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Review article

# Review of floating object manipulation by autonomous multi-vessel systems

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## ABSTRACT

The regulatory endorsement of the International Maritime Organization (IMO) and the support of pivotal shipping market players in recent years motivate the investigation of the potential role that autonomous vessels play in the shipping industry. As the complexity and scale of the envisioned applications increase, research works gradually transform the focus from single-vessel systems to multi-vessel systems. Thus, autonomous multi-vessel systems applied in the shipping industry are becoming a promising research direction. One of the typical research directions is floating object manipulation by multiple tugboats.

This paper offers a comprehensive literature review of the existing research on floating object manipulation by autonomous multi-vessel systems. Based on the prior knowledge of object manipulation problems in multi-robot systems, four typical ways of maritime object manipulation are summarized: attaching, caging, pushing, and towing. The advantages and disadvantages of each manipulation way are discussed, including its typical floating object and application scenarios. Moreover, the aspects of control objective, control architecture, collision avoidance operation, disturbances consideration, and role of each involved vessel are analyzed for gaining insight into the approaches for solving these problems. Finally, challenges and future directions are highlighted to give possible inspiration.

## 1. Introduction

### 1.1. Background

Since the first experiments were carried out in the 1940s, autonomous vessels have been studied for over 80 years (Bertram, 2008). With the increasing maturity and popularity of the advancing technologies of information, communication, sensors, automatic control, and computational intelligence, it has been seen that the application scenarios of autonomous vessels gradually extend from fundamental research to civil and commercial uses (Coelho, Daltry, Dobbin, Lachaud, & Miller, 2015; Devaraju, Chen, & Negenborn, 2018).

To ensure that the regulatory framework for autonomous vessels keeps pace with technological developments, the Maritime Safety Committee (MSC) of the International Maritime Organization (IMO) has started the autonomous vessels development in discussions since its 98th session in 2017 (International Maritime Organization, 2017). For a better regulatory scoping exercise in the future, the IMO considers the generic concept“Maritime Autonomous Surface Ship (MASS)”, which is defined as a ship that can operate independently of human interaction to a varying degree (International Maritime Organization, 2018). The IMO considered the 4 degrees of autonomy are defined as shown in Fig. 1: Degree 1 means only part of processes and operations are automated, while the main control of the vessel has to be seafarers; Degrees 2 and 3 refer to a remotely controlled vessel, the difference being that seafarers are on board in the case of Degree 2 while no seafarers are on board in the case of Degree 3; Degree 4 refers to the fully autonomous vessel, which is able to make decisions and determine actions by itself. It is expected that as the level of development and adoption of autonomous vessels increases, much more than the 4 IMO degrees, defined at a much more detailed level, will be required, as discussed in Schiaretti, Chen, and Negenborn (2017).

The endorsement of the IMO facilitates a large number of research works focusing on autonomous vessels. Meanwhile, the involved applications become more complex and larger scale, such as coastal reconnaissance (Xie et al., 2020), marine assets protection (Raboin, Švec, Nau, & Gupta, 2014), marine habitat mapping (Aguiary et al., 2009), oil spill response (Sierra, Gheorghita, & Jimenez, 2015), ship towage (Hajieghrary, Kularatne, & Hsieh, 2017), offshore platform transportation (Ianagui & Tannuri, 2019), and many more. However, the majority of work has been done on autonomy for single vessels. There is a lack of research on considering explicit interactions between multiple autonomous vessels. Moreover, to realize the above-mentioned complex applications, more than one vessel is required to carry out the tasks. Thus, the focus on autonomous vessel-related research works is starting to move from single vessel systems to multi-vessel systems.

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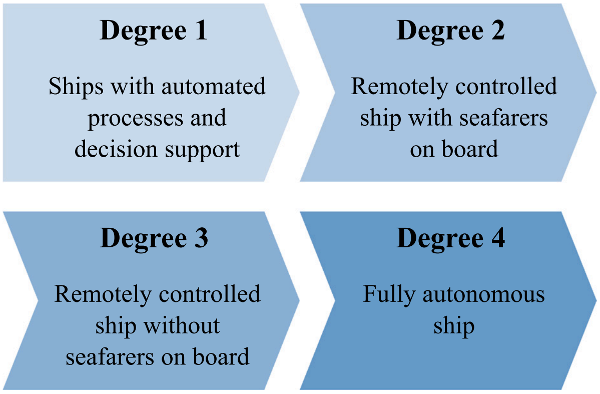


**Fig. 1.** Four degrees of autonomy (International Maritime Organization, 2018).

The studies of autonomous multi-vessel systems are categorized into two main directions according to the way of connections between vessels: formation cluster control and floating object manipulation (Du, Negenborn, & Reppa, 2021b). Formation cluster control involves clustering multiple vessels as a formation while keeping a certain distance for collision avoidance. The connections between vessels are realized through digital networks. The formation can adopt various shapes and is flexible to be maintained, deconstructed, and reconstructed based on the different specific applications. Floating object manipulation refers to multiple vessels cooperatively manipulating a floating object for transport. The connections between the vessels and the floating object are through physical contact. Because of the physical connection, the floating object manipulation system has less ability to maneuver and more constraints on its dynamics.

Since the beginning of the 21st century, the topic of formation cluster control has started to attract scholars' attention (Skjetne, Moi, & Fossen, 2002). Several matured formation control methods, like leader–follower (Shojaei, 2015), virtual structure (Thorvaldsen & Skjetne, 2011), and behavior-based (Arrichiello, Chiaverini, & Fossen, 2006b), are proposed to cope with different typical missions. However, the research on floating object manipulation has just started in recent years; the existing works are limited and in their infancy.

### 1.2. Motivation

The emerging technologies and the endorsement of the IMO motivate the key shipping market players to consider the development of "smart shipping" or "autonomous shipping" (Alop, 2019). However, due to the poor maneuverability and control performance of large ships (Li, Landsburg, Barr, & Calisal, 2005), meanwhile, to investigate the potential advantages of low cost, high mobility, and eco-friendly (Peng, Wang, Wang, & Han, 2021), the present smart ships are usually designed as small to medium sizes, ranging from 2 m long to 15 m long (Bertram, 2008). Thus, the main direction of smart ships is to develop small-size autonomous surface vessels (ASV). In the shipping industry, there is a kind of small-size vessel that plays an important role in building the connections between large cargo ships or offshore platforms and the port, which is the tugboat. Therefore, the tugboat is a good candidate for being one of the first vessel classes to become autonomous (Port Technology International Team, 2017).

There have been already some autonomous tugboat-related collaboration projects carried out between marine-related technology companies, research institutes, and local governments (Du, Reppa, & Negenborn, 2020). Some well-known projects are listed in Table 1. It can be seen that these projects have started about six years ago and the places of implementation are across Europe, Asia, and America. Some of them are supported by local port authorities and maritime bureaus (e.g., the maritime and port authority of Singapore and the American bureau of shipping). Although the majority of projects focus on remotely controlled tugboats that belong to autonomy degrees 2 and 3 according to IMO definition (Fig. 1), they took a big step to develop fully autonomous vessels for smart shipping.

Despite the advantages of low cost, high mobility, and eco-friendly characterizing the small-size autonomous vessels, it is noticed that the limited power and capacity of these small-size vessels restrain their capabilities to carry out more complex missions (Liu & Bucknall, 2018). That is why the multi-vessel cooperative system is a significant and promising direction for the next development of ASVs. The working process of tugboats is a typical example of multi-vessel cooperation, where the operation characteristics depend on waterborne floating object manipulation.

Motivated by the regulatory endorsement of MASS from IMO, the development plan of "smart shipping" from the shipping industry, and the latest collaborative projects of autonomous tugboats, this paper presents a comprehensive literature review of the limited existing research on autonomous multi-vessel systems for floating object manipulation. This survey is divided into three parts:

(1) An overview of the characteristics of the typical maritime object manipulation ways, including the type of floating object and the application scenario;
(2) A systematic analysis of the control-related properties of the floating object manipulation system, including control objective, control architecture, collision avoidance operation, disturbances consideration, and role of each tugboat;
(3) A prospect of potential challenges and future research directions.

### 1.3. Contribution

This work collects and summarizes the existing research works about floating object manipulation, for the benefit of the research community in investigating physically-connected multi-vessel systems. The main contributions of this paper are summarized as follows:

1. Recapitulation and summary of four typical maritime floating object manipulation ways, including their definition, advantages, disadvantages, type of floating object, and application scenarios.
2. Elaboration of the control-related characteristics for the physically connected multi-vessel systems, consisting of control objective, control architecture, collision avoidance operation, disturbances consideration, and role of each tugboat.

### 1.4. Outline

This paper is organized as follows: Section 2 briefly introduces the problem of object manipulation in robotics. Section 3 summarizes four typical maritime floating object manipulation ways from the existing research works. Section 4, 5, and 6 conduct comprehensive surveys on the control-related characteristics for such physically connected multi-vessel systems. Where Section 4 focuses on the control objectives and the control architecture, Section 5 pays attention to the collision avoidance operation and disturbances consideration. Section 6 concentrates on the role of each tugboat in the floating object manipulation system. Challenging issues and future directions are proposed in Section 7. Finally, Section 8 draws conclusions.

## 2. The problem of object manipulation

Object manipulation or object transportation is a typical research problem in the field of cooperative mobile robots. When an object is required to move to a specific place but its size or weight is so large or heavy that it cannot be manipulated by a single robot, multiple robots are clustered together to cooperatively transport the object (Tuci, Alkilabi, & Akanyeti, 2018). Research works on object manipulation by

**Table 1**
Projects of autonomous tugboat.

| Start Year | Demonstration Place | Collaborators | Project |
|---|---|---|---|
| 2016 | TRANSAS Navi-Trainer Simulation System | 1. Pacific Maritime Institute;<br>2. Robert Allan Ltd;<br>3. Transas Maritime Industry. | Testing of control systems for the remotely operated "Ramora" tug (The Maritime Executive, 2016) |
| 2017 | Denmark | 1. Svitzer;<br>2. Kongsberg Maritime;<br>3. American Bureau of Shipping. | RECOTUG: fully remotely controlled commercial tug (The Maritime Executive, 2017) |
| 2017 | Denmark | 1. Rolls-Royce;<br>2. Svitzer;<br>3. Lloyd's Register. | Remotely operated tug "Svitzer Hermod" (Marine Insight, 2017) |
| 2018 | Japan | 1. NYK Group (Japan);<br>2. Japan Marine Science;<br>3. Japan's Ministry of Land, Infrastructure, Transportation and Tourism. | Remotely controlled coastal ships and tugboats (Port Technology, 2018) |
| 2018 | Netherlands | 1. KOTUG;<br>2. Rotortug;<br>3. Captain AI (in 2020). | Remotely controlled tugboat "RT Borkum" (The Maritime Executive, 2018) |
| 2019 | Singapore | 1. Wˋartsilˊa;<br>2. PSA Marine;<br>3. Maritime and Port Authority of Singapore. | IntelliTug project: Autonomous harbour tug (Marine Insight, 2019) |
| 2020 | Singapore | 1. ST Engineering;<br>2. PACC offshore services holdings. | Smart Maritime Autonomous Vessel (SMAV) project for autonomous tug (The Maritime Executive, 2020) |
| 2020 | United Arab Emirates | 1. Robert Allan Ltd;<br>2. Abu Dhabi Ports. | Develop fully unmanned autonomous commercial marine tugs (Marine Insight, 2020) |
| 2020 | Netherlands | 1. Herman Senior;<br>2. Sea Machines Robotics;<br>3. Damen Shipyards. | Upgrade a shoal tugboat "Teddy" for remote control (Riviera Maritime Media, 2020) |
| 2021 | Singapore | 1. Technology company ABB;<br>2. Keppel Offshore & Marine;<br>3. Maritime and Port Authority of Singapore. | Remotely controlled tug "Maju 510" (The Maritime Executive, 2021e) |
| 2021 | Denmark | 1. Damen Shipyards;<br>2. Sea Machines Robotics. | Remotely controlled tug "Nellie Bly" for the voyage around Denmark (Machine Odyssey) (The Maritime Executive, 2021d) |
| 2021 | Turkey | 1. Vallianz Holdings Limited;<br>2. SeaTech Solutions. | All-electric tug "EVT-60" (The Maritime Executive, 2021b) |
| 2021 | China | 1. Wˋartsilˊa;<br>2. China Classification Society;<br>3. Tianjin Port Group. | Semi-Autonomous Tugs (The Maritime Executive, 2021c) |
| 2021 | United States | 1. Foss Maritime;<br>2. Sea Machines Robotics. | Autonomous tug "Rachael Allen" (The Maritime Executive, 2021a) |
| 2021 | United States | 1. Technology company ABB;<br>2. Crowley Maritime Corporation. | Fully Electric Tug "eWolf" (Marine Insight, 2021) |

multi-robot systems (MRS) can be categorized into three types (as shown in Fig. 2): **grasping**, **pushing**, and **caging** (Wang & Kumar, 2002).

**Grasping** manipulation (Fig. 2(a)) is the way that all robots are physically attached to the object, and the configuration of the manipulation system is unchangeable during transportation. The advantage of this manipulation is that the connections between the object and the robots are tight and the object can be fully controlled by the robots so that the motion of the object is easy to predict (Eoh, Jeon, Choi, & Lee, 2011). Thus, the condition of form closure (the object has no way out from the surrounding robots) or force closure (the object is in a state of force equilibrium) is usually satisfied in this case. However, the disadvantage is that grasping requires additional tools such as a gripper or a manipulator. Besides, the effective positioning of the robots around the object to form an optimal configuration is an issue that has to be solved to avoid the case of unbalanced distribution for the grasping manipulation system (Tuci et al., 2018).

**Pushing** (Fig. 2(b)) is a manipulation way that multiple robots exert pushing forces on the object. Because there is no strict requirement of physical contact with the object all the time, this type is also called conditional closure manipulation (Wang & Kumar, 2002). Pushing manipulation does not guarantee form closure or force closure, so the manipulated object is easily "escaping" from the control of robots or moving on an inefficient trajectory, which is the main disadvantage (Tuci et al., 2018). On the other hand, pushing is a simple strategy easy to implement, and it can manipulate a large object which is hard to be grasped (Eoh et al., 2011). Thus, this type of manipulation is tackled as a "box-pushing" problem (González, Torres, & Pulido, 2008).

**Caging** manipulation (Fig. 2(c)) is also called object closure, which means multiple robots are distributed forming a bounded movable area to entrap the object toward the destination. In some scholars' opinion, because the contact between the object and robots does not need to be maintained all the time, caging is seen as a special case of pushing manipulation (Tuci et al., 2018). On the other hand, the formed bounded area ensures robots do not lose control of the object,

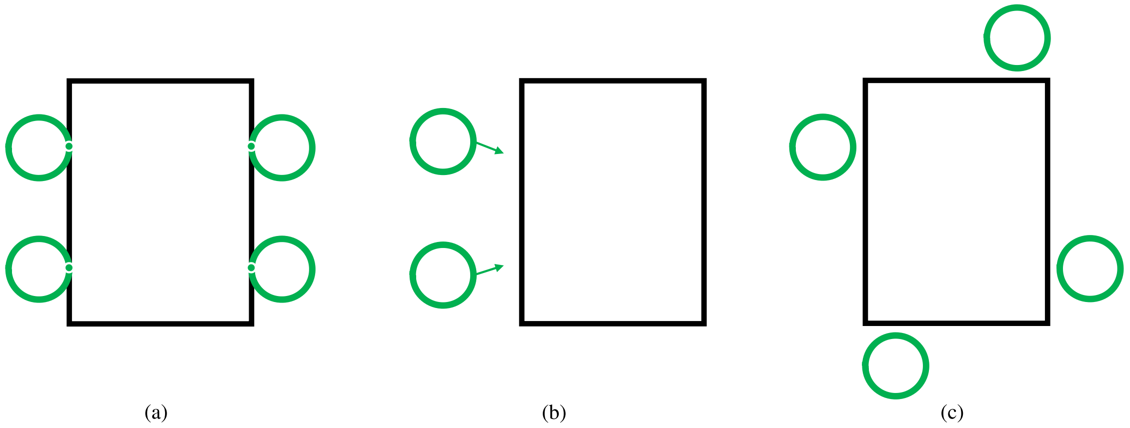


**Fig. 2.** Three types of object manipulation by multi-robot systems (the black box stands for the manipulated object, the green circle is the robot): (a) grasping; (b) pushing; (c) caging.

