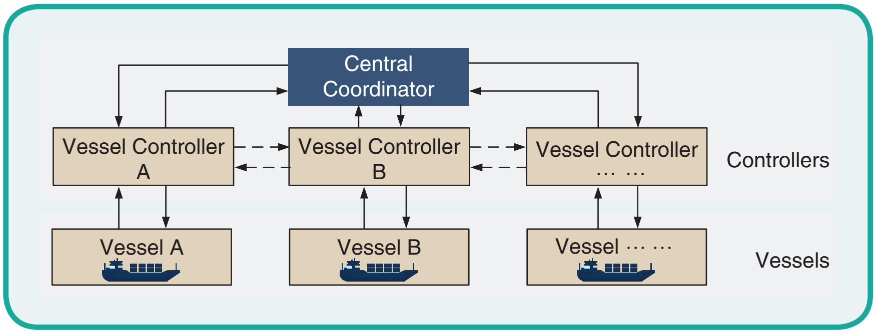

**FIG 5** The structure of multilayer negotiation methods.

Table 3. A comparison of the methods for cooperative CA.

| | Rule-Based Method | Communication-Based Method |
|---|---|---|
| Cooperation | Partially cooperative | Partially cooperative (single-layer sequential structure), fully cooperative (single/multilayer negotiation structure) |
| Basis | Predefined rules for possible situations, e.g., COLREGs | Communication, information provided by other controllers |
| Advantage | - Simple and direct<br>- Easy to understand for humans<br>- Potential in coordinating rule-compliant manned vessels<br>- Low communication demand | - Additional information beyond the reach of the sensors<br>- More accurate information about other vessels<br>- Balance between local and overall performance |
| Disadvantage | - Difficult to figure out all possible situations<br>- Difficult to handle multivessel encounter situations<br>- Difficult to quantify descriptive rules<br>- Limit to actions that vessels can choose | - Challenges in communication and connectivity among the controllers, such as delays and packet losses<br>- Reliability of the provided information<br>- Long computation time<br>- Nonconvergence in certain circumstances |

vehicles [53]–[56], and autonomous underwater vehicles [57]. Like other modes of transport, the formation of vessels can be used for cooperation sensing, searching, and target tracking. Moreover, specific applications of waterborne transport have been mentioned in the literature, such as ice-breaking [58].

### Classification

According to different objectives, formation control can be divided into two processes:

- Formation generation aims at controlling a fleet of vessels located at random positions with arbitrary headings to form a specific geometric configuration.
- Formation tracking aims at controlling a fleet of vessels to follow a predefined trajectory while maintaining the geometric configuration.

According to explicitly prescribed desired formation shapes, two types of formation control are identified [50]:

- Morphous formation control: Desired formations are explicitly specified by desired positions of vessels, desired displacements, and so on. Formation generation and formation tracking belong to this type.
- Amorphous formation control: Without explicitly specified desired formations, desired behaviors, such as cohesion, speed consensus, and so on, are given for controllers. Representative research of this type is flocking.

In existing review papers, formation control methods are usually classified into three types [54], [56]:

- Leader-follower approach: A (virtual) leader is assigned to the formation, and other vessels are designated followers. The followers track the position of the leader with some prescribed offsets, while the leader tracks its desired trajectory.
- Behavioral approach: Final control is derived from the weighting of the relative importance of several desired behaviors, such as cohesion, CA, formation keeping, and so on.
- Virtual structure approach: The formation is considered as a single object, i.e., a virtual structure. The desired motions for the vessels are determined from that of the virtual structure.

Regarding the basic principle in the determination of the final control input, formation control methods usually use the following three cooperative strategies:

- The consensus-based method achieves cooperation through controlling a group of vessels toward some common states, such as heading, speed, average position, and so on. There are no specified desired formation shapes. This category includes existing flocking approaches.
- The relation-based method determines the control inputs for each vessel according to the desired relative distance, orientation, or position of the vessel to a preset point (a leader or target). The previously mentioned leader-follower approach belongs to this category.
- The position-based method calculates paths for each vessel according to the desired configuration, and the formation is achieved when each vessel converges on its desired position. The previously mentioned virtual structure approach belongs to this category.

An overview of the literature for formation control of vessels is presented in Table 4. In existing research, formation control is divided into two subproblems, i.e., motion control and cooperative strategy design. Proportional integral derivative control, sliding mode control, and model predictive control are frequently used to control the motion of each vessel. The back-stepping technique is often used for designing stabilizing controls for the vessels considering the nonlinear dynamics. Lyapunov-based approaches are used to prove system stability. In research in which external disturbances and uncertainties are considered, fuzzy logic, disturbance observer, and neural networks are used to estimate the disturbances.