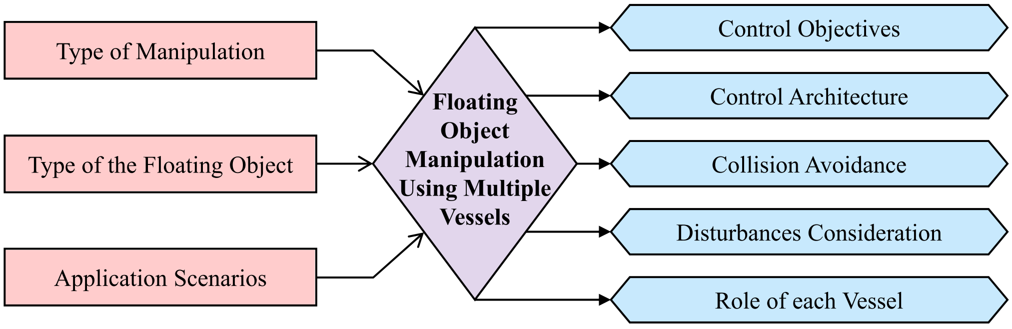


**Fig. 3.** Framework of the floating object manipulation problem.

so the object closure is analogous to form closure with less strict conditions (Eoh et al., 2011). Caging requires less degree of precision in relative positions and orientations between the object and robots, so the advantage lines in more freedom and robustness compared to the manipulations relying on force closure (Pereira, Campos, & Kumar, 2004). However, the shape and size of the object should be carefully investigated because these features are related to the minimum number of robots required to surround the object (Tuci et al., 2018).

The above three typical manipulations briefly summarize the solutions to the problem of object manipulation by multi-robot systems, and the definition, characteristics, advantages, and disadvantages of each manipulation category are introduced. However, the operation space of multi-robot systems is usually ground, which is characterized by being flat and stable with fewer disturbances. When the operation space switches to the waters, the working conditions are full of uncertainties, so the solutions to the problem of floating object manipulation by multi-vessel systems have to be reframed.

## 3. Floating object manipulation in the maritime field

### 3.1. Research framework

Fig. 3 shows the framework of the floating object manipulation problem by multi-vessel systems used in this section to review the existing related research works. Where the type of manipulation, type of the floating object, and application scenarios are the elements to determine the modeling of the system and the problem; the control objectives, control architecture, collision avoidance, disturbances consideration, and the role of each tugboat are the elements to decide the approach used to solve the problem.

The type of manipulation can be used as a key factor to summarize the typical ways of floating object manipulation by multi-vessel systems in the maritime field. As shown in Fig. 4, there are four types of manipulation for the solution of the floating object manipulation problem: **attaching**, **caging**, **pushing**, and **towing**. The floating object is categorized into two types, diffused liquids (e.g. spilled oil and hazardous chemicals) and large structures (e.g. large ship and offshore platform); while the application scenarios can be classified into three categories: port areas, inland waterways, and offshore waters. Different manipulation ways will reflect their own advantages of dealing with a certain type of floating object in specific application scenarios. The detailed characteristics of each manipulation way are illustrated next.

### 3.2. Manipulation of attaching

**Attaching** is the manipulation that multiple vessels clustered together attached to the floating object in a fixed manner, as shown in Fig. 5. In this manipulation way, multiple vessels approach the manipulated object and form a proper configuration to prevent the object from escaping. After all the vessels are physically attached to the object, the configuration of the manipulation system will not change, which is similar to the way of grasping in object manipulation by multi-robot systems. The attached vessels are regarded as thrusters to provide power for the object, so the combined body is usually an over-actuated system and the main research question is how to allocate the multiple control inputs to the manipulated object (Johansen & Fossen, 2013).

The difference between the grasping manipulation by multi-robot systems and the object attaching manipulation by multi-vessel systems is that the latter is more strict with the number and distribution of vessels, which should be an even number and evenly distributed. The reason lies in that the water surface is dynamic with fluctuations, and the attached vessels have to make the object force equilibrium in the

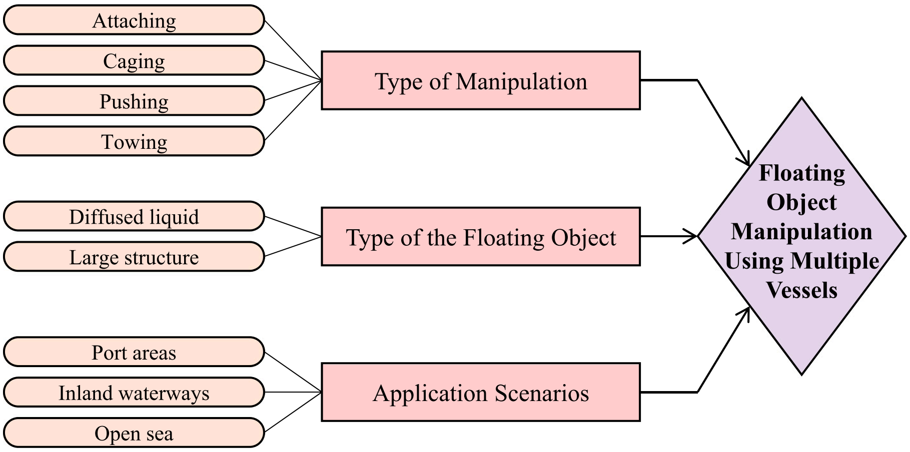


**Fig. 4.** Summarized information of the type of manipulation, type of the floating object, and application scenario from the existing literature of floating object manipulation.

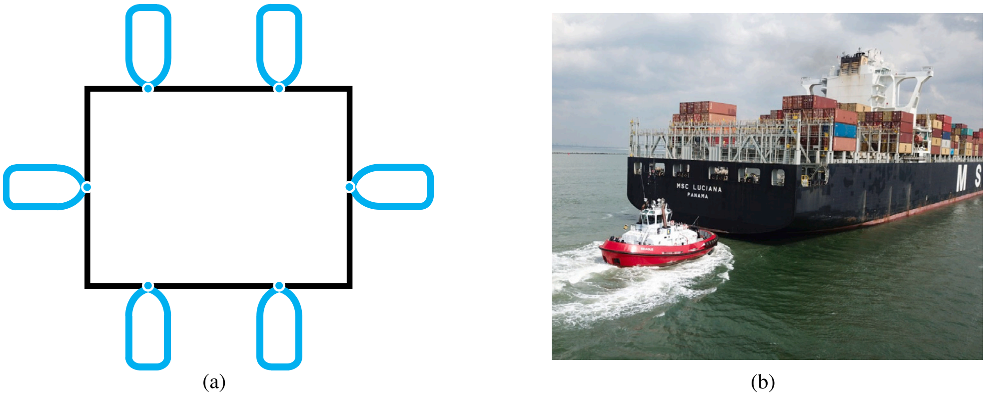

(a) (b)

**Fig. 5.** Manipulation of attaching: (a) Schematic diagram (the black box stands for the manipulated object, the blue shape is the vessel); (b) Application example of a tugboat attaching to a large ship (dJI FORUM, 2019).

vertical direction to ensure the motion of the system is stable in the plane.

The related research works of object attaching are listed in Table 2. It can be seen that the number of vessels in the manipulation of object attaching is usually four (Bidikli, Tatlicioglu, & Zergeroglu, 2015, 2016; Braganza, Feemster, & Dawson, 2007; Esposito, Feemster, & Smith, 2008; Feemster & Esposito, 2010; Feemster, Esposito, & Nicholson, 2006; Smith, Feemster, & Esposito, 2007) and six (Bishop, 2008; Bui, Ji, Jang, & Kim, 2012; Bui, Kawai, Kim, & Lee, 2011; Bui & Kim, 2011; Ji, Choi, & Kim, 2012; Lee et al., 2021), which is the number to satisfy force closure and form closure, respectively. While in some cases, the floating object is too large that requires more than ten vessels to manipulate (Esposito, 2008, 2009, 2010). The research work (Chen, Hopman, & Negenborn, 2019) adopts a special object-attaching manipulation by using three vessels: two vessels are symmetrically and closely located on the two sides of the object connected by short cables, and one vessel attaches at the back of the object laying on its central axis. The type of floating objects in research of object attaching are large structures, and the application scenarios are mainly the port areas and offshore waters.

There is a special case in the attaching manipulation called self-attaching. As shown in Fig. 6, multiple vessels gather together and are physically attached to each other to become a floating platform, and the object can be loaded on such a combined platform. Although the manipulated object in this way is not floating on the water, the connection process between the vessels can be a reference for the realization of the manipulation way of object attaching. The main research questions in this manipulation are how to design the connection device and how to cooperatively plan the trajectories of multiple vessels. These issues are usually ignored in the research on object-attaching manipulation.

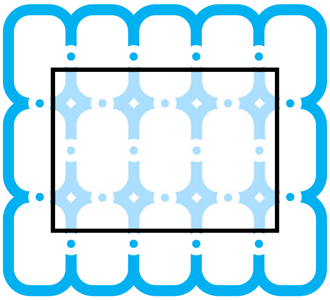


**Fig. 6.** Schematic diagram of self-attaching manipulation, the black box stands for the manipulated object and the blue shape is the vessel.

The connection device should be designed to make sure that the connection between vessels is tight and docked precisely. The connection device usually consists of two parts: "male" and "female" located on the two sides of the vessel. Some examples can be seen in Fig. 7. The cooperative trajectory planning of multiple vessels is solved by using the graph theory and optimization methods, for example, the Dijkstra algorithm combined with the Hungarian algorithm (Paulos et al., 2015) and the B-spline curve combined with the mixed integer quadratic programming (Gheneti et al., 2019) so that each vessel can reach its goal point for docking without collisions.

The related research works of object attaching are listed in Table 3, the number of vessels is greatly varying according to their applications

**Table 2**
Classification of existing literature on object-attaching.

| Literature | Number of vessels | Type of the floating object | | Application scenarios | | |
|---|---|---|---|---|---|---|
| | | Diffused liquids[a] | Large structure | Port areas | Inland waterways | Open sea |
| Feemster et al. (2006) | 6 | | ✓ | ✓ | | |
| Smith et al. (2007) (Esposito et al., 2008) (Bidikli et al., 2015) (Bidikli et al., 2016) (Braganza et al., 2007) | 6 | | ✓ | | | ✓ |
| Feemster and Esposito (2010) | 6 | | ✓ | ✓ | | |
| Esposito (2008) (Esposito, 2009)<br>(Esposito, 2010) | ≥ 10 | | ✓ | | | ✓ |
| Bui et al. (2011) (Bui & Kim, 2011) (Lee et al., 2021) | 4 | | ✓ | ✓ | | |
| Ji et al. (2012) (Bui et al., 2012) (Bishop, 2008) | 4 | | ✓ | | | ✓ |
| Chen et al. (2019) | 3 | | ✓ | | ✓ | |

[a] The reason for this column being empty is that the manipulation of object-attaching can only carry out on a solid floating object.

**Table 3**
Classification of existing literature on self-attaching.

| Literature | Number of vessels | Object to be transported | Application scenarios | | |
|---|---|---|---|---|---|
| | | | Port areas | Inland waterways | Open sea |
| Paulos et al. (2015) Hara et al. (2014) | > 10 | Autonomous cars, drones | | ✓ | |
| Wang et al. (2020) | > 10 | People, supplies, goods | | ✓ | |
| Park, Kayacan, Ratti, and Rus (2019) Kayacan, Park, Ratti, and Rus (2019) | 3 | Daily wastes, supplies, goods | | ✓ | |
| Gheneti et al. (2019) | 3 | Small objects | | ✓ | |
| Mateos et al. (2019) | 2 | Daily wastes, supplies, goods | | ✓ | |

and the loaded objects. If the application is to make vessels self-assembling as a floating platform or a bridge connecting the banks for the transport of other vehicles (autonomous cars, drones) or people, the number of vessels is usually more than ten (Hara et al., 2014; Paulos et al., 2015; Wang et al., 2020). While if the load is a small object, like domestic waste, the numbers can be just two or three (Gheneti et al., 2019; Kayacan et al., 2019; Mateos et al., 2019; Park et al., 2019). Different from the manipulation of object-attaching, the application scenarios in self-attaching are only inland waterways. The self-assembled system is sensitive to disturbances, and there are fewer environmental disturbances in the inland waters. Thus, to ensure the safety of the self-assembled system, inland waterways are the best option.

### 3.3. *Manipulation of caging and pushing*

Compared to the way of attaching, the manipulated floating object in manipulations of caging and pushing has more degrees of freedom but fewer degrees of control.

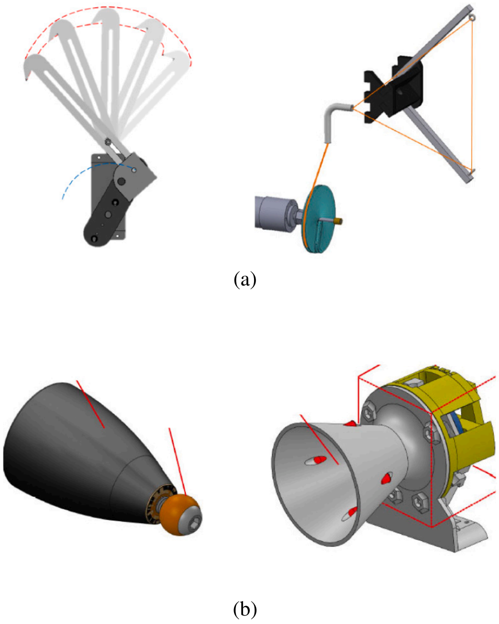
Caging manipulation (as shown in Fig. 8(a)) in the maritime field means the object is manipulated by a long enough floating rope connected to one or more vessels. It is noticed that the definition of caging here is different from the definition used in research on multi-robot object manipulation. In the multi-robot systems, the caging manipulation happens on the ground environments which are usually three degrees of freedom (DOF) (surge, sway, and yaw), so the object can be safely and stably restrained by the multiple robots with proper configurations. However, there are six DOF (surge, sway, heave, roll, pitch, and yaw) in waters. It is difficult to prevent collisions between the object and vessels in such a fluctuating and harsh environment. Thus, the caging manipulation in the maritime field has to be implemented with the help of a media, the floating rope.

Pushing manipulation (as shown in Fig. 8(b)) in the maritime field has the same meaning as that of in the research of multi-robot object manipulation, implying that multiple vessels exert only pushing forces on the floating object. Despite the same definition, the manipulation details are different. For the multi-robot systems, because of the static operation space of the ground, the contact between the object and robots does not have to maintain all the time (Mas & Kitts, 2012, 2013). Consequently, the motion of the object is more flexible. While for the multi-vessel systems, restrained by the dynamic operation space of the waters, a part of the research work aims to make the vessels keep in touch with the floating object through the whole process for the sake of safety (Choi, 2020; Rosario, Cunha, & Rosa, 2020).

The related research works of caging and pushing manipulation are listed in Table 4 and Table 5, respectively. It is observed from Table 4 that the number of vessels in the manipulation of caging is usually two (Arrichiello et al., 2011; Bhattacharya et al., 2011a,

**Table 4**
Classification of existing literature on caging.

| Literature | Number of vessels | Type of the floating object | | Application scenarios | | |
|---|---|---|---|---|---|---|
| | | Diffused liquids | Large structure | Port areas | Inland waterways | Open sea |
| Arrichiello, Heidarsson, Chiaverini, and Sukhatme (2011) | 2 | Small solid floating object | | | | ✓ |
| Pereda, de Marina, Sierra, and Jimenez (2011)<br>Sierra, Gheorghita, and Jimenez (2015)<br>Sierra, Gheorghita, Angulo, and Jimenez (2014)<br>Sierra, Gheorghita, Angulo, and Jimenez (2015)<br>Jimenez and Sierra (2018)<br>Bhattacharya, Heidarsson, Sukhatme, and Kumar (2011b)<br>Bhattacharya, Heidarsson, Sukhatme, and Kumar (2011a) | 2 | ✓ | | | | ✓ |
| Gapingsi, Korbas, and Santos (2017) | 6 | ✓ | | | | ✓ |
| Zhou, Ge, Li, and Ye (2021) | 5 | ✓ | | | | ✓ |
| Sierra and Jimenez (2018)<br>Jimenez and Sierra (2020) | 1 | | ✓ | ✓ | | |

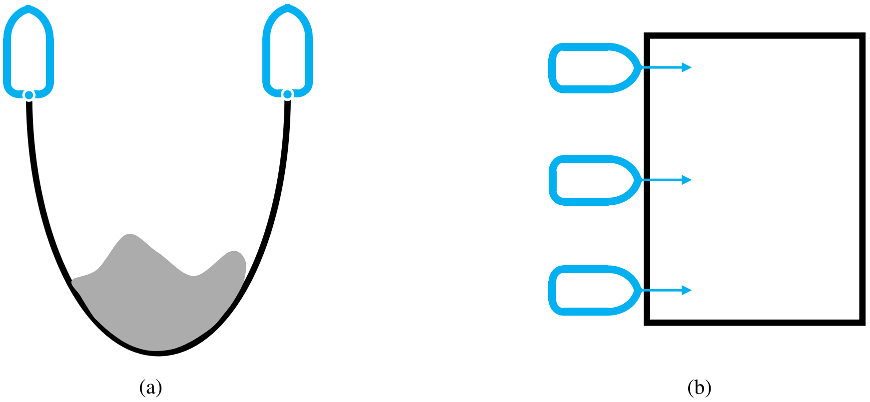

(a)

(b)

**Fig. 7.** Two examples of the designed connection device: (a) the left hook is "male", the right loop is "female" (Hara et al., 2014); (b) the left bearing stud is "male", the right funnel is "female" (Mateos et al., 2019).

2011b; Jimenez & Sierra, 2018; Pereda et al., 2011; Sierra et al., 2014; Sierra, Gheorghita, Angulo, & Jimenez, 2015; Sierra, Gheorghita, & Jimenez, 2015), and the type of floating object is only the spilled oil (Bhattacharya et al., 2011a, 2011b; Gapingsi et al., 2017; Jimenez & Sierra, 2018; Pereda et al., 2011; Sierra et al., 2014; Sierra, Gheorghita, Angulo, & Jimenez, 2015; Sierra, Gheorghita, & Jimenez, 2015; Zhou et al., 2021). The mission of oil spill skimming and cleaning is a typical operation in maritime accident emergency response (as shown in Fig. 9(a)). The whole procedure can be summarized in four steps: first, two vessels drag a boom (the device that can prevent oil from floating around) toward the accident location; then, the two vessels adjust their states to adopt a proper angle of attack of the boom to capture the oil spill; next, the vessels converge to a closer mutual distance to confine the oil spill; finally, the vessels drag the oil spill to a suitable place (Sierra, Gheorghita, & Jimenez, 2015). Thus, the application area of the caging manipulation is mainly offshore waters. Besides the floating object of spilled oil, the small object (Arrichiello et al., 2011) and large ship (Jimenez & Sierra, 2020; Sierra & Jimenez, 2018) can be also manipulated by caging. The process of a small object caging is similar to that of the oil spill recovery, cooperated by two vessels. The operations of a large ship caging are implemented by only one vessel which tows a boom around the ship to moor it along the quayside (as shown in Fig. 9(b)).

For the research of pushing manipulation from Table 5, there is no specific value for the number of vessels. The type of the object belongs to the large structure, the same as in the research of object attaching manipulation. Usually, two or three vessels are deployed to


(a)

(b)

**Fig. 8.** Two manipulation ways that the floating object has more degrees of freedom (the black box and the gray shadow stand for the manipulated object, the blue shape is the vessel, and the black curve stands for the towing boom or floating rope): (a) caging; (b) pushing.


(a)

(b)

**Fig. 9.** Applications of the caging manipulation: (a) oil spill skimming and cleaning (Marine Oil Gobbler, 2018); (b) quayside ship mooring (Texas Boom Company, 2018).

**Table 5**
Classification of existing literature on pushing.

| Literature | Number of vessels | Type of the floating object | | Application scenarios | | |
|---|---|---|---|---|---|---|
| | | Diffused liquids[a] | Large structure | Port areas | Inland waterways | Open sea |
| Sartoretti, Shaw, and Hsieh (2016) | 4 | | ✓ | ✓ | | |
| Zhang, Wang, Yu, and Tan (2007) Nesi et al. (2019) Choi (2020) | 3 | | ✓ | ✓ | | |
| Hu, Wang, Liang, and Wang (2010) | 2 | | ✓ | ✓ | | |
| Hu, Wang, Wang, and Liang (2011) | 2 | | ✓ | ✓ | | |
| Rosario et al. (2020) | 1 | | ✓ | ✓ | | |

[a]The reason for this column being empty is that the manipulation of pushing can only carry out on a solid floating object.

manipulate a box-shaped object (Choi, 2020; Hu et al., 2010, 2011; Nesi et al., 2019; Zhang et al., 2007). If the vessel has enough power, the number can be one (Rosario et al., 2020), otherwise, more vessels are required for manipulation (Sartoretti et al., 2016). However, the application scenarios are restrained in port areas. Because the vessels in this manipulation can only provide pushing forces, the floating object is difficult to be controlled. In addition, compared to the open sea, the port areas are characterized by fewer environmental disturbances; compared to the inland waterways, the port areas have more operational space. So the typical application is to push a large ship approaching the berth by tugboats in port areas (Paulauskas & Paulauskas, 2011).

### 3.4. *Manipulation of towing*

Towing is the manipulation that the object is controlled by tied ropes (or cables) that are connected to vessels, as shown in Fig. 10(a). This is the type that the research of multi-robot object manipulation does not consider but it is very often applied in the maritime field, such as ship towing for port berthing, as shown in Fig. 10(b). Besides the maritime field, the application of towing manipulation actually can be found in the road (tractor-trailer (Li, Zhang, Acarma, Kong, & Zhang, 2019)) and air transport (drone delivery (Rossomando et al., 2020)).

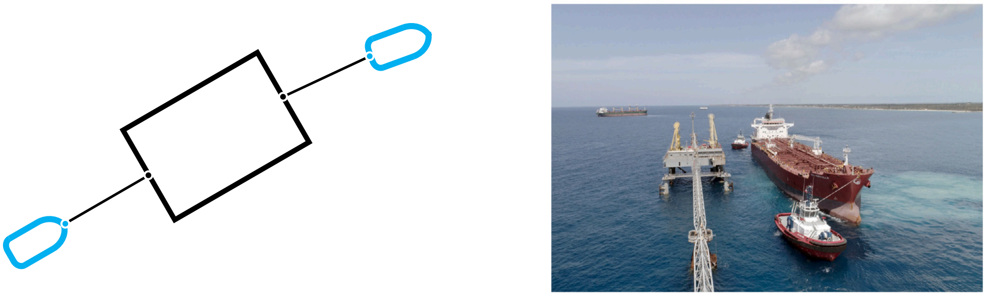

(a) (b)

**Fig. 10.** Manipulation of towing: (a) schematic diagram; (b) application example of ship towing for port berthing (KOTUG Canada, 2017).

However, the majority of research works still focus on maritime transport, because the ropes between the object and vessels are the distance from each other to ensure safety in the manipulation process, especially in some dangerous cases, like harsh sea conditions and restricted waters (passing congested canals and narrow bridges) (Hensen, 2003). Thus, towing is a proper way for multiple vessels to manipulate a floating object in dynamic water environments.

The related research works on towing manipulation are listed in Table 6. Except for literature (Berntsen et al., 2008), whose focus is on moored interconnected structures of self-manipulation, the number of vessels can be classified into three cases: one, two, and four. In the manipulation of one vessel towing case (Amin et al., 2021; Bruzzone et al., 2013, 2016; Ismail et al., 2021; Lee et al., 2020; Mateos, 2020; Quan et al., 2019; Tao et al., 2019; Zhang et al., 2019; Zheng et al., 2021), the floating object can be transported from the initial area to the goal area with the desired heading but is difficult to the specific location. Because the vessel in front of the object provides a pulling force that can only move the object and slowly adjust its heading, while the braking is realized by the damping of the waters. For the two-vessel towing manipulation, there are other two situations. The first one is when deploying both vessels in front of the object to increase the efficiency of the heading adjusting, but the braking operation is still passive (Hajieghrary et al., 2017, 2018; Wu et al., 2021; Yun & Jian, 2018). In the second situation, the object is located between the two vessels so that the front vessel can increase and the behind vessel can decrease the speed of the object (Du et al., 2021a, 2021b, 2021c, 2022a, 2022c, 2020; H́offmann et al., 2021). The last case is to use four vessels towing a large floating platform (Du et al., 2022b; Ianagui & Tannuri, 2019; Xia et al., 2021). In this case, the manipulated object and vessels combine an over-actuated system, so the object is fully controlled. The type of floating object in this manipulation is a large marine structure, and their application scenarios vary from port areas to inland waterways to offshore waters.

### 3.5. Summary

The research share of existing literature on the four floating object manipulations is summarized and compared in Table 7. From the existing related literature, the research of attaching and towing manipulation are dominant, because they have wild application scenarios.

Attaching is an effective manipulation. The advantage lies in that the connection between the object and the vessels is tight and secure, and the manipulated object is fully controlled by multiple vessels. So the object has good maneuverability. While the disadvantage is that it puts extra demand on the design of the connection device, and the trajectory of each vessel is required to plan for preventing collisions with each other. The type of floating object is a large structure and the application scenarios are mainly port areas and the open sea.

Caging is a gentle manipulation. The connection between the object and the vessels is not strong but gives more freedom to the floating object. This manipulation is usually applied for coping with a specific problem of oil spill skimming and cleaning. There is no need to direct contact between the object and vessels, so there is no need to take measures to avoid collisions. But the model of the floating boom is required to be derived. The type of floating object is diffused liquids and the application scenario is the open sea.

Pushing is a simple manipulation. It is easy to implement and the floating object in this manipulation has more freedom. However, the incomplete control of the object restrains its application and increases the manipulation risk under disturbance environments. So the research works on this manipulation are not many. In real cases, pushing is used as an auxiliary operation to collaborate with other manipulations for assisting ship berthing. The type of floating object is a large structure and the application scenarios are port areas.

Towing is a practical manipulation. The connection between the object and vessel requires a media of rope or cable, which reserves certain distances between the object and vessels to ensure manipulation safety. So it can manipulate a floating object in the environment of dynamic waters with harsh weather conditions. The manipulated object has more freedom than attaching and better maneuverability than caging and pushing. Thus, towing operation is a common practice in maritime transport. But the model of the towing manipulation system is difficult to derive. The type of floating object is a large structure and the application scenarios can be port areas, inland waterways, and the open sea.

Thus, it is noticed from the last column in Table 7 that, the research works related to the attaching and towing manipulation take over 70%, and the pushing way takes the least.

## 4. Analysis of control objectives & control architecture

This section analyzes the control objectives concerned and the control architecture used in the existing research works on floating object manipulation. As shown in Fig. 11, the control objective here means the states that the manipulated object is expected to achieve, which consist of three aspects: position, heading, and velocity. The control architecture is another important property for floating object manipulation. For a multi-vessel system, the control architecture can be centralized, decentralized, and distributed. In a centralized architecture, all vessels are independent and directly interact only with a center; for decentralized control, each vessel is controlled by itself with no information exchange for each other; in distributed control architecture, all agents are allowed to communicate with neighbors to share their information (Pourbabak, Chen, & Su, 2019). For a floating object manipulation system, to transport an object in the dynamic water environments, the vessels have to collaborate either following commands by a center that processes information or communicating with each other by sharing its local information. Thus, the control architecture of centralized and distributed are usually applied in this field.

**Table 6**
Classification of existing literature on the manipulation of towing.

| Literature | Number of vessels | Type of the floating object | | Application scenarios | | |
|---|---|---|---|---|---|---|
| | | Diffused liquids[a] | Large structure | Port areas | Inland waterways | Open sea |
| Ismail, Chalhoub, and Pilipchuk (2021) Zheng et al. (2021) Amin, Oterkus, Ali, Shawky, and Oterkus (2021) Zhang, Peng, Ding, Hu, and Shi (2019) Tao et al. (2019) | 1 | | ✓ | | | ✓ |
| Hajieghrary et al. (2017) Hajieghrary, Kularatne, and Hsieh (2018) Yun and Jian (2018) | 2 | | ✓ | | | ✓ |
| Ianagui and Tannuri (2019) Xia, Sun, Zhao, Sun, and Xia (2021) | 4 | | ✓ | | | ✓ |
| Quan, Suh, and Kim (2019) Lee, Chakir, Kim, and Tran (2020) (Mateos, 2020) | 1 | | ✓ | | | ✓ |
| Bruzzone, Bibuli, Zereik, Ranieri, and Caccia (2016) Bruzzone, Bibuli, Caccia, and Zereik (2013) | 1 | | ✓ | ✓ | | |
| Wu, Zhao, Sun, and Wang (2021) Du et al. (2020) Du, Negenborn, and Reppa (2021a) H́offmann et al. (2021) | 2 | | ✓ | ✓ | | |
| Du et al. (2021b) Du, Negenborn, and Reppa (2021c) Du, Negenborn, and Reppa (2022a) Du, Negenborn, and Reppa (2022c) | 2 | | ✓ | | ✓ | |
| Du, Negenborn, and Reppa (2022b) | 4 | | ✓ | | | ✓ |
| Berntsen, Aamo, Leira, and Sørensen (2008) | 5 | | ✓ | | | ✓ |

[a] The reason for this column being empty is that the manipulation of towing can only carry out on a solid floating object.

In the existing research works, the only path or trajectory planning-related and self-attaching-related articles are not included in the summary of this section. The control methods for the floating object manipulation in existing literature are classified in Table 8. It can be seen that for attaching manipulation, the Feedback Control, Lyapunov's Direct Method, Optimization-based Control, and Sliding Model Control are used in the majority of works; for caging manipulation, the main adopted methods are Nonlinear Control, Null-Space-Based Behavior Control, and PID control; for pushing manipulation, besides the above-mentioned methods, the Fuzzy Control strategy is also applied; for towing manipulation, Model Predictive Control, Optimization-based Control, and PID control are dominant. For some research works, the

**Table 7**
Comparison of different manipulations.

| Manipulation | Advantage | Disadvantage | Share |
|---|---|---|---|
| Attaching | 1. The connection is tight;<br>2. The object is fully controlled and has good maneuverability. | 1. Additional device is required to design;<br>2. Trajectory of tugboat needs to be planned. | 36% |
| Caging | 1. Without collisions between the object and tugboats;<br>2. The object has more degrees of freedom. | 1. The type of the object is limited;<br>2. The model of the floating boom is required to established. | 18% |
| Pushing | 1. Simple to implement;<br>2. The object has more degrees of freedom. | 1. The application scenario is limited;<br>2. The manipulation is unsafe under the environmental disturbances. | 10% |
| Towing | 1. The towline reserves safe distances between the object and tugboats;<br>2. The freedom and the controllability of the object is balanced. | 1. The modeling of the towing system is challenging | 36% |

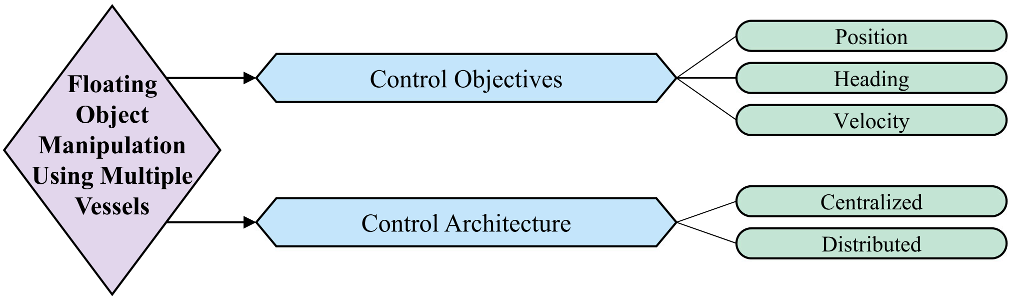


**Fig. 11.** Summary of the control objectives and control architecture in the research of floating object manipulation.

used control methods are more than one, such as (Feemster & Esposito, 2010), Bui and Kim (2011), Lee et al. (2021), and Bishop (2008) in attaching research; (Sartoretti et al., 2016) and Choi (2020) in pushing research; (Ianagui & Tannuri, 2019), Xia et al. (2021), Quan et al. (2019), and Lee et al. (2020) in towing research.