Most studies only consider intraformation CA: Distance control constraints and potential functions are often used to avoid colliding with formation mates. Other obstacles, such as other vessels not within the formation and static obstacles, are usually considered before the formation is generated. For the obstacles in reference paths, the formation uses shape variation or dispersion and regeneration to avoid collision. The potential function (PF) approach is the most frequently used method when considering obstacles.

### Consensus-Based Methods

The main idea behind consensus-based methods is that each vessel's state is driven toward the states of its neighbors. A typical example is so-called flocking: a group of vessels moves together in a crowd. Basic models of flocking behavior are controlled by three rules [99]: 1) cohesion, stay close to nearby neighbors; 2) separation, avoid collisions with nearby neighbors; and 3) alignment, match velocity with nearby neighbors.

A common form of control inputs using consensus-based methods is the so-called local voting protocol:

$$u_i = \sum_{j \in N_i} w_{ij}(x_j - x_i), \tag{1}$$

where $u_i$ is the control input of vessel $i$; $w_{ij}$ is the weights; $N_i$ is the neighbor of vessel $i$, which is the set of vessels that form the formation with vessel $i$; and $x_i$ and $x_j$ are the states of vessels $i$ and $j$ that need to be synchronized. The state can be the average position (flocking centering protocol), speed, and/or heading (velocity-matching protocol).

In [59], the flocking strategy is designed based on the swarm members' average positions and distance variances. The strategy leads to a cohesion behavior of the vessels without a specific formation shape. Potential function is designed for avoiding collision between swarm members. When avoiding obstacles in the path, the swarm will disperse and regenerate.

Table 4. An overview of formation control methods.

| | | | Morphous | | Cooperative Strategy | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Reference | Main Method | Amorphous | Formation Generation* | Formation Tracking** | Consensus Based | Relation Based | Position Based | Uncertainties and Disturbances | Obstacle Avoidance |
| [59] | Sliding mode method, flock-centering, Lyapunov method | Flocking (6) | | | Average position | | | | PF (dispersion) |
| [60] | Back-stepping, exponential remapping | Target sensing (2) | | → | | ● | | | |
| [61] | Neural network, extended state observer | Target tracking (3) | | ↻ | | ● | | + | |
| [62] | Null-space-based behavioral control | | ○ (8) | → | | ● | | + | PF (dispersion) |
| [63], [64] | PD control, Lagrangian approach | | △ (3) | ⇝ | | ● | | | |
| [65] | Nonlinear model predictive control | | ⋯ (2 and 3) | | | ● | | + | PF (variation) |
| [66], [67] | Lyapunov techniques | | △ (3) | | | ● | | | |
| [68] | Input-output linearization technique | | □ (4) | | | ● | | | |
| [69] | Sliding mode method | | □ to △ (6) | | | ● | | + | |
| [70]–[72] | Line-of-sight, nonlinear cascade theory | | △ (3) | → | | ● | | | |
| [73] | Nonlinear cascade theory, back-stepping | | △ (3) | ⇝ | | ● | | + | |
| [74] | Adaptive nonlinear control, Lyapunov stability, back-stepping | | ⋯ (3) | ↻ | | ● | | + | |
| [75] | Sliding mode method, Lyapunov's direct method | | △ (3) | ↻ | | ● | | | |
| [76] | Adaptive robust control techniques, neural network | | ⋀ (5) | ↻ | | ● | | + | |
| [77] | Gradient-based adaptive control, sliding mode method | | □ (4) | ↻ | | ● | | | |
| [78] | Feedback control, Lyapunov stability | | △ (3) | ⇝ | | ● | | | |
| [79] | Sliding mode method, back-stepping | | ⋀ (5) | → | | ● | | + | |
| [80], [81] | Neural network, back-stepping, minimal learning parameter | | △, ⋯ (3) | ⇝ | | ● | | + | |

(*Continued*)

As the consensus-based method aims at making the state difference between a vessel and its neighbors equal to zero, this method cannot guarantee that the vessels form a specific formation. Thus, the consensus-based method is usually combined with path-following and distance-keeping methods.

In [91]–[95], formation tracking is divided into two steps: one is to steer each vessel to track a given spatial path, and the other is to synchronize the speed of each vessel to maintain the desired formation pattern. In [96], a path-following controller is derived to force each vessel