The control objective and control architecture of the rest literature are summarized in Table 9.

In the way of attaching, the main control objective is to simultaneously control the position and heading of the object, where the specific control tasks are manipulation of a large marine structure to (1) track a predefined trajectory (Bui et al., 2012; Chen et al., 2019); (2) move to the desired position with the desired heading (Bidikli et al., 2015, 2016; Bishop, 2008; Braganza et al., 2007; Bui et al., 2011; Bui & Kim, 2011; Esposito et al., 2008; Feemster & Esposito, 2010; Feemster et al., 2006; Ji et al., 2012; Lee et al., 2021; Smith et al., 2007). A few papers work on velocity control to make the manipulation system maintain an expected speed (Esposito, 2009, 2010). For the control architecture, because of the large number of vessels (usually more than 4 according to Table 2) working on this type of manipulation, the majority of works propose a distributed architecture, which has the advantage of lower computation time, scalable application scenarios, and tolerance to failures (Negenborn & Maestre, 2013).

In the way of caging, the control objective is only the position of the floating object, because this manipulation cannot fully control the object. Therefore, the specific control tasks are (1) transportation of the spilled oil or a small object to a safe place (Arrichiello et al., 2011; Bhattacharya et al., 2011a, 2011b; Gapingsi et al., 2017; Jimenez & Sierra, 2018; Pereda et al., 2011; Sierra et al., 2014; Sierra, Gheorghita, Angulo, & Jimenez, 2015; Sierra, Gheorghita, & Jimenez, 2015); (2) restriction of a large ship within a safe place (Jimenez & Sierra, 2020; Sierra & Jimenez, 2018). For the control architecture, 50% of the research works use distributed architecture for better implementation of real vessel tests (Arrichiello et al., 2011; Jimenez & Sierra, 2018; Pereda et al., 2011; Sierra et al., 2014; Sierra, Gheorghita, Angulo, & Jimenez, 2015; Sierra, Gheorghita, & Jimenez, 2015). The remainder works choose the centralized one to control one vessel (Jimenez & Sierra, 2020; Sierra & Jimenez, 2018) or to do simulation experiments and simple field tests (Bhattacharya et al., 2011a, 2011b; Gapingsi et al., 2017).

In the way of pushing, the control objective focuses on the object's position and heading, where scholars in Hu et al. (2010, 2011), Nesi et al. (2019), Zhang et al. (2007) use 2 to 3 vessels pushing a box-shaped object to a goal position, and researchers in Choi (2020), Rosario et al. (2020), Sartoretti et al. (2016) control the vessel's direction to adjust the heading of the object in the pushing process. For the control architecture, the majority of works use centralized architecture to find global optimal control inputs for the pushing vessels (Choi, 2020; Hu et al., 2010, 2011; Rosario et al., 2020; Zhang et al., 2007). While a few papers consider distributed control architecture to increase the robustness of the pushing manipulation system.

In the way of towing, the control objective is similar to the way of attaching which involves all three states of the manipulated object. Papers (Bruzzone et al., 2013, 2016; Mateos, 2020; Tao et al., 2019) focus on position control to tow the object following the path. The research work (Zheng et al., 2021) focuses on heading control to tow the object keeping its course. In the research works of simultaneously controlling the position and heading of the object, the research papers (Hajieghrary et al., 2017, 2018; Ismail et al., 2021; Lee et al., 2020; Quan et al., 2019; Xia et al., 2021; Yun & Jian, 2018) focus on trajectory tracking, while the research papers (Du et al., 2021a, 2021b, 2022a, 2022b, 2020; Ianagui & Tannuri, 2019; Wu et al., 2021) focus on the desired position and heading reaching. A few works study the control of all the states (position, heading, and velocity) of the object to make the manipulation system follow the waypoints, adjust its heading, and track the speed profile (Du et al., 2021c, 2022c). For the control architecture, more than half of the research works use centralized architecture, but the majority of these works consider a one-vessel manipulation system.

Overall, the majority of research works emphasize the position and heading control of the floating object, while the control objective of velocity is a lack of concern. For the control architecture, except for the attaching manipulation, more than half of the works in the other three manipulation ways adopt centralized control.

**Table 8**
Statistics of the control method for the floating object manipulation literature.

| Control method[a] | Attaching | Caging | Pushing | Towing |
|---|---|---|---|---|
| AC | Braganza et al. (2007) | | | |
| BSC | | | | Hajieghrary et al. (2017) Hajieghrary et al. (2018) Quan et al. (2019) Lee et al. (2020) |
| CC | | | | Ianagui and Tannuri (2019) |
| DSC | | | | Xia et al. (2021) |
| FBC | Smith et al. (2007) Feemster and Esposito (2010) Bidikli et al. (2015) Bidikli et al. (2016) | | Sartoretti et al. (2016) | Wu et al. (2021) |
| FC | | | Zhang et al. (2007) Nesi et al. (2019) Choi (2020) | |
| LADRC | | | | Zheng et al. (2021) Tao et al. (2019) |
| LDM | Esposito et al. (2008) Feemster and Esposito (2010) Esposito (2009) Bidikli et al. (2015) Bidikli et al. (2016) Bui et al. (2011) Ji et al. (2012) Bui and Kim (2011) Lee et al. (2021) | | | |
| MPC | Chen et al. (2019) | | | Du et al. (2021b) Du et al. (2022a) Du et al. (2021c) Du et al. (2022c) Du et al. (2022b) |
| NC | | Bhattacharya et al. (2011b) Bhattacharya et al. (2011a) Gapingsi et al. (2017) | Sartoretti et al. (2016) Choi (2020) | |
| NSBC | Bishop (2008) | | | |
| NSBBC | | Arrichiello et al. (2011) Pereda et al. (2011) | | |
| OC | Feemster and Esposito (2010) Esposito (2010) Bui et al. (2011) Bui and Kim (2011) Lee et al. (2021) Bishop (2008) | | Nesi et al. (2019) | Xia et al. (2021) Quan et al. (2019) Du et al. (2020) Du et al. (2021a) |
| PID | | Sierra, Gheorghita, and Jimenez (2015) Sierra et al. (2014) Sierra, Gheorghita, Angulo, and Jimenez (2015) Jimenez and Sierra (2018) Sierra and Jimenez (2018) Jimenez and Sierra (2020) | Hu et al. (2010) Hu et al. (2011) | Yun and Jian (2018) Ismail et al. (2021) Ianagui and Tannuri (2019) Lee et al. (2020) Tao et al. (2019) Bruzzone et al. (2016) Bruzzone et al. (2013) |

(continued on next page)

**Table 8** (*continued*).

| Control method[a] | Attaching | Caging | Pushing | Towing |
|---|---|---|---|---|
| RC | Feemster et al. (2006) | | | Xia et al. (2021) |
| RL | | | | Zheng et al. (2021) |
| SMC | Ji et al. (2012) Bui et al. (2012) Bui and Kim (2011) Lee et al. (2021) | | Rosario et al. (2020) | |
| VC | | | | Mateos (2020) |

[a] AC: Adaptive Control; BSC: Backstepping Control; CC: Consensus Control; DSC: Dynamic Surface Control; FBC: Feedback Control; FC: Fuzzy Control; LADRC: Linear Active Disturbance Rejection Control; LDM: Lyapunov's Direct Method; MPC: Model Predictive Control; NC: Nonlinear Control; NSBC: Null-Space-Based Control; NSBBC: Null-Space-Based Behavior Control; OC: Optimization-based Control; PID: Proportional Integral Derivative; RC: Robust Control; RL: Reinforcement Learning; SMC: Sliding Model Control; VC: Vision-based Control.

**Table 9**
Statistics of the control objectives and control architecture for the floating object manipulation literature.

| Research works | | Control objective | | | Control architecture | |
|---|---|---|---|---|---|---|
| | | Position | Heading | Velocity | Centralized | Distributed |
| Attaching | Feemster et al. (2006) Smith et al. (2007) Esposito et al. (2008) Feemster and Esposito (2010) Bidikli et al. (2015) Bidikli et al. (2016) Bui et al. (2011) Ji et al. (2012) Bui et al. (2012) Bui and Kim (2011) Chen et al. (2019) | ✓ | ✓ | | | ✓ |
| | Lee et al. (2021) Bishop (2008) Braganza et al. (2007) | ✓ | ✓ | | ✓ | |
| | Esposito (2009) Esposito (2010) | | | ✓ | | ✓ |
| Caging | Arrichiello et al. (2011) Pereda et al. (2011) Sierra, Gheorghita, and Jimenez (2015) Sierra et al. (2014) Sierra, Gheorghita, Angulo, and Jimenez (2015) Jimenez and Sierra (2018) | ✓ | | | | ✓ |
| | Bhattacharya et al. (2011b) Bhattacharya et al. (2011a) Gapingsi et al. (2017) Sierra and Jimenez (2018) Jimenez and Sierra (2020) | ✓ | | | ✓ | |
| Pushing | Zhang et al. (2007) Hu et al. (2010) Hu et al. (2011) | ✓ | | | ✓ | |
| | Nesi et al. (2019) | ✓ | | | | ✓ |
| | Choi (2020) Rosario et al. (2020) | ✓ | ✓ | | ✓ | |
| | Sartoretti et al. (2016) | ✓ | ✓ | | | ✓ |

(*continued on next page*)

**Table 9** (*continued*).

| Research works | | Control objective | | | Control architecture | |
|---|---|---|---|---|---|---|
| | | Position | Heading | Velocity | Centralized | Distributed |
| Towing | Tao et al. (2019)<br>Bruzzone et al. (2016) Bruzzone et al. (2013)<br>Mateos (2020) | ✓ | | | ✓ | |
| | Zheng et al. (2021) | | ✓ | | ✓ | |
| | Ismail et al. (2021)<br>Wu et al. (2021)<br>Quan et al. (2019)<br>Lee et al. (2020) Du et al. (2021a) Du et al. (2021b)<br>Du et al. (2022b) | ✓ | ✓ | | ✓ | |
| | Hajieghrary et al. (2017) Hajieghrary et al. (2018) Yun and Jian (2018)<br>Ianagui and Tannuri (2019) Xia et al. (2021) Du et al. (2020)<br>Du et al. (2022a) | ✓ | ✓ | | | ✓ |
| | Du et al. (2021c)<br>Du et al. (2022c) | ✓ | ✓ | ✓ | | ✓ |

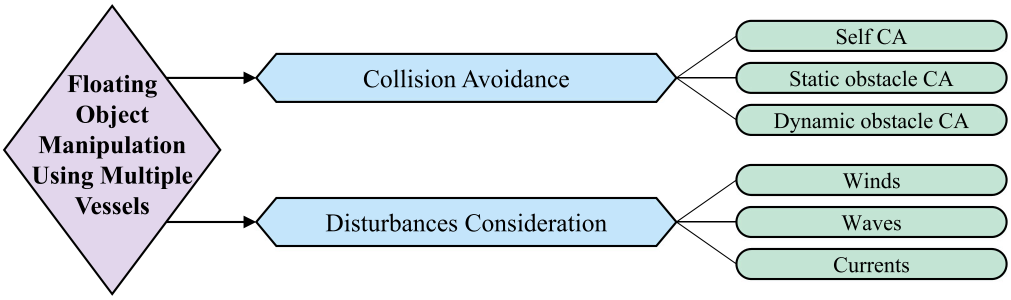


**Fig. 12.** Summary of the collision avoidance and disturbances consideration in the research of floating object manipulation.

## 5. Consideration of collision avoidance & disturbances

This section analyzes the safety and robustness of the floating object manipulation system when dealing with collisions and environmental disturbances. As shown in Fig. 12, there are three aspects of collision avoidance (CA) for the floating object manipulation system: self-CA, static obstacle CA, and dynamic obstacle CA. Self-CA means to prevent collisions between the object and vessels and the vessel each other. It is a basic safety measure to ensure that the towing manipulation works properly. Static and dynamic obstacle CA is to keep the manipulation system away from the external potential dangerous targets, such as no-navigation zone, anchorage, and other moving vessels.

Considering disturbances is an important issue to increase the robustness of the manipulation system. In the maritime environment, disturbances usually refer to winds, waves, and currents. Wind effects can be formulated by wind speed and direction (Ahmed & Hasegawa, 2013; Mizuno, Uchida, & Okazaki, 2015; Pereira, Das, & Sukhatme, 2008; Shuai et al., 2019), and can also be represented by simplifying as external bounded forces to the system (Arrichiello, Chiaverini, & Fossen, 2006a; Ghommam, Mnif, Benali, & Derbel, 2006; Li, Lee, Jun, & Lim, 2008; Zhang, Jia, & Qi, 2011). Wave effects are relatively complex because the wave model is built based on the wave spectra and the theory of response amplitude operators (RAOs) (Fossen, 2011). Thus, scholars usually use trigonometric functions to simulate wave influence (Li & Sun, 2011; Pan, Lai, Yang, & Wu, 2013; Peng, Wang, Chen, Hu, & Lan, 2013; Tee & Ge, 2006). As to currents, whose effects are reflected in the relative velocities of the vessels to the waters (Fossen, 2011).

Existing research works that tackle the problem of collision avoidance and handling disturbances for the floating object manipulation system are summarized in Table 10.

In the way of attaching, a large number of research works do not consider the collision avoidance problem (Bidikli et al., 2015, 2016; Bishop, 2008; Braganza et al., 2007; Bui et al., 2012, 2011; Bui & Kim, 2011; Esposito, 2009; Esposito et al., 2008; Feemster & Esposito, 2010; Feemster et al., 2006; Ji et al., 2012; Lee et al., 2021; Smith et al., 2007). They ignore the approaching process of the vessels to the floating object and assume that all the vessels have already attached to the object. On the contrary, scholars of Esposito (2010) use the artificial potential field for regulating the motion of the vessels to avoid collisions with each other while establishing contact with the object. Authors in Chen et al. (2019) use distributed model predictive control to ensure safe distances from vessels to the floating object and from the manipulation system to the static and dynamic obstacles. For the disturbances consideration, research works (Bidikli et al., 2015, 2016; Bui & Kim, 2011; Ji et al., 2012) take into account wave influence on a large floating object manipulation system in the offshore environment; (Lee et al., 2021) focuses on wind and current effects in port areas. While the rest of the papers have no investigation of environmental disturbances.

In the way of caging, only a few papers address the collision avoidance problem, where the focus is just on the collisions between vessels each other (Arrichiello et al., 2011; Pereda et al., 2011). The

**Table 10**
Statistics of the collision avoidance and disturbances consideration for the floating object manipulation literature.

| Research works | | Collision avoidance | | | Disturbances | | |
|---|---|---|---|---|---|---|---|
| | | Self | Static | Dynamic | Winds | Waves | Currents |
| Attaching | Feemster et al. (2006) Smith et al. (2007) Esposito et al. (2008) Feemster and Esposito (2010) Esposito (2009) Bui et al. (2011) Bui et al. (2012) Bishop (2008) Braganza et al. (2007) | – | | | | | |
| | Esposito (2010) | ✓ | | | | | |
| | Chen et al. (2019) | ✓ | ✓ | ✓ | | | |
| | Bidikli et al. (2015)<br>Bidikli et al. (2016)<br>Ji et al. (2012)<br>Bui and Kim (2011) | | | | | ✓ | |
| | Lee et al. (2021) | | | | ✓ | | ✓ |
| Caging | Sierra, Gheorghita, Angulo, and Jimenez (2015) Jimenez and Sierra (2018) Bhattacharya et al. (2011b) Bhattacharya et al. (2011a) Gapingsi et al. (2017) | – | | | | | |
| | Arrichiello et al. (2011) Pereda et al. (2011) | ✓ | | | | | |
| | Sierra, Gheorghita, and Jimenez (2015) Sierra et al. (2014) | | | | ✓ | | |
| | Sierra and Jimenez (2018) Jimenez and Sierra (2020) | | | | ✓ | ✓ | |
| Pushing | Nesi et al. (2019) Choi (2020) Rosario et al. (2020) | – | | | | | |
| | Sartoretti et al. (2016) Zhang et al. (2007) Hu et al. (2010) Hu et al. (2011) | ✓ | | | | | |

(continued on next page)

reason can be analyzed as follows. First, the manipulated object is captured and transported by a long floating rope or boom, which highly reduces the risk of colliding with vessels. Second, the manipulation scenarios are usually offshore waters, where no static obstacles are considered. Third, the manipulated floating object is usually flammable and explosive dangerous goods (spilled oil), so no vessels or other moving targets are close to the caging manipulation system. More than half of the works do not concern the problem of disturbance effects. Research works (Sierra et al., 2014; Sierra, Gheorghita, & Jimenez, 2015) consider wind influence causing motion errors of the boom-towing system for oil spill recovery, and they use the distributed PID controller to compensate for such errors. Papers (Jimenez & Sierra, 2020; Sierra & Jimenez, 2018) consider wind and wave effects in the deployment of booms along with quayside mooring ships. Such effects in the authors' opinion are positive because it helps to get a suitable shape for the boom being towed.

In the way of pushing, none of the papers concern collision avoidance of the external static and dynamic obstacles, because the motion of the floating object in this manipulation is not fully controlled by vessels, the pushing manipulation system has no ability to cope with external obstacles. Despite this, half of the works focus on collision avoidance between the object and vessels. In works (Hu et al., 2010, 2011; Sartoretti et al., 2016), researchers control and plan the approaching speeds and trajectories of the vessels respectively to prevent collisions between the object and vessels and among the vessel themselves. In Zhang et al. (2007), a limit cycle approach is used to control the vessels' posture and prevent collisions, which is to control the vessels' velocity and orientation to avoid the elliptical cycle around an obstacle. No works consider disturbances, probably due to the limited control of the floating object.

In the way of towing, due to the safe distance enabled by the towline, it is observed that all the research works have addressed the problem of self-CA by establishing the desired kinematics towing system model. Scholars in Bruzzone et al. (2013, 2016) define line-following and circle-following guidance paths to make the towing vessel have no collisions with another moving vessel. Scholars in Du et al. (2021b, 2022a, 2022c) combine model predictive control strategy and the designed ship reference guidance system to make the towing

**Table 10** (*continued*).

| Research works | | Collision avoidance | | | Disturbances | | |
|---|---|---|---|---|---|---|---|
| | | Self | Static | Dynamic | Winds | Waves | Currents |
| Towing | Hajieghrary et al. (2017) Hajieghrary et al. (2018) Quan et al. (2019)<br>Lee et al. (2020) Du et al. (2020) Du et al. (2021c) | ✓ | | | | | |
| | Wu et al. (2021) | ✓ | | | ✓ | | |
| | Xia et al. (2021)<br>Mateos (2020) | ✓ | | | | ✓ | |
| | Yun and Jian (2018) Zheng et al. (2021) Du et al. (2021a) | ✓ | | | ✓ | ✓ | |
| | Tao et al. (2019) | ✓ | | | ✓ | | ✓ |
| | Ismail et al. (2021)<br>Ianagui and Tannuri (2019) Du et al. (2022b) | ✓ | | | ✓ | ✓ | ✓ |
| | Bruzzone et al. (2016) Bruzzone et al. (2013) | ✓ | | ✓ | | | |
| | Du et al. (2021b)<br>Du et al. (2022a)<br>Du et al. (2022c) | ✓ | ✓ | ✓ | | | |

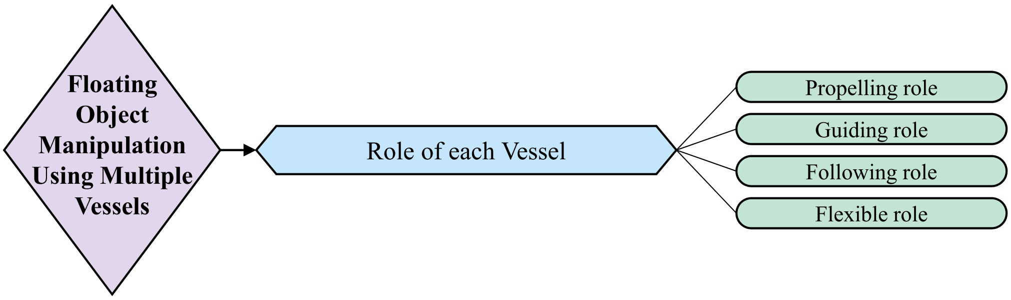


**Fig. 13.** Summary of the role of each vessel in the research of floating object manipulation.

system avoid static and dynamic obstacles in complex water traffic environments, and the collision avoidance operations comply with the COLREGS rules. For the disturbances consideration, the number of papers in this type of manipulation is larger than the other three ones. Some research works consider one type of disturbance, like winds (Wu et al., 2021) and waves (Mateos, 2020; Xia et al., 2021); while some scholars focus on two types of disturbance effects, such as both winds and waves (Du et al., 2021a; Yun & Jian, 2018; Zheng et al., 2021) and both winds and currents (Tao et al., 2019). Especially, there are papers that consider all the environmental disturbances (wind, wave, and current) to a towing system in the scenario of offshore waters (Du et al., 2022b; Ianagui & Tannuri, 2019; Ismail et al., 2021).

Overall, few papers focus on the collision avoidance of external static and dynamic obstacles for the floating object manipulation system. For the disturbances consideration, except for the towing manipulation, the majority of the works in the other three manipulation ways do not address this issue.

## 6. Assignment of vessel role

This section focuses on the role of each vessel in the floating object manipulation system. As shown in Fig. 13, there are four roles for the vessels in the manipulation system summarized from the existing research works: propelling, guiding, following, and flexible role.

A vessel has the role of propelling means that it is directly in contact with the floating object and provides pushing force to move this object. The direction of the provided pushing force is the heading of the vessel. Because it is required to be contacted directly, the floating object cannot be a liquid. Guiding and following roles need media (usually ropes, cables, or booms) to make a physical connection between the object and vessels. A vessel plays the role of guiding means that it is located in front of the object along the direction of motion and provides pulling force to lead this object moving; while a vessel plays the role of following means that it is located behind the object along the direction of motion and provides dragging force to brake this object. The schematic diagram of these three roles is shown in Fig. 14. The flexible role means that a vessel can switch roles between guiding and following. The reason for being able to role exchange is that the vessels in the guiding and the following roles have the same way of manipulation, which is towing. These two roles can be switched by adjusting the position and heading of the vessel.

The role of each vessel in the floating object manipulation system in the existing research works is summarized in Table 11.

In the way of attaching, only one paper (Chen et al., 2019) uses three vessels where one vessel plays propelling role attached behind the object and two vessels play guiding roles located at the two sides of the obstacle. The rest of the works consider all the vessels in their manipulation system as the propelling role. Because one vessel can provide the propelling force in only one direction, to fully control the

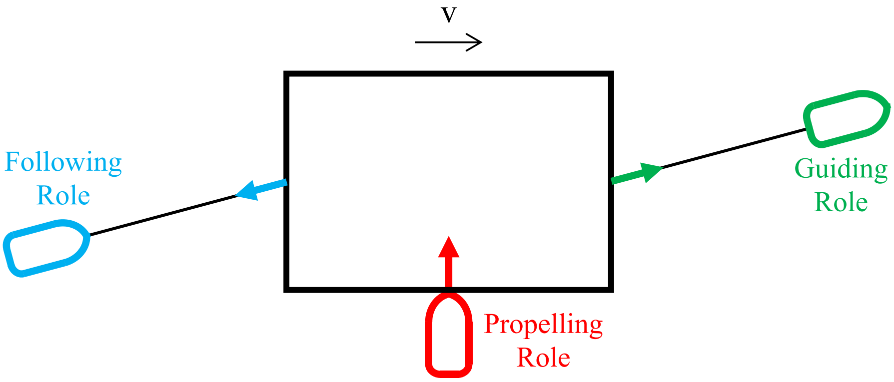


**Fig. 14.** Schematic diagram of the vessel roles in the floating object manipulation system.

**Table 11**
Statistics of the role of each vessel for the floating object manipulation literature.

| Research works | | Number of vessels | Role of the vessel | | | |
|---|---|---|---|---|---|---|
| | | | Propelling | Guiding | Following | Flexible |
| Attaching | Feemster et al. (2006) Smith et al. (2007) Esposito et al. (2008) Esposito (2008) Feemster and Esposito (2010) Esposito (2009) Esposito (2010) Bidikli et al. (2015) Bidikli et al. (2016) Bui et al. (2011) Ji et al. (2012) Bui et al. (2012) Bui and Kim (2011) Lee et al. (2021) Bishop (2008) Braganza et al. (2007) | ≥ 4 | all | | | |
| | Chen et al. (2019) | 3 | 1 | 2 | | |
| Caging | Arrichiello et al. (2011) Pereda et al. (2011) Sierra, Gheorghita, and Jimenez (2015) Sierra et al. (2014) Sierra, Gheorghita, Angulo, and Jimenez (2015) Jimenez and Sierra (2018) Bhattacharya et al. (2011b) Bhattacharya et al. (2011a) Gapingsi et al. (2017) Sierra and Jimenez (2018) Jimenez and Sierra (2020) | 1 ~ 2 | | all | | |
| Pushing | Sartoretti et al. (2016) Zhang et al. (2007) Hu et al. (2010) Hu et al. (2011) Nesi et al. (2019) Choi (2020) Rosario et al. (2020) | 1 ~ 4 | all | | | |

(*continued on next page*)

object, the number of vessels is usually more than four. In the way of caging, due to the floating object being manipulated by a rope or boom towed by one or two vessels, the vessels in the research works of this manipulation type have the guiding role. In the way of pushing, the role of vessels is the same as in the majority of works in attaching manipulation, the propelling role. The difference is since the vessels do

**Table 11** (*continued*).

| Research works | | Number of vessels | Role of the vessel | | | |
|---|---|---|---|---|---|---|
| | | | Propelling | Guiding | Following | Flexible |
| Towing | Ismail et al. (2021)<br>Zheng et al. (2021)<br>Amin et al. (2021)<br>Zhang et al. (2019)<br>Tao et al. (2019)<br>Quan et al. (2019)<br>Lee et al. (2020)<br>Bruzzone et al. (2016)<br>Bruzzone et al. (2013)<br>Mateos (2020) | 1 | | 1 | | |
| | Hajieghrary et al. (2017)<br>Hajieghrary et al. (2018)<br>Yun and Jian (2018)<br>Wu et al. (2021) | 2 | | 2 | | |
| | Hʹoffmann et al. (2021)<br>Du et al. (2020)<br>Du et al. (2021a)<br>Du et al. (2021b)<br>Du et al. (2021c)<br>Du et al. (2022a)<br>Du et al. (2022c) | 2 | | 1 | 1 | |
| | Ianagui and Tannuri (2019)<br>Xia et al. (2021) | 4 | | 4 | | |
| | Du et al. (2022b) | 4 | | | | 4 |

not have to contact the object all the time, the force direction to move the object is not fixed, and the number of vessels does not require to be large (usually 1 to 4).

The vessels of the floating object manipulation system in the above three ways of manipulation have their specific fixed roles. However, the vessel roles in towing manipulation can be more flexible and complex.

As shown in Fig. 15, there are five situations of the vessel role in the existing research works. In literature (Amin et al., 2021; Bruzzone et al., 2013, 2016; Ismail et al., 2021; Lee et al., 2020; Mateos, 2020; Quan et al., 2019; Tao et al., 2019; Zhang et al., 2019; Zheng et al., 2021), authors use one guiding tugboat to control the position and heading of the object (Fig. 15(a)). To improve the efficiency of the heading control, some scholars use two guiding vessels towing the object (Hajieghrary et al., 2017, 2018; Wu et al., 2021; Yun & Jian, 2018) (Fig. 15(b)). There is another configuration of the two-vessel towing system, taking one vessel as the guiding role and another vessel as the following role (Du et al., 2021a, 2021b, 2021c, 2022a, 2022c, 2020; Hʹoffmann et al., 2021) (Fig. 15 (c)). The advantages of this configuration are that the velocity and trajectory of the object are fully controlled and well maintained, respectively, since the role of the following vessel can reduce the speed and stabilize the heading of the object. When the number of vessels increases to four, some researchers assign the guiding role to all the vessels to cooperatively manipulate the floating object (Ianagui & Tannuri, 2019; Xia et al., 2021) (Fig. 15 (d)). The object in this configuration has good maneuverability, however, the fact is that the hydrodynamic parameters of the vessel model are calculated based on the forward motion (the heading is toward the goal). If the configuration of Fig. 15(d) is applied, at least two vessels' heading is opposite to the goal in the process of manipulation, and the hydrodynamic parameters of these vessels are changed. This will result in the problem of model uncertainties. To solve this problem, some scholars adopt the flexible role for all the vessels (Du et al., 2022b) (Fig. 15(e)). In this way, the manipulation system can always keep two vessels with the guiding and two vessels with the following roles in the towing process. Without reducing maneuverability, the manipulation system can effectively transport the floating object and the motions of all the vessels are satisfied with their hydrodynamic models.

Overall, the vessels in the manipulation of attaching, caging, and pushing have their specific fixed roles. For the manipulation of towing, the vessels in the manipulation system have more situations of roles, and the role of the vessel can even be switched.

## 7. Challenges and future directions

Since the research on floating object manipulation by autonomous multi-vessel systems has just started, there exist significant challenges for the implementation in real applications. These challenges are also potential future directions to improve the existing research works for better feasibility and practicality.

### 7.1. Precise manipulation system model

Scholars usually simplify the manipulation system model to make the floating object manipulation problem simple. This simplification is good for finding a control solution quickly and reducing the computation time. But for validating the proposed solution to the real system in practice, it is necessary to establish a relatively precise manipulation system model.