Table 4. An overview of formation control methods. (*Continued*)

| | | | Morphous | | Cooperative Strategy | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Reference | Main Method | Amorphous | Formation Generation* | Formation Tracking** | Consensus Based | Relation Based | Position Based | Uncertainties and Disturbances | Obstacle Avoidance |
| [82] | Line-of-sight, nonlinear cascaded theory | | ⋮ (5) | ↺ | | | ● | | |
| [83], [84] | Feedback control, back-stepping | | ⋯ (3) | ⇝ | | | ● | + | |
| [85] | Sliding mode method, radial basis function neural network | | ⋯ (5) | ⇝ | | | ● | + | |
| [86], [87] | Fast marching method | | △ (3) | ⇝ | | | ● | | PF (variation) |
| [88] | Passivity-based techniques, radial basis function neural network, Lyapunov theory | | ⋯ (4) | ⇝ | | | ● | + | |
| [89] | Back-stepping, Lyapunov direct method, potential function | | ○ (10) | ⇝ | | | ● | | |
| [90] | Back-stepping, Lyapunov direct method, potential function | | ⋯ (7) | ⇝ | | | ● | | |
| [91] | Line-of-sight, neural network, back-stepping | | ⋯ (3) | ○ | Speed | | ● | + | |
| [92] | Echo state network | | ⋯ (5) | ○ | Speed | | ● | + | |
| [93] | Recurrent neural network | | ⋯ (5) | ⇝ | Speed | | ● | + | |
| [94] | Recurrent neural network | | △ (5) | → | Speed | | ● | + | |
| [95] | Feedback control, neural network | | ⋯ (3) | ○ | Speed | | ● | + | |
| [96] | Back-stepping | | ⋯ (3) | ⇝ | Path parameter | | ● | + | |
| [97] | Back-stepping | | ⏢ (4) | ↺ | Path parameter | | ● | | |
| [98] | Back-stepping | | ⋯ (4) | ◯ | Path parameter | | ● | | |

* △, □, ○, ⏢, and ⩓ represent the shape of the formation; ⋯ and ⋮ represent an in-line and a queue formation. The numbers in parentheses indicate the number of ASVs.

** →, ⇝, ○, ↺, and ◯ represent a straight path, a curved path, a circular path, an elliptical path, and a generic closed curved path.

PF: potential function.

to follow a reference path subject to constant disturbances. The speeds of the vehicles are adjusted so as to synchronize the positions of the corresponding virtual targets. In [97], [98], path following is achieved through driving the value of the orbit function to the nominated value, while formation motion along orbits is accomplished by forcing relative arc lengths to the reference values. In [74], a nonlinear adaptive controller is designed that yields the convergence of the trajectories of the closed-loop system to the path in the presence of constant unknown ocean currents and parametric model uncertainty. Vessel cooperation is achieved by adjusting the speed of each vessel along its path according to its position relative to other vessels.

> Vessel cooperation is achieved by adjusting the speed of each vessel along its path according to its position relative to other vessels.

### Relation-Based Method

A relation-based method decides the actions each vessel should take according to the relative distance, orientation, or position to a prescribed point. The determination of the control inputs can be described with the following equation:

$$u_i = \operatorname*{argmin}_{u_i} \sum_{j \in N_i} w_{ij} \| (x_j - x_i) - r_{ij}^d \|, \tag{2}$$

where $r_{ij}^d$ is the desired relative distance, orientation, and so on.

The relation-based method is usually used to solve the leader-follower problem, in which each vessel maintains a prescribed relative position of a (virtual) leader. In [65], [69], [73], [76], [79], a virtual leader with a global path planner determines the gross path of the formation, and then each vessel controls its relative position with respect to the leader(s). In [78], the virtual leader formation structure is adopted. The desired position of the vessels is calculated such that the virtual leader follows a reference path.

Another application of the relation-based method is target-tracking, i.e., to track a moving target and maintain a certain relative distance. In [61], a bounded controller is designed to solve this problem when only the instantaneous motion of target is available. In [60], the authors use this method to keep the target within a cone-like sensing field of other vessels.

### Position-Based Method

Position-based method is similar to the virtual structure method. First, the formation is regarded as a rigid body. The desired position of each vessel is calculated according to the desired geometric configuration and the path that the formation needs to follow. The desired formation is achieved by making each vessel follows its own path. The position-based method can be described using the following equations:

$$P_i^* = Conf(P_{\forall j \in N_i}, P^*_{\text{Formation}}), \tag{3}$$

$$u_i = \operatorname*{argmin}_{u_i} \| P_i - P_i^* \|, \tag{4}$$

where $P_i$ and $P_i^*$ are the position and desired position of vessel $i$, $P^*_{\text{Formation}}$ is the reference path that the formation should follow, and $Conf(\cdot)$ indicates the desired geometric configuration.

In [83], a formation is viewed as a flexible system (as one unit) that maneuvers along a parameterized path. The formation is ensured when the individual vessels converge to their positions in the formation and stay on their respective paths. In [84], the authors used a similar method, and the capability of handling a severe single vessel failure is illustrated for path-following behavior.

### Remarks

In problems of formation control, vessels have to keep in touch for maintaining desired configurations, such as line, triangle, or circle. Various methods have been proposed, such as consensus-based, relation-based, and position-based methods. Distance control constraints and potential functions are often used to avoid colliding with formation mates. Other obstacles, such as vessels not within the formation or static obstacles, are usually considered during formation generation. For those dynamic or static obstacles encountered during trajectory tracking, vessels in the formation use shape variation or dispersion and regeneration.