1. Attaching: The manipulation system model in the existing research of attaching way often makes the following simplification: for the self-attaching, the combined floating structure is reconstructed by the linear combination of the key matrices (mass, Coriolis and centripetal, damping, etc.) of the single vessel model (Hara et al., 2014; Wang et al., 2020); for the object-attaching system, the attached floating object is seen as a large ship surrounded by several actuators, so the changed part of the model is the controllable forces and moment (Bidikli et al., 2016; Braganza et al., 2007; Bui & Kim, 2011; Chen et al., 2019; Esposito et al., 2008; Lee et al., 2021). However, the parameters in the non-linear part of the model of the combined floating system are uncertain, and the dynamic constraints of each tugboat influence the motion of the attached floating system. A few works noticed this issue that defined the robust stability (Park et al., 2019) and designed the uncertainty management (Feemster &

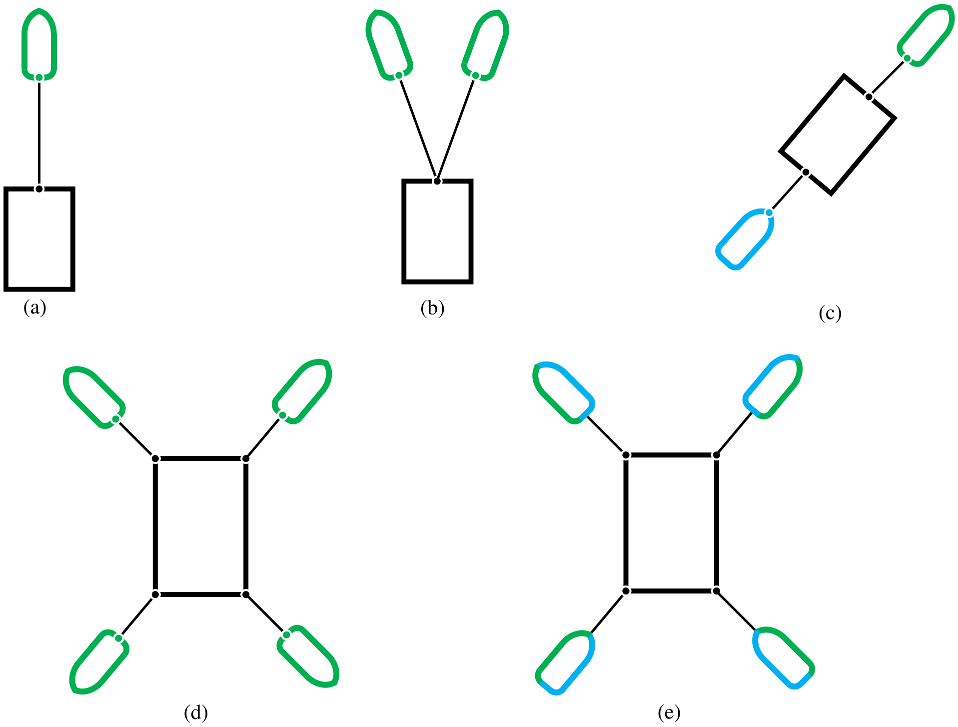


**Fig. 15.** Situations of the vessel role in the existing research works (the black box represents the manipulated object, the green shape is the guiding vessel, the blue shape is the following vessel, the green and blue combined shape stands for the vessels can switch roles between guiding and following): (a) one guiding vessel; (b) two guiding vessels; (c) one guiding and one following vessel; (d) four guiding vessels; (e) four flexible vessels. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Esposito, 2010), respectively, for dealing with model uncertainties. Thus, finding a proper way to deal with the problem of model uncertainties for the attached manipulation system can improve the precision of the control.

2. Caging: The manipulation system model in the way of caging consists of two parts, the vessel model and the boom model, where the boom model is the key and difficult one. Most of the research works treat the boom as a series of interconnected “links” (Gapingsi et al., 2017; Jimenez & Sierra, 2018, 2020; Pereda et al., 2011; Sierra & Jimenez, 2018). Each “link” is treated as a rigid floating long and thin structure and affects the motion of its neighbors provided that the joints among the links remain connected.
   To increase the precision of the boom model, some limited works treat the boom component as a small cylindrical element moving in a fluid with a velocity at a low Reynolds number, and the connected boom line as the catenary analogy model (Bhattacharya et al., 2011a, 2011b). Thus, the introduction of hydrodynamics and the physics geometry model can improve the practicality of the boom motion.
3. Pushing: Due to no fixed contact between the object and the tugboats, the manipulation system model in the pushing way is a separated tugboat and floating object model, both of which can be represented by a vessel motion model (Choi, 2020; Nesi et al., 2019; Rosario et al., 2020). Usually, the vessel motion model is established based on navigating forward (the heading is toward the goal). However, in most cases of pushing manipulation, the floating object is required to move laterally, while the original vessel motion model does not apply to such a “un-normal” motion. Thus, the control performance can be improved by considering the changeable model of the floating object for dealing with different motion situations.
4. Towing: The key to the manipulation system model in the way of towing is the interconnection between the tugboat and the floating object, namely, the towline. In most cases, the towline is treated as a massless cable transferring the towing forces from the tugboat to the floating object (Amin et al., 2021; Du et al., 2021a, 2021b, 2021c, 2022a, 2022b, 2022c, 2020; Hajieghrary et al., 2017, 2018; H́offmann et al., 2021; Ismail et al., 2021; Lee et al., 2020; Yun & Jian, 2018). To simulate real towing operations, some scholars use the catenary model to calculate the towline tension and resistance in the horizontal direction (Ianagui & Tannuri, 2019; Tao et al., 2019; Wu et al., 2021; Xia et al., 2021; Zheng et al., 2021). In these research works, the simulated manipulation system is usually composed of real tugboats and a floating platform so that the mass of the towline cannot be omitted. Thus, for different scales of scenario, the towing manipulation system model should be changed to adjust to different situations.

### 7.2. Multi-DOF motion control

The majority of the works in floating object manipulation focus on the 3-DOF planar motion control. However, in the real marine environment, the winds, waves, and currents will cause the manipulation system in vertical movement. Therefore, apart from the surge, sway, and yaw, the motion of pitch, roll, and heave should also be concerned.

1. Attaching: The additional DOF that should be considered in this manipulation way is the pitch, as shown in Fig. 16(a). Because usually the floating object is symmetrical along the $x$-axis and the number of attached tugboats is even, the attached manipulation system is torque balanced with respect to the $x$-axis (has no roll). However, for some floating objects, like a large ship, the symmetry is not guaranteed along the $y$-axis, and it is also difficult to make the attached manipulation system torque balanced with respect to the $y$-axis by adjusting the attaching position of the tugboats. Thus, the motion of pitch should be considered in the design of the control.
2. Caging: For the manipulation way of caging, the additional DOF is the heave, as shown in Fig. 16(b). The floating object in this way is often the spilled oil whose motion is much influenced by

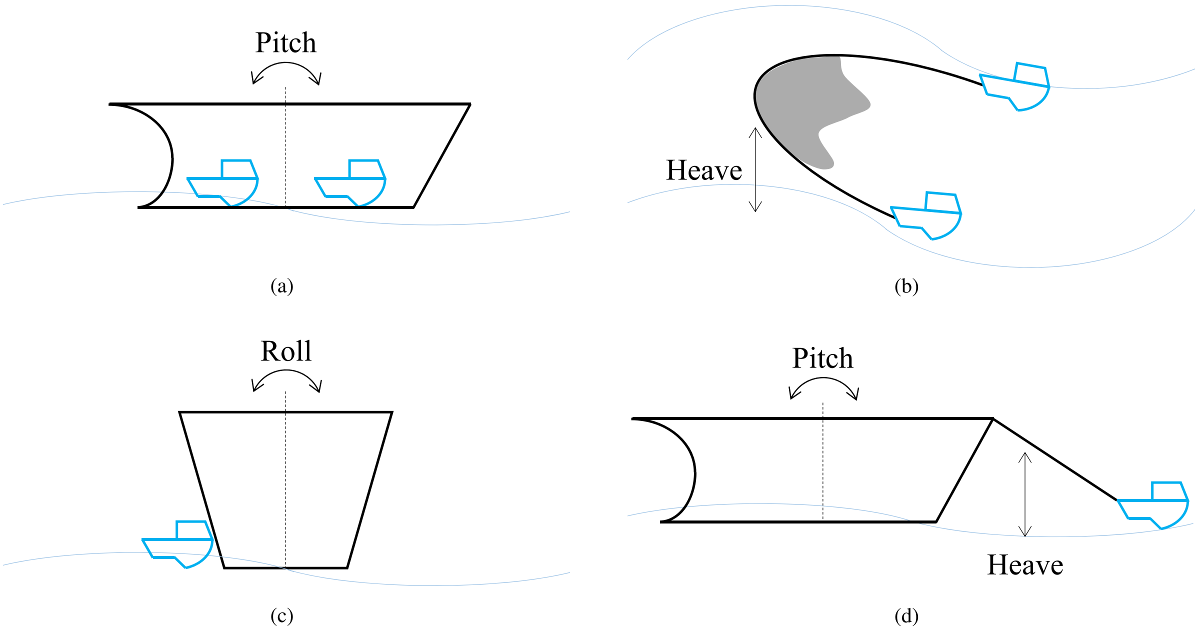


**Fig. 16.** Additional DOF that should be considered in four manipulation ways (the black vessel and the gray shadow stand for the floating object, the blue vessel is the tugboat): (a) Attaching; (b) Caging; (c) Pushing; (d) Towing. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

environmental disturbances, where the effects of waves can cause heave motion. Thus, the control of heave motion is also significant to prevent the spilled oil from escaping from the floating boom.

3. Pushing: The characteristic of the pushing way is that the multiple tugboats exert pushing forces along one side of the $x$-axis of the floating object. Due to there being the height difference between the tugboat and the floating object, the additional DOF in this manipulation way, hence, is the roll, as shown in Fig. 16(c).
4. Towing: The additional DOF that should be considered in towing manipulation way is the pitch and heave, as shown in Fig. 16(d). The height difference between the tugboat and the floating object makes the towing force from the tugboat to the object decompose into two components. The component force along the $x$-axis makes the floating object move in the forward direction (surge motion), and the component force along the $z$-axis makes the floating object move in the vertical direction (heave motion). In addition, both the $x$-axis and $z$-axis component forces generate torques with respect to the $y$-axis (pitch motion). Under environmental disturbances (especially the waves), the motion of heave and pitch will be more obvious.

### 7.3. Observer design

The state information output from sensors is important for designing the cooperative control strategy for the floating object manipulation system. The observer, then, is necessary to be designed to estimate this information. The basic information for the manipulation system is the state of motion containing position, heading, and velocity. Besides, the other information has its specific focus according to different manipulation ways.

1. Attaching: In the attaching manipulation system, the magnitude of the force provided by each tugboat to the floating object should be measured and estimated. Because of the fixed attaching point, the direction of the force provided by each tugboat is unchanged. The motion of the floating object is controlled by altering the magnitude of these forces. Thus, an observer for the force magnitude from each tugboat should be designed to get this data and feedback to the corresponding controller.
2. Caging: The focused information in this manipulation way is the distance between the two tugboats. As mentioned in Section 3.3, the typical application of the caging manipulation is oil spill skimming with two tugboats. The implementation of each step of oil skimming is through changing the configuration of the floating boom, and this configuration change is achieved by controlling the distance between the two tugboats. Thus, the value of this distance requires to be measured and estimated.
3. Pushing: Similar to the attaching way, the concerned information on the pushing manipulation is the pushing force provided by each tugboat. The difference lies in that this force information may also include the direction and pushing point: in the research of Choi (2020), Nesi et al. (2019), Rosario et al. (2020), the pushing point on the floating object is fixed, the force information contains the magnitude and direction; for the research works in Hu et al. (2010, 2011), Sartoretti et al. (2016), Zhang et al. (2007), the tugboats are more degree of freedom, the force information should also include the pushing position on the floating object.
4. Towing: For the towing manipulation system, the necessary information is the towing angle and force. These two variables are the control inputs of the floating object. The desired states of the floating object are reached by controlling the towing force and angle. Thus, two observers should be designed onboard each tugboat to measure and estimate the towing force by the winch and the towing angle from the tugboat to the floating object.

### 7.4. Collision avoidance in different situations

As analyzed in Section 5, the number of research works focusing on collision avoidance of external obstacles is limited. However, the research on collision avoidance is important for ensuring the safety of the floating manipulation system, it is also the premise to implement other tasks. Due to the different maneuverability of the studied system in each manipulation way, the collision avoidance tasks paid attention to are also varied.

1. Attaching: The maneuverability of an attachment manipulation system is the best, and a few research has already started to investigate the collision avoidance of static and dynamic obstacles (Chen et al.,

2019). However, in a busy water traffic environment, there is a situation of multiple target vessels (dynamic obstacles). How to avoid multiple dynamic obstacles simultaneously is a challenging but also worthwhile research problem for an attachment manipulation system.

2. Caging: There is no existing research on collision avoidance of the external obstacles for a caging manipulation system because of the open water application scenarios and the particularity of the manipulated floating object (spilled oil). However, in the manipulation process, the spilled oil caging system may come across some areas that are not allowed to enter, such as anchorage and fishing grounds. In such a case, these “forbidden areas” should be bypassed.
3. Pushing: Same to the way of caging, no existing research on collision avoidance of the external obstacles for a pushing manipulation system. Considering the limited application scenarios, the possible research direction for collision avoidance in this manipulation way is to prevent a large ship from colliding with the terminal during the task of berthing.
4. Towing: For a towing system, the research works on collision avoidance of external obstacles are more than other manipulation ways (Bruzzone et al., 2013, 2016; Du et al., 2021b, 2022a, 2022c). But due to the restricted maneuverability and the redundant structure of the towline-connected multi-vessel system, the challenging point lies in the long response time of the avoiding operation and the limited collision avoidance space, especially in the narrow waterways. Thus, in what way a towing manipulation system can fast and efficiently take actions to eliminate collision risk is a worthwhile research direction.

### *7.5. Tugboat replacement and increment*

In some cases, the floating object may be so heavy than expected that the working tugboats are not enough; or in other cases, a part of the tugboats in the manipulation system may be faulty and out of work. If the above situation happens, the manipulation system has to increase or replace some tugboats to make sure the manipulation task carries on smoothly.

1. Attaching: The tugboat replacement and increment are common in the self-attaching manipulation system (Gheneti et al., 2019; Kayacan et al., 2019; Paulos et al., 2015; Seo, Yim, & Kumar, 2016). The procedure can be summarized as assembly planning, multi-agent trajectory planning, and robust docking. In the way of object-attaching, only a little research tries to address the problem of a new robot (tugboat) joining the attaching system to improve its manipulation capabilities (Esposito, 2008).
2. Caging: The tugboat replacement and increment are not common in the pushing manipulation way. A possible situation is to use multiple tugboats cooperatively to capture a large area of the spilled oil (Zhou et al., 2021). Under environmental disturbances, the spilled oil may diffuse, so the accident area will enlarge which requires a larger number of tugboats involved.
3. Pushing: It is relatively simple for the way of pushing manipulation to replace and increase tugboats because there is no fixed contact between the floating object and the tugboats. But it is noticed that during the process of the update, the trajectories of the new tugboats should be controlled to have no conflict with the other original tugboats.
4. Towing: It is rare for a towing manipulation system to replace or increase tugboats. Besides the tugboat fault, a possible situation may come from the sudden bad weather during the towing process. In this case, the original tugboats may have no ability to fully control the floating object with the harsh winds, waves, and currents. Thus, in this emergency, it is necessary to dispatch additional tugboats to help the manipulation system on the verge of getting out of control.

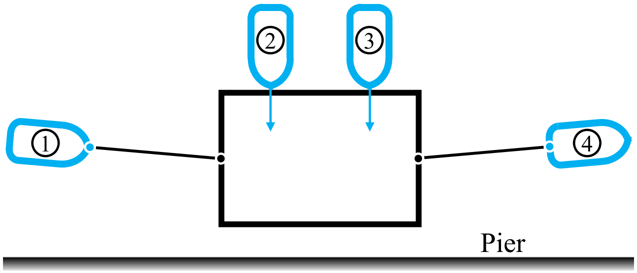


**Fig. 17.** Hybrid object manipulation with towing and pushing.

### *7.6. Hybrid floating object manipulation*

Different floating object manipulation ways can cooperate to take advantage of their strengths. For the attaching way, because of the fully controllable manipulation system brought from the fixed connection between the floating object and tugboats, there is no need for other manipulation ways to help. For the caging way, the limited floating object and application scenarios result in this manipulation is also difficult to work together with other manipulation ways. Thus, hybrid manipulation can only happen between pushing and towing ways.

A typical scenario is shown in Fig. 17. In the operation of berthing near the pier, the towing manipulation can control the floating object to reach the goal position in the lateral direction (tugboats 1 and 4 in Fig. 17). To make the floating object close to the pier in the longitudinal direction, other tugboats are usually required for providing pushing manipulation from the outside to the inside of the pier (tugboats 2 and 3 in Fig. 17). Meanwhile, the tugboats in the towing manipulation should also control the speed of the floating object for preventing it from colliding with the pier. Thus, the way of towing and pushing is required to cooperate tacitly to accomplish the hybrid manipulation task.

## 8. Conclusions

In the near future, autonomous multi-vessel systems will become a significant investigation subject, where the direction of floating object manipulation has the potential to make profound differences in the shipping industry. Inspired by the object manipulation research in the field of multi-robot systems, this paper summarized four typical floating object manipulation ways from the existing research works: attaching, caging, pushing, and towing. For each manipulation way, its definition and characteristics, the type of the floating object, and the application scenarios are discussed in detail. Besides, the control objectives concerned, the control architecture used, the collision avoidance involved, the environmental disturbances considered, and the role of each vessel in the floating object manipulation system are analyzed for digging into the control properties. Potential challenges and future directions have been put forward to facilitate the research progress of autonomous multi-vessel floating object manipulation.

## Declaration of competing interest

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

## Data availability

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

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## References

Aguiary, A., Almeiday, J., Bayaty, M., Cardeiray, B., Cunhay, R., Hauslery, A., et al. (2009). Cooperative autonomous marine vehicle motion control in the scope of the EU GREX project: Theory and practice. In *Proceedings of the oceans 2009-EUROPE* (pp. 1–10). Bremen, Germany.

Ahmed, Y. A., & Hasegawa, K. (2013). Automatic ship berthing using artificial neural network trained by consistent teaching data using nonlinear programming method. *Engineering Applications of Artificial Intelligence*, *26*(10), 2287–2304.

Alop, A. (2019). The main challenges and barriers to the successful "smart shipping". *TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation*, *13*(3), 521–528.

Amin, I., Oterkus, S., Ali, M. E. A., Shawky, H., & Oterkus, E. (2021). Experimental investigation on a towing assessment for a floating desalination plant for Egypt. *Ocean Engineering*, *238*, Article 109746.

Arrichiello, F., Chiaverini, S., & Fossen, T. (2006a). Formation control of underactuated surface vessels using the null-space-based behavioral control. In *Proceedings of the 2006 IEEE/RSJ international conference on intelligent robots and systems* (pp. 5942–5947). Beijing, China.

Arrichiello, F., Chiaverini, S., & Fossen, T. (2006b). Formation control of underactuated surface vessels using the null-space-sased sehavioral control. In *Proceedings of the 2006 IEEE/RSJ international conference on intelligent robots and systems* (pp. 5942–5947). Beijing, China.

Arrichiello, F., Heidarsson, H. K., Chiaverini, S., & Sukhatme, G. S. (2011). Cooperative caging and transport using autonomous aquatic surface vehicles. *Intelligent Service Robotics*, *5*(1), 73–87.

Berntsen, P. I. B., Aamo, O. M., Leira, B. J., & Sørensen, A. J. (2008). Structural reliability-based control of moored interconnected structures. *Control Engineering Practice*, *16*(4), 495–504.

Bertram, V. (2008). Unmanned surface vehicles-a survey. In *Proceedings of the skibsteknisk selskab* (pp. 1–14). Copenhagen, Denmark.

Bhattacharya, S., Heidarsson, H., Sukhatme, G. S., & Kumar, V. (2011a). *Supplementary report: Cooperative control of autonomous surface vehicles for oil skimming and cleanup*: *Tech. rep*, The GRASP Laboratory, University of Pennsylvania, http://www.subhrajit.net/files/Projects-Work/OilBoom_Catenary_2010/icra2011_Supplementary.pdf.

Bhattacharya, S., Heidarsson, H., Sukhatme, G. S., & Kumar, V. (2011b). Cooperative control of autonomous surface vehicles for oil skimming and cleanup. In *Proceedings of the 2011 IEEE international conference on robotics and automation* (pp. 2374–2379). Shanghai, China.

Bidikli, B., Tatlicioglu, E., & Zergeroglu, E. (2015). Robust control design for positioning of an unactuated surface vessel. In *Proceedings of the 2015 IEEE/RSJ international conference on intelligent robots and systems* (pp. 1071–1076). Hamburg, Germany.

Bidikli, B., Tatlicioglu, E., & Zergeroglu, E. (2016). Robust dynamic positioning of surface vessels via multiple unidirectional tugboats. *Ocean Engineering*, *113*, 237–245.

Bishop, B. E. (2008). Swarm-based object manipulation using redundant manipulator analogs. In *Proceedings of the 2008 IEEE international conference on robotics and automation* (pp. 1495–1500). Pasadena, CA, USA.

Braganza, D., Feemster, M., & Dawson, D. (2007). Positioning of large surface vessels using multiple tugboats. In *Proceedings of the 2007 American control conference* (pp. 912–917). New York, NY, USA.

Bruzzone, G., Bibuli, M., Caccia, M., & Zereik, E. (2013). Cooperative robotic maneuvers for emergency ship towing operations. In *Proceedings of the 2013 MTS/IEEE OCEANS* (pp. 1–7). Bergen, Norway.

Bruzzone, G., Bibuli, M., Zereik, E., Ranieri, A., & Caccia, M. (2016). Cooperative adaptive guidance and control paradigm for marine robots in an emergency ship towing scenario. *International Journal of Adaptive Control and Signal Processing*, *31*(4), 562–580.

Bui, V. P., Ji, S. W., Jang, J. S., & Kim, Y. B. (2012). Ship trajectory tracking in harbour area by using autonomous tugboats. *IFAC Proceedings Volumes*, *45*(13), 740–745.

Bui, V. P., Kawai, H., Kim, Y. B., & Lee, K. S. (2011). A ship berthing system design with four tug boats. *Journal of Mechanical Science and Technology*, *25*(5), 1257–1264.

Bui, P. V., & Kim, Y. B. (2011). Development of constrained control allocation for ship berthing by using autonomous tugboats. *International Journal of Control, Automation and Systems*, *9*(6), 1203–1208.

Chen, L., Hopman, H., & Negenborn, R. R. (2019). Distributed model predictive control for cooperative floating object transport with multi-vessel systems. *Ocean Engineering*, *191*, Article 106515.

Choi, J. K. (2020). Preliminary study on the docking control of a large ship using tugboats. *Journal of Advanced Marine Engineering and Technology*, *44*(4), 311–317.

Coelho, R., Daltry, R., Dobbin, V., Lachaud, E., & Miller, I. (2015). Design process and validation of an autonomous surface vehicle for the offshore industry. In *Proceedings of the offshore technology conference* (pp. 1–14). Rio de Janeiro, Brazil: Offshore Technology Conference.

Devaraju, A., Chen, L., & Negenborn, R. R. (2018). Autonomous surface vessels in ports: Applications, technologies and port infrastructures. In *Proceedings of the international conference on computational logistics 2018* (pp. 86–105). Vietri sul Mare, Italy.

dJI FORUM (2019). Tugboat attaching to big ship. https://forum.dji.com/thread-191617-1-1.html, (Accessed: 16 May 2022).

Du, Z., Negenborn, R. R., & Reppa, V. (2021a). Cooperative multi-agent control for autonomous ship towing under environmental disturbances. *IEEE/CAA Journal of Automatica Sinica*, *8*(8), 1365–1379.

Du, Z., Negenborn, R. R., & Reppa, V. (2021b). MPC-based COLREGS compliant collision avoidance for a multi-vessel ship-towing system. In *Proceedings of the European control conference* (pp. 1857–1862). Delft, Netherlands.

Du, Z., Negenborn, R. R., & Reppa, V. (2021c). Multi-vessel cooperative speed regulation for ship manipulation in towing scenarios. *IFAC-PapersOnLine*, *54*(16), 384–389.

Du, Z., Negenborn, R. R., & Reppa, V. (2022a). COLREGS-compliant collision avoidance for physically coupled multi-vessel systems with distributed MPC. *Ocean Engineering*, *260*, Article 111917.

Du, Z., Negenborn, R. R., & Reppa, V. (2022b). Dynamic coordination of multiple vessels for offshore platform transportation. In *Proceedings of the 6th IEEE conference on control technology and applications* (pp. 1–8). Trieste, Italy.

Du, Z., Negenborn, R. R., & Reppa, V. (2022c). Multi-objective cooperative control for a ship-towing system in congested water traffic environments. *IEEE Transactions on Intelligent Transportation Systems*, http://dx.doi.org/10.1109/TITS.2022.3208328.

Du, Z., Reppa, V., & Negenborn, R. R. (2020). Cooperative control of autonomous tugs for ship towing. *IFAC-PapersOnLine*, *53*(2), 14470–14475.

Eoh, G., Jeon, J. D., Choi, J. S., & Lee, B. H. (2011). Multi-robot cooperative formation for overweight object transportation. In *Proceedings of the 2011 IEEE/SICE international symposium on system integration* (pp. 726–731). Kyoto, Japan.

Esposito, J. M. (2008). Distributed grasp synthesis for swarm manipulation with applications to autonomous tugboats. In *Proceedings of the 2008 IEEE international conference on robotics and automation* (pp. 1489–1494). Pasadena, CA, USA.

Esposito, J. M. (2009). Decentralized cooperative manipulation with a swarm of mobile robots. In *Proceedings of the 2009 IEEE/RSJ international conference on intelligent robots and systems* (pp. 5333–5338). St. Louis, MO, USA.

Esposito, J. M. (2010). Decentralized cooperative manipulation with a swarm of mobile robots: The approach problem. In *Proceedings of the 2010 American control conference* (pp. 4762–4767). Baltimore, MD, USA.

Esposito, J., Feemster, M., & Smith, E. (2008). Cooperative manipulation on the water using a swarm of autonomous tugboats. In *Proceedings of the 2008 IEEE international conference on robotics and automation* (pp. 1501–1506). Pasadena, CA, USA.

Feemster, M. G., & Esposito, J. M. (2010). Comprehensive framework for tracking control and thrust allocation for a highly overactuated autonomous surface vessel. *Journal of Field Robotics*, *28*(1), 80–100.

Feemster, M., Esposito, J., & Nicholson, J. (2006). Manipulation of large object by swarms of autonomous marine vehicles, part I: Rotational motions. In *Proceedings of the 2006 thrity-eighth southeastern symposium on system theory* (pp. 205–209). Cookeville, TN, USA.

Fossen, T. I. (2011). *Handbook of marine craft hydrodynamics and motion control*. Chichester, West Sussex, UK: John Wiley & Sons.

Gapingsi, G. E., Korbas, R., & Santos, M. (2017). Modelling and control of a flexible floating boom: First approach. *IFAC-PapersOnLine*, *50*(1), 13108–13113.

Gheneti, B., Park, S., Kelly, R., Meyers, D., Leoni, P., Ratti, C., et al. (2019). Trajectory planning for the shapeshifting of autonomous surface vessels. In *Pordeedings of the 2019 international symposium on multi-robot and multi-agent systems* (pp. 76–82). New Brunswick, NJ, USA.

Ghommam, J., Mnif, F., Benali, A., & Derbel, N. (2006). Asymptotic backstepping stabilization of an underactuated surface vessel. *IEEE Transactions on Control Systems Technology*, *14*(6), 1150–1157.

González, E. F. P., Torres, G. R., & Pulido, G. T. (2008). Motion planning for cooperative multi-robot box-pushing problem. In *Proceedings of the advances in artificial intelligence* (pp. 382–391). Berlin, Heidelberg: Springer Berlin Heidelberg.

Hajieghrary, H., Kularatne, D., & Hsieh, M. A. (2017). Cooperative transport of a buoyant load: A differential geometric approach. In *Proceedings of the 2017 IEEE/RSJ international conference on intelligent robots and systems* (pp. 2158–2163). Vancouver, BC, Canada.

Hajieghrary, H., Kularatne, D., & Hsieh, M. A. (2018). Differential geometric approach to trajectory planning: Cooperative transport by a team of autonomous marine vehicles. In *Proceedings of the 2018 annual American control conference* (pp. 858–863). Milwaukee, WI, USA.

Hara, I. O., Paulos, J., Davey, J., Eckenstein, N., Doshi, N., Tosun, T., et al. (2014). Self-assembly of a swarm of autonomous boats into floating structures. In *Proceedings of the 2014 IEEE international conference on robotics and automation* ICRA, (pp. 1234–1240). Hong Kong, China.

Hensen, H. (2003). *Tug use in port: A practical guide*. London, UK: Nautical Institute.

H́offmann, M., Roy, S., Berger, A., Bergmann, W., Chan, K., Shubbak, M., et al. (2021). Wind affected maneuverability of tugboat-controlled ships. *IFAC-PapersOnLine*, *54*(16), 70–75.

Hu, Y., Wang, L., Liang, J., & Wang, T. (2010). Underwater box-pushing with multiple vision-based autonomous robotic fish. In *Proceedings of the 2010 IEEE/RSJ international conference on intelligent robots and systems* (pp. 4219–4224). Taipei, Taiwan.

Hu, Y., Wang, T., Wang, L., & Liang, J. (2011). Cooperative box-pushing with multiple autonomous robotic fish in underwater environment. *IET Control Theory & Applications*, *5*(17), 2015–2022.

Ianagui, A. S. S., & Tannuri, E. A. (2019). Automatic load maneuvering and hold-back with multiple coordinated DP vessels. *Ocean Engineering*, *178*, 357–374.

International Maritime Organization (2017). Maritime safety committee (MSC), 98th session. https://www.imo.org/en/MediaCentre/MeetingSummaries/Pages/MSC-98th-session.aspx, (Accessed 01 February 2022).

International Maritime Organization (2018). IMO takes first steps to address autonomous ships. https://www.imo.org/en/MediaCentre/PressBriefings/Pages/08-MSC-99-MASS-scoping.aspx, (Accessed 01 February 2022).

Ismail, M. M., Chalhoub, N. G., & Pilipchuk, V. (2021). Dynamics and control of a two-ship ensemble connected by a massless towline. *Ocean Engineering*, *234*, Article 109295.

Ji, S. W., Choi, K. H., & Kim, Y. B. (2012). Nonlinear observer and sliding mode control design for dynamic positioning of a surface vessel. In *Proceedings of the 2012 12th international conference on control, automation and systems* (pp. 1900–1904). JeJu Island, South Korea.

Jimenez, J., & Sierra, J. M. G. (2018). Modelling the automatic deployment of oil-spill booms: A simulation scenario for sea cleaning. In *Proceedings of the 2018 winter simulation conference* (pp. 1192–1203). Gothenburg, Sweden.

Jimenez, J. F., & Sierra, J. M. G. (2020). USV based automatic deployment of booms along quayside mooring ships: Scaled experiments and simulations. *Ocean Engineering*, *207*, Article 107438.

Johansen, T. A., & Fossen, T. I. (2013). Control allocation: A survey. *Automatica*, *49*(5), 1087–1103.

Kayacan, E., Park, S., Ratti, C., & Rus, D. (2019). Learning-based nonlinear model predictive control of reconfigurable autonomous robotic boats: Roboats. In *Proceedings of the 2019 IEEE/RSJ international conference on intelligent robots and systems* (pp. 8230–8237). Macau, China.

KOTUG Canada (2017). KOTUG and SEABULK awarded contact at BAHAMAS. https://www.kotugcanada.ca/newsmedia/kotug-seabulk-maritime-starts-bahamas, (Accessed 16 February 2022).

Lee, D. H., Chakir, S., Kim, Y. B., & Tran, D. Q. (2020). Control system design for vessel towing system by activating rudders of the towed vessel. *International Journal of Naval Architecture and Ocean Engineering*, *12*, 943–956.

Lee, S. M., Lee, J. H., Roh, M., Kim, K. S., Ham, S. H., & Lee, H. W. (2021). An optimization model of tugboat operation for conveying a large surface vessel. *Journal of Computational Design and Engineering*, *8*(2), 654–675.