## *Cooperative Manipulation*

Cooperative manipulation is the behavior in which a fleet of vessels coordinate their actions to fulfill certain tasks, such as moving an object and towing a boom. Cooperative manipulation with multirobot systems has been studied for decades. Many coordination strategies have been proposed. A comprehensive summary of recent advancements in multirobot systems for cooperative manipulation is provided in [100].

A generic structure of cooperative manipulation is presented in Figure 6. First, a high-level motion control algorithm

Cooperative manipulation is the behavior in which a fleet of vessels coordinate their actions to fulfill certain tasks, such as moving an object and towing a boom.

computes the virtual control effort, e.g., forces and moments, to meet the overall control objectives. Second, a control allocation algorithm decides the effort each vessel should provide such that they jointly produce the desired virtual control efforts. Third, low-level control algorithms are used to control the individual vessels. In this structure, control allocation is the main problem that needs to be solved for cooperative manipulation. Control allocation is usually represented as an optimization problem considering saturation or other limitations of the vessels. An overview of control allocation methods can be found in [101].

According to the tasks, cooperative manipulation can be divided into three types, i.e., cooperative object transport, caging, and self-assembly. Cooperative object transport requires the cooperation of a fleet of vessels to move an object to the desired state (e.g., course, speed, and position). In existing research, a typical application of cooperative object transport is the manipulation of large vessels with multiple tugboats. In [102]–[104], control strategies that enable a barge to track a reference trajectory or orientation using a swarm of autonomous tugboats are discussed. In those papers, the tugboats are attached to the barge and apply forces at some fixed incident angles. The tugboats appear in essence as independent azimuth thrusters. In [105], [106], the initial position of the members is arbitrary.

Nonetheless, once contact is established, the locations of the tugboats are time-invariant. Moreover, only rotational motion is considered. The tugs are normal to the surface of the vessel to provide torque to rotate the vessel from current orientation to the desired orientation. In those papers, the attitude of the tugboats is not considered. The heading of tugboats usually differs sharply from the path direction, which is an inefficiency while moving the object. Besides, obstacles are not considered in those papers. In [107], a group of ASVs coordinate their actions to transport floating objects. The ASVs and the floating object are connected with towlines, and the mass and elasticity of the towline are considered when calculating the forces each ASV should provide.

Caging indicates the application in which two vessels are connected by a rope or boom to trap and transport something. It is usually used to collect liquid on the water, such as spilling oil. In [108]–[110], a caging system consisting of two vessels is proposed for oil skimming and cleanings. In [111], two vessels are connected to each other with a flexible floating rope. They coordinate with each other to capture a floating target from a given location and transport it to a designated position.

In [112], [113], the problem of self-assembly of large teams of autonomous robotic boats into floating platforms is investigated. Small self-propelled ASVs dock together and form connected structures with controllable variable stiffness. These structures can self-reconfigure into arbitrary shapes limited only by the number of rectangular elements assembled in brick-like patterns. The Roboat project [114] proposes to make the ASV units join together to create floating bridges and stages for alleviating congestion on Amsterdam's centuries-old bridges and canalside streets.

To conclude, for cooperative manipulation, there are usually physical connections between the participants, such as towlines, ropes, or booms. Problems related to cooperative object transport, caging, and self-assembly have been investigated in existing research. For the most part, avoiding collision with other vessels or static obstacles is not considered in those papers. Little research focuses on

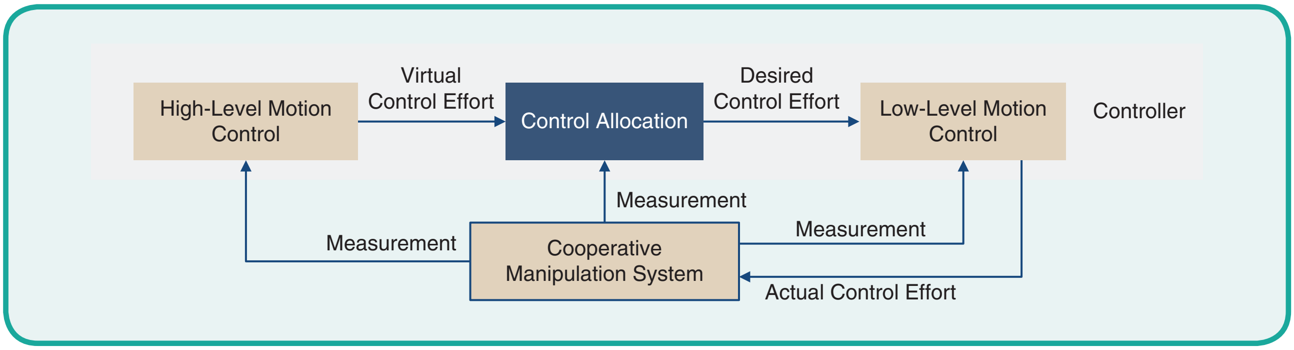

**FIG 6** The generic control structure of cooperative manipulation.

coordinating fleets of vessels for long-distance transport.