Li, Y., Landsburg, A. C., Barr, R. A., & Calisal, S. M. (2005). Improving ship maneuverability standards as a means for increasing ship controllability and safety. In *Proceedings of the IEEE/MTS/ OCEANS 2005* (pp. 1972–1981). Washington, DC, USA.

Li, J. H., Lee, P. M., Jun, B. H., & Lim, Y. K. (2008). Point-to-point navigation of underactuated ships. *Automatica*, *44*(12), 3201–3205.

Li, Z., & Sun, J. (2011). Disturbance compensating model predictive control with application to ship heading control. *IEEE Transactions on Control Systems Technology*, *20*(1), 257–265.

Li, B., Zhang, Y., Acarma, T., Kong, Q., & Zhang, Y. (2019). Trajectory planning for a tractor with multiple trailers in extremely narrow environments: A unified approach. In *Proceedings of 2019 international conference on robotics and automation* (pp. 8557–8562). Montreal, QC, Canada.

Liu, Y., & Bucknall, R. (2018). A survey of formation control and motion planning of multiple unmanned vehicles. *Robotica*, *36*(7), 1019–1047.

Marine Insight (2017). Rolls-Royce demonstrates world's first remotely operated commercial vessel. https://www.marineinsight.com/shipping-news/rolls-royce-demonstrates-worlds-first-remotely-operated-commercial-vessel/, (Accessed 01 February 2022).

Marine Insight (2019). Wartsila's autonomous harbour tug takes A big leap towards reality. https://www.marineinsight.com/shipping-news/wartsilas-autonomous-harbour-tug-takes-a-big-leap-towards-reality/, (Accessed 01 February 2022).

Marine Insight (2020). Abu Dhabi ports to develop world's first unmanned autonomous commercial tugboats. https://www.marineinsight.com/shipping-news/abu-dhabi-ports-to-develop-worlds-first-unmanned-autonomous-commercial-tugboats/, (Accessed 01 February 2022).

Marine Insight (2021). ABB to power first fully electric US tugboat for zero-emission operations. https://www.marineinsight.com/shipping-news/abb-to-power-first-fully-electric-us-tugboat-for-zero-emission-operations/, (Accessed 01 February 2022).

Marine Oil Gobbler (2018). Environmentally acceptable oil spill dispersant for the effective treatment of marine oil spills. https://www.ecozyme.co.za/marine-oil-spill-dispersant.pdf, (Accessed 14 February 2022).

Mas, I., & Kitts, C. (2012). Object manipulation using cooperative mobile multi-robot systems. In *Proceedings of the world congress on engineering and computer science: vol. 1*, (pp. 1–6). San Francisco, USA.

Mas, I., & Kitts, C. (2013). Cooperative tasks using teams of mobile robots. In *Lecture notes in electrical engineering* (pp. 83–99). Springer Netherlands.

Mateos, L. A. (2020). Bio-inspired adaptive latching system for towing and guiding power-less floating platforms with autonomous robotic boats. (pp. 1–7). arXiv preprint arXiv:2001.04293.

Mateos, L. A., Wang, W., Gheneti, B., Duarte, F., Ratti, C., & Rus, D. (2019). Autonomous latching system for robotic boats. In *Proceedings of the 2019 international conference on robotics and automation* (pp. 7933–7939). Montreal, QC, Canada.

Mizuno, N., Uchida, Y., & Okazaki, T. (2015). Quasi real-time optimal control scheme for automatic berthing. *IFAC-PapersOnLine*, *48*(16), 305–312.

Negenborn, R. R., & Maestre, J. M. (2013). On 35 approaches for distributed MPC made easy. In *Distributed model predictive control made easy* (pp. 1–37). Springer Netherlands.

Nesi, L., Pepe, G., Bibuli, M., Zereik, E., Carcaterra, A., & Caccia, M. (2019). A new tow maneuver of a damaged boat through a swarm of autonomous sea drones. *IFAC-PapersOnLine*, *52*(21), 360–366.

Pan, C. Z., Lai, X. Z., Yang, S. X., & Wu, M. (2013). An efficient neural network approach to tracking control of an autonomous surface vehicle with unknown dynamics. *Expert Systems with Applications*, *40*(5), 1629–1635.

Park, S., Kayacan, E., Ratti, C., & Rus, D. (2019). Coordinated control of a reconfigurable multi-vessel platform: Robust control approach. In *Proceedings of the 2019 international conference on robotics and automation* ICRA, (pp. 4633–4639). Montreal, QC, Canada.

Paulauskas, V., & Paulauskas, D. (2011). Research on work methods for tugs in ports. *TRANSPORT*, *26*(3), 310–314.

Paulos, J., Eckenstein, N., Tosun, T., Seo, J., Davey, J., Greco, J., et al. (2015). Automated self-assembly of large maritime structures by a team of robotic boats. *IEEE Transactions on Automation Science and Engineering*, *12*(3), 958–968.

Peng, Z., Wang, D., Chen, Z., Hu, X., & Lan, W. (2013). Adaptive dynamic surface control for formations of autonomous surface vehicles with uncertain dynamics. *IEEE Transactions on Control Systems Technology*, *21*(2), 513–520.

Peng, Z., Wang, J., Wang, D., & Han, Q. L. (2021). An overview of recent advances in coordinated control of multiple autonomous surface vehicles. *IEEE Transactions on Industrial Informatics*, *17*(2), 732–745.

Pereda, F. J., de Marina, H. G., Sierra, J. M. G., & Jimenez, J. (2011). Towards automatic oil spill confinement with autonomous marine surface vehicles. In *Proceedings of the IEEE/MTS OCEANS 2011* (pp. 1–6). Santander, Spain.

Pereira, G. A. S., Campos, M. F. M., & Kumar, V. (2004). Decentralized algorithms for multi-robot manipulation via caging. *International Journal of Robotics Research*, *23*(7–8), 783–795.

Pereira, A., Das, J., & Sukhatme, G. S. (2008). An experimental study of station keeping on an underactuated ASV. In *Proceedings of the 2008 IEEE/RSJ international conference on intelligent robots and systems* (pp. 3164–3171). Nice, France.

Port Technology (2018). Kotug shows how remotely operated tugs can work. https://www.porttechnology.org/news/kotug_shows_how_remotely_operated_tugs_can_work/, (Accessed 01 February 2022).

Port Technology International Team (2017). Autonomous tugs: A feature of the future? https://www.porttechnology.org/news/autonomous_tugs_a_feature_of_the_future/, (Accessed 01 February 2022).

Pourbabak, H., Chen, T., & Su, W. (2019). Centralized, decentralized, and distributed control for energy internet. In *The Energy Internet* (pp. 3–19). Elsevier.

Quan, T. D., Suh, J. H., & Kim, Y. B. (2019). Leader-following control system design for a towed vessel by tugboat. *Journal of Ocean Engineering and Technology*, *33*(5), 462–469.

Raboin, E., Švec, P., Nau, D. S., & Gupta, S. K. (2014). Model-predictive asset guarding by team of autonomous surface vehicles in environment with civilian boats. *Autonomous Robots*, *38*(3), 261–282.

Riviera Maritime Media (2020). Dutch tug owner takes autonomous command punt. https://www.rivieramm.com/news-content-hub/dutch-tug-owner-takes-an-autonomous-command-punt-61988, (Accessed 01 February 2022).

Rosario, R. V. C., Cunha, J. P. V. S., & Rosa, P. B. G. (2020). Stabilizing control of an unmanned surface vehicle pushing a floating load. *International Journal of Control, Automation and Systems*, *18*(12), 3194–3203.

Rossomando, F., Rosales, C., Gimenez, J., Salinas, L., Soria, C., Sarcinelli-Filho, M., et al. (2020). Aerial load transportation with multiple quadrotors based on a kinematic controller and a neural SMC dynamic compensation. *Journal of Intelligent & Robotic Systems*.

Sartoretti, G., Shaw, S., & Hsieh, M. A. (2016). Distributed planar manipulation in fluidic environments. In *Proceedings of the 2016 IEEE international conference on robotics and automation* (pp. 5322–5327). Stockholm, Sweden.

Schiaretti, M., Chen, L., & Negenborn, R. R. (2017). Survey on autonomous surface vessels: Part I - A new detailed definition of autonomy levels. In *Proceedings of the 8th international conference on computational logistics* (pp. 219–233). Southampton, UK.

Seo, J., Yim, M., & Kumar, V. (2016). Assembly sequence planning for constructing planar structures with rectangular modules. In *Proceedings of the 2016 IEEE international conference on robotics and automation* (pp. 5477–5482). Stockholm, Sweden.

Shojaei, K. (2015). Leader–follower formation control of underactuated autonomous marine surface vehicles with limited torque. *Ocean Engineering*, *105*, 196–205.

Shuai, Y., Li, G., Cheng, X., Skulstad, R., Xu, J., Liu, H., et al. (2019). An efficient neural-network based approach to automatic ship docking. *Ocean Engineering*, *191*, Article 106514.

Sierra, J. M. G., Gheorghita, A. T., Angulo, G., & Jimenez, J. F. (2014). Towing a boom with two USVs for oil spill recovery: Scaled experimental development. In *Proceedings of the 2014 13th international conference on control automation robotics & vision* (pp. 1729–1734). Singapore, Singapore.

Sierra, J. M. G., Gheorghita, A. T., Angulo, G., & Jimenez, J. F. (2015). Preparing the automatic spill recovery by two unmanned boats towing a boom: Development with scale experiments. *Ocean Engineering*, *95*, 23–33.

Sierra, J. M. G., Gheorghita, A. T., & Jimenez, J. F. (2015). Fully automatic boom towing by unmanned ships: Experimental study. In *Proceedings of the IEEE/MTS OCEANS 2015* (pp. 1–10). Washington, DC, USA.

Sierra, J. M. G., & Jimenez, J. F. (2018). Using an USV for automatic deployment of a boom around a ship: Simulation and scale experiment. In *Proceedings of the IEEE/MTS OCEANS 2018* (pp. 1–10). Charleston, SC, USA.

Skjetne, R., Moi, S., & Fossen, T. I. (2002). Nonlinear formation control of marine craft. In *Proceedings of the 41st IEEE conference on decision and control* (pp. 1699–1704). Las Vegas, NV, USA.

Smith, E. T., Feemster, M. G., & Esposito, J. M. (2007). Swarm manipulation of an unactuated surface vessel. In *Proceedings of the 2007 39th southeastern symposium on system theory* (pp. 16–20). Macon, GA, USA.

Tao, J., Du, L., Dehmer, M., Wen, Y., Xie, G., & Zhou, Q. (2019). Path following control for towing system of cylindrical drilling platform in presence of disturbances and uncertainties. *ISA Transactions*, *95*, 185–193.

Tee, K. P., & Ge, S. S. (2006). Control of fully actuated ocean surface vessels using a class of feedforward approximators. *IEEE Transactions on Control Systems Technology*, *14*(4), 750–756.

Texas Boom Company (2018). Oil spill containment booms. https://texasboom.com, (Accessed 14 February 2022).

The Maritime Executive (2016). PMI teams with Robert Allan on autonomous tug. https://maritime-executive.com/corporate/pmi-teams-with-robert-allan-on-autonomous-tug, (Accessed 01 February 2022).

The Maritime Executive (2017). Developing world's first fully remotely controlled commercial tug. https://www.maritime-executive.com/article/developing-world-s-first-fully-remotely-controlled-commercial-tug, (Accessed 01 February 2022).

The Maritime Executive (2018). Japan prepares for autonomous tugboat test. https://www.maritime-executive.com/article/japan-prepares-for-autonomous-tugboat-test, (Accessed 01 February 2022).

The Maritime Executive (2020). Initial sea trials for autonomous tug project. https://maritime-executive.com/corporate/initial-sea-trials-for-autonomous-tug-project, (Accessed 01 February 2022).

The Maritime Executive (2021a). Foss builds first U.S. tug with autonomous capabilities. https://www.maritime-executive.com/article/foss-builds-first-u-s-tug-with-autonomous-capabilities, (Accessed 01 February 2022).

The Maritime Executive (2021b). OSV operator vallianz joins the all-electric tugboat trend. https://www.maritime-executive.com/article/osv-operator-vallianz-joins-the-all-electric-tugboat-trend, (Accessed 01 February 2022).

The Maritime Executive (2021c). Port of Tianjin signs up for semi-autonomous tugs. https://www.maritime-executive.com/article/port-of-tianjin-signs-up-for-semi-autonomous-tugs, (Accessed 01 February 2022).

The Maritime Executive (2021d). Sea machines sets out to prove AI potential with tugboat voyage. https://www.maritime-executive.com/article/sea-machines-to-prove-autonomous-tech-potential-with-tugboat-voyage, (Accessed 01 February 2022).

The Maritime Executive (2021e). Testing autonomous remote control of ships in Singapore. https://www.maritime-executive.com/article/testing-autonomous-remote-control-of-ships-in-singapore, (Accessed 01 February 2022).

Thorvaldsen, C. F. L., & Skjetne, R. (2011). Formation control of fully-actuated marine vessels using group agreement protocols. In *Proceedings of the IEEE conference on decision and control and European control conference* (pp. 4132–4139). Orlando, FL, USA.

Tuci, E., Alkilabi, M. H. M., & Akanyeti, O. (2018). Cooperative object transport in multi-robot systems: A review of the state-of-the-art. *Frontiers in Robotics and AI*, *5*, 59.

Wang, Z., & Kumar, V. (2002). Object closure and manipulation by multiple cooperating mobile robots. In *Proceedings of the 2002 IEEE international conference on robotics and automation* (pp. 394–399). Washington, DC, USA.

Wang, W., Wang, Z., Mateos, L., Huang, K. W., Schwager, M., Ratti, C., et al. (2020). Distributed motion control for multiple connected surface vessels. In *Proceedings of the 2020 IEEE/RSJ international conference on intelligent robots and systems* (pp. 11658–11665). Las Vegas, NV, USA.

Wu, G., Zhao, X., Sun, Y., & Wang, L. (2021). Cooperative maneuvering mathematical modeling for multi-tugs towing a ship in the port environment. *Journal of Marine Science and Engineering*, *9*(4), 384.

Xia, G., Sun, C., Zhao, B., Sun, X., & Xia, X. (2021). Robust cooperative trajectory tracking control for an unactuated floating object with multiple vessels system. *ISA Transactions*, 1–9.

Xie, J., Luo, J., Peng, Y., Xie, S., Pu, H., Li, X., et al. (2020). Data driven hybrid edge computing-based hierarchical task guidance for efficient maritime escorting with multiple unmanned surface vehicles. *Peer-To-Peer Networking and Applications*, 1–11.

Yun, L., & Jian, Z. (2018). Design and implementation of cooperative turning control for the towing system of unpowered facilities. *IEEE Access*, *6*, 18713–18722.

Zhang, L. J., Jia, H. M., & Qi, X. (2011). NNFFC-adaptive output feedback trajectory tracking control for a surface ship at high speed. *Ocean Engineering*, *38*(13), 1430–1438.

Zhang, P., Peng, Y., Ding, H., Hu, R., & Shi, J. (2019). Numerical analysis of offshore integrated meteorological mast for wind farms during wet towing transportation. *Ocean Engineering*, *188*, Article 106271.

Zhang, D., Wang, L., Yu, J., & Tan, M. (2007). Coordinated transport by multiple biomimetic robotic fish in underwater environment. *IEEE Transactions on Control Systems Technology*, *15*(4), 658–671.

Zheng, Y., Tao, J., Sun, Q., Sun, H., Sun, M., & Chen, Z. (2021). An intelligent course keeping active disturbance rejection controller based on double deep Q-network for towing system of unpowered cylindrical drilling platform. *International Journal of Robust and Nonlinear Control*, *31*(17), 8463–8480.

Zhou, X., Ge, Y., Li, W., & Ye, G. (2021). Time-constrained multiple unmanned surface vehicles cooperation for sea surface oil pollution cleanup. In *Proceedings of the 2021 6th international conference on robotics and automation engineering* (pp. 40–45). Guangzhou, China.

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