### V2I Cooperation at the Local Layer

V2I cooperation at the local layer aims at minimizing the time that vessels need to pass through an infrastructure, such as a lock, a movable bridge, an intersection, and a terminal. Vessels passing through those pieces of infrastructure can be regarded as occupying time and space resources. Thus, the main problem that needs to be solved is the allocation of resources and time slots. The scheduling of the infrastructure is usually formulated as different types of scheduling problems, i.e., mapping of jobs to machines and processing times, such as single machine problems, parallel machine problems, job shop problems, and so on. For algorithms for solving the scheduling problems, please refer to [115].

Cooperative object transport requires the cooperation of a fleet of vessels to move an object to the desired state.

#### *V2I Cooperation at a Terminal*

For waterborne transport in ports, V2I cooperation is mainly related to the operation of terminal equipment. Two related topics are berth allocation and quay crane assignment and scheduling. Berth allocation refers to the decision process of assigning a berth position to a vessel. Quay crane assignment and scheduling decide which quay cranes are assigned to the vessel for loading and unloading operations. Quay crane assignment depends on the accessibility and availability of cranes at the berth. Optimizations on the operations of terminals have been studied extensively in the literature, see [14].

#### *V2I Cooperation at a Lock*

For inland shipping, locks are the infrastructures receiving the most attention, as they are usually the main bottlenecks in waterway networks [116]. A lock has at least one chamber but may consist of multiple parallel chambers of different dimensions. Each chamber has a limited capacity and lockage duration. The lock scheduling problem considers the order in which a number of vessels should be transferred through a lock. Different congestion-solving strategies for the Upper Mississippi River are discussed in [117], [118]. A generalized lock scheduling problem and an overview of methods to solve the lock scheduling problem can be found in [13], [18].

Processing a vessel to pass through a lock requires two decisions: determining a position for the vessel and setting a starting time for the lockage operation. Thus, the lock scheduling problem can be divided into two subproblems, i.e., the vessel placement subproblem (VPSP) and the lockage scheduling subproblem (LSSP).

The VPSP aims at minimizing the number of lockages needed to place all vessels. The VPSP includes two steps. The first step is to decide the sequence of vessels that should be placed, which is determined by the service policy, such as first-come-first-serve or shortest processing time first. Currently, most locks are managed by means of a first-come-first-serve policy, i.e., vessels are handled in the order they arrive. In [20], [119], the authors investigate various strategies that are applied in vessel scheduling and report that the shortest processing time first yields a smaller system-wide delay than the classical first-come-first-serve policy. The second step is to decide how to arrange the vessels in a chamber. Generally, it is reminiscent of the classic 2D bin packing problem where a set of rectangular items (vessels) needs to be positioned inside as few rectangular bins (lockage) as possible [18]. In [120], the authors provide a complete mathematical model for the ship placement problem and compare an exact decomposition method and a multiorder best fit heuristic method for computing the solutions.

The LSSP deals with chamber assignment and lockage operation planning. This problem is often modeled as a parallel machine scheduling problem where chambers map to machines and the lockage to jobs [18], [19]. In [121], a number of (meta)heuristics for minimizing both the water usage and the waiting time of all of the vessels are presented. In [122], the authors focus on the determination of the order in which a number of vessels should be transferred through a lock. The authors identify the problem as the identical parallel machine scheduling problem with sequence-dependent setup times and release dates.

#### *V2I Cooperation at an Intersection*

Few studies focus on the problem of intersection crossing of vessels. In [123] and [124], the process of a vessel passing through the intersection is regarded as occupying time and space resources. The conflicts of vessels are handled by solving a job shop scheduling problem.

Vessels passing through intersections is comparable to the situation of vehicles crossing nonsignalized intersections. In the field of road transport, intersection crossing is one of the most challenging problems and attracts much attention. Related research can provide valuable references for the studies on intersection crossing of vessels. An intersection is a shared resource that a limited number of vehicles want to utilize at the same time [125]. An intersection

In the field of road transport, intersection crossing is one of the most challenging problems and attracts much attention.

controller needs to solve a resource allocation problem to avoid conflicts. In the method cooperative resource reservation, the intersection is modeled as a collection of tiles. Vehicles need to reserve the tiles on their planned route for certain time slots and pass the intersection according to the reservation [126]. Another method is to modify the trajectories (velocity) to minimize overlap and evacuation time [127] or maximize the capacity [128]. A review of cooperative intersection management systems for road transport can be found in [125].

### *Remarks*

V2I cooperation at the local layer usually refers to the scheduling problems of infrastructure. The main problem that needs to be solved is the allocation of resources and time slots. Related research usually focuses on the scheduling for terminals and locks. However, there are many intersections in waterway networks. Vessels in intersections have to frequently interact with vessels from different directions. Intersections are one of the places where accidents frequently occur. Thus, the interactions of vessels at the intersections need to be investigated for the safety and efficiency of inland shipping.

### Cooperation at the Network Layer

Cooperation among vessels and infrastructure at the network layer is related to the distribution of traffic flow and the determination of the route and departure time of the vessels in waterway networks. In the literature, only a few studies focus on the interactions between vessels and infrastructure in inland waterway networks. In [129], the route choice behavior of vessels in an inland waterway network is investigated based on historical data. In [21], the scheduling problem for locks in sequence is studied, which shows the interdependence of infrastructure. In [124], a multilayer framework is employed to improve the efficiency of transport in a canal network. The cooperation among vessel controllers and intersection controllers is achieved through iterative negotiations.

A traditional planning problem that is closely related to cooperation at the network layer is the vehicle routing problem (VRP). The VRP calls for the determination of the optimal set of routes to be performed by a fleet of vehicles to serve customers, and it is one of the most important and studied combinatorial optimization problems [130]. Considerable research has been done to solve the VRP and its variants. Details can be found in [130]–[132].

Some of the existing research related to network layer cooperation considers vessels sailing in a large seaport. In the port, each vessel has to visit a sequence of terminals. Two research topics have been investigated.

One is the so-called interterminal transport (ITT). ITT refers to the transportation of goods between terminals within a port [133]. Conventionally, ITT usually involves dispatching and routing of automated guided vehicles (AGVs) or automated lift vehicles. In [134], a fleet of waterborne AGVs are used to handle a set of ITT requests for advantages like handling the expected large throughput instead of exploiting limited land, energy savings for terminals with longer distances by land than by water, and so on. A closed-loop scheduling and control approach is proposed: By solving a pick-up and delivery problem, a sequence of terminals to visit for each waterborne AGV is generated; a cooperative distributed model predictive control method is applied to control the waterborne AGVs to execute the schedules.

The other type of research on cooperation in ports is the vessel rotation planning problem (VRPP), which decides the sequence of multiple terminals that an inland vessel visits in the port area. In [135], the VRPP is first proposed, in which the terminal and vessel operators cooperate to obtain better alignment. In [6], the authors compare four approaches to solve the VRPP, which concerns deciding on the optimal sequence of vessel visits to different terminals in a large seaport.

To conclude, only a few studies focus on the cooperative control of vessels and infrastructure in waterway networks. Most research focuses on VRP when taking the network structure into account. Some research concentrates on the ITT and VRPP in a port, which can be regarded as a small waterway network. However, research that considers the interdependence of interconnected infrastructures is lacking in general.

### Research Trends and Gaps

Figure 7 presents the word cloud of research on cooperative control for waterborne transport. The color of the keywords indicates the year these words were popular, which shows the research trends.

Figure 7 demonstrates that three keywords that have been frequently used since 2010 are “cooperation,” “collision avoidance,” and “formation.” It shows that the cooperative CA and vessel formation control have been hot topics for years. Since communication is the premise of cooperation, the term “communication” is also frequently used. Some constraints on communication, such as the ranges of sensing and communicating, are considered in the research for target tracking [137] and formation [89], [90]. Recently, with the rapid development of information and communication technologies, an increasing number of researchers focus on autonomous shipping ("USV" and "ASV"). Moreover, most of the control methods rely on mathematical models. Thus, "model uncertainties" is highlighted in recent years. Methods that consider model uncertainties are proposed, such as adaptive control [80], [82], [88]. Besides, "data" plays a more and more important role, such as in situation awareness and on-line parameter identification. Furthermore, theoretical analysis of the designed controllers, such as feasibility, stability, and robustness, is gaining increasing attention, as it is an essential process to guarantee the performance of the controllers.

As mentioned in earlier literature [49], [64], [74], the dynamics of vessels are strongly influenced by environmental disturbances, such as wind, waves, and currents. Thus, "disturbance" has become a hot spot of research. Generally, existing studies consider external disturbances as white noise when design controllers [138], [139]. Additionally, rules ("COLREGs") have been considered in some simple encounter situations. The infrastructure that attracts the most attention is the lock, which is regarded as the main bottleneck in waterborne transport systems. Time is the key parameter that links locks and vessels: Vessel controllers tell the lock operators the estimated time of arrival, and the lock operators inform vessel controllers of the desired time of arrival.

Some research gaps are identified, which desire further developments.

### *Vessel Motion Models*

Various models have been proposed to describe the dynamics of vessels [12]. However, no model can predict the dynamics of vessels operating in real-life environments without any error, as the dynamics are influenced by many factors, such as the shape and dimensions of the hull. Even for a vessel, its dynamics can vary with different loads, sailing in shallow water, and so on [140]. In particular, for varying and uncertain parameters in dynamic models, more work could be done using methods such as on-line parameter

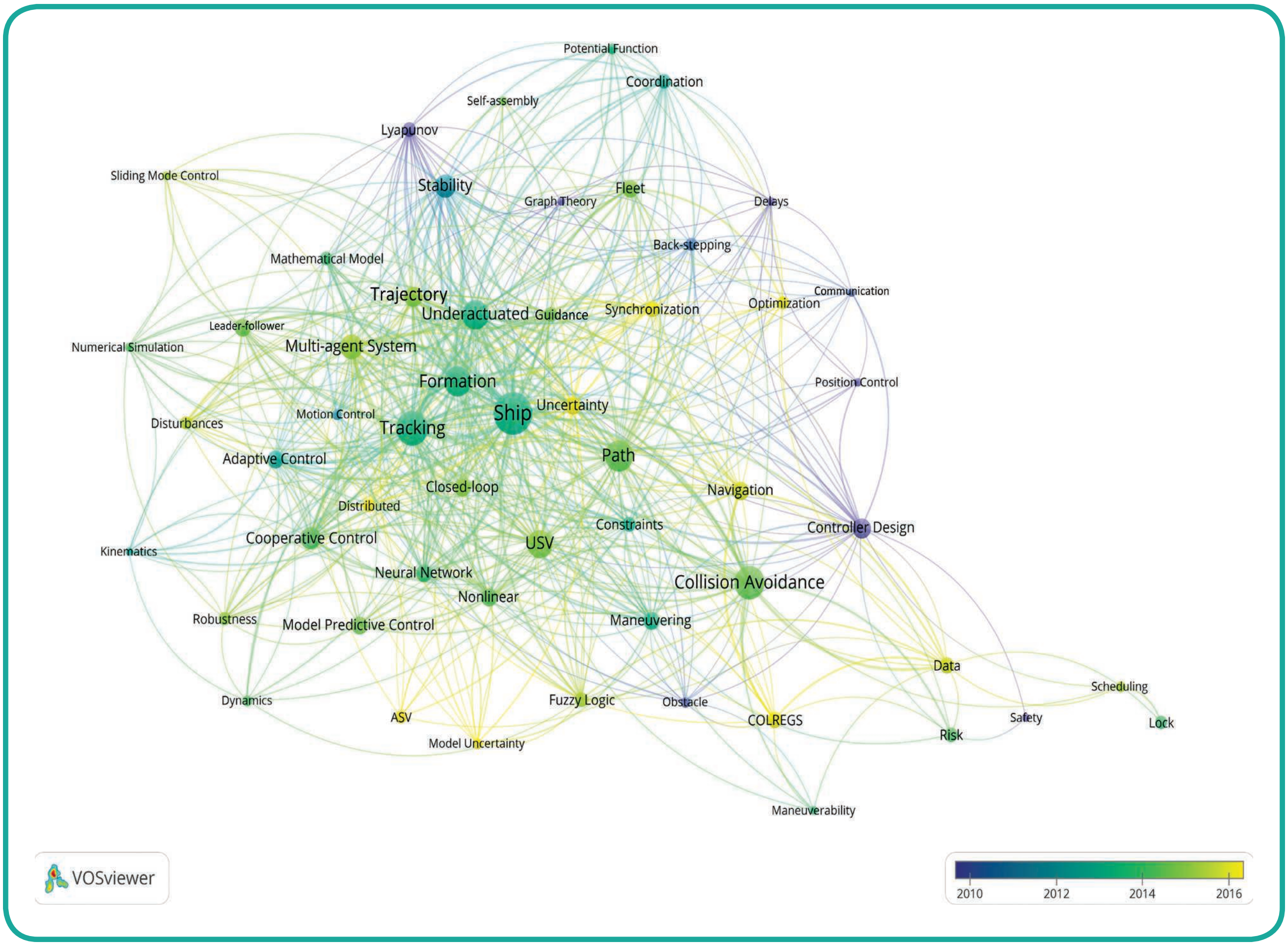

**FIG 7** Research trends on cooperative control for waterborne transport. Note that the word cloud is generated by VOSviewer from 112 papers described in the "Scope and Methodology" section. VOSviewer is a tool for visualizing bibliometric networks that has been used in literature reviews [12], [136].

identification or model-less control methods. Moreover, in maneuvering, a vessel experiences motion in 6 DOF. The motion in all DOF is coupled. Therefore, motion models with 6 DOF are needed to maneuver a vessel safely and accurately.

### *Environmental Disturbances*

Research considering external disturbances regards the disturbances as white noise. However, environmental disturbances, e.g., wind, wave, and current, are not white noise with stationary parameters. Future research addressing how to deal with those disturbances is needed, e.g., by considering the integration of Robust MPC ideas [49] or a behavior model of vessels under different external situations [141].

### *Communication Constraints and Failure*

Most existing research presumes ideal communication, while the quality of communication at sea is questionable. The range of sensors and communications has been considered in some research. Other communication constraints, such as delays, packet loss, or connection failure, should be considered in future research. Possible directions that need to be considered before the proposed systems can be used in practice include, but are not limited to, bandwidth, communication protocol (e.g., frequency and content), asynchronous communication, response to communication failure (or dealing with noncooperative participants), and reliability of the provided information.

### *Hydrodynamic Effect*

Many pieces of collected research ignore the hydrodynamic effects. However, during cooperation, vessels stay close to each other. The ship-ship effect is strong. Ignoring the hydrodynamic effects may lead to collisions. Moreover, for vessels sailing in restricted waters, such as shallow waters and canals, the ship-bank effect is also an important factor that needs to be taken into consideration [142]. Besides, vessels sailing in a V-shape may reduce the drag force; therefore, this type of formation may help to reduce fuel consumption [143], [144]. However, the optimal formation of the ASVs that balance energy savings and safety needs further studies.

### *Interdependence of Interconnected Infrastructure*

For infrastructure, the number of studies that consider whole waterway networks is small. Most of the existing research focuses on lock scheduling problems. Research that considers the interdependence of interconnected infrastructures is lacking in general.

### *Equity and Fairness*

In a cooperative transport system, infrastructure controllers may ask some vessels to slow down or wait to shorten the total travel time. That is to say, global improvements are achieved at the sacrifice of some participants, making equity the most critical success factor for cooperation.

## Conclusion

This article provides a survey on cooperative control for waterborne transport. We first proposed a hierarchical architecture of cooperation in the waterborne transport systems. Three control layers of cooperation are identified according to the range of communication and cooperation, i.e., the individual layer, the local layer, and the network layer. We then analyzed existing methods for cooperation among controllers in the local layer and the network layer, and we identified gaps and trends in cooperative control for vessels and infrastructures in waterborne transport systems.

At the local layer, research is focused on V2V cooperation and V2I cooperation, in which the studies of V2V cooperation are the majority. V2V cooperation includes cooperative collision avoidance (CA), formation, and cooperative manipulation. For cooperative CA, the rule-based method and communication-based method are found. The rule-based method presumes ships follow a common protocol and coordinate with each other based on the protocol. However, the rule-based method is not suitable for multiple-encounter situations, and quantifying rules is still challenging for the machine. The communication-based method, on the other hand, finds solutions through information exchange.

Most existing research presumes ideal communication, while the connectivity and quality of communication are questionable. Constraints, such as bandwidth, package loss, and asynchronous communication, need to be considered. In the problems of formation control, various methods have been proposed, such as consensus-based, relation-based, and position-based methods. Distance control constraints and potential functions are often used to avoid colliding with formation mates. Other obstacles, such as vessels not within the formation or static obstacles, are usually considered during formation generation. For the obstacles encountered during trajectory tracking, vessels in the formation use shape variation or dispersion and regeneration. Regarding cooperative manipulation, there are usually physical connections between the participants, such as towlines, ropes, or booms. Problems related to cooperative object transport, caging, and self-assembly have been investigated in existing research. For the most part, avoiding collision with other vessels or static obstacles is not considered in those papers. Little research focuses on coordinating fleets of vessels for long-distance transport. V2I cooperation at the local layer usually refers to the scheduling problems of infrastructure. The main problem that needs to be solved is the allocation of resources and time slots. Related research usually focuses on the scheduling for terminals and locks. Few studies focus on the problem of intersection crossing of vessels.

At the network layer, only a few studies focus on the vehicle routing problem when taking the network structure into account. The review reveals that I2I cooperation considering the interdependence of interconnected infrastructures in research is lacking in general. According to the analysis of existing research and the identified research gaps, future research can consider the following six perspectives: (1) the varying and uncertain parameters in vessel models, (2) environmental disturbances rather than white noise, (3) communication constraints and reliability of the provided information, (4) the impacts of ship-ship and ship-bank hydrodynamic effects on the control of vessels, (5) the interdependence of interconnected infrastructures, and (6) balancing efficiency and fairness.

## Acknowledgment

This research is supported by the National Science Foundation for Young Scientists of China under grants 52001242 and 52001241 and the Researchlab Autonomous Shipping at Delft University of Technology.

